First MINOS Results from the NuMI Beam

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For the MINOS Collaboration

Joint Experimental/Theoretical Physics Seminar
Fermilab March 30th 2006

Overview of the talk

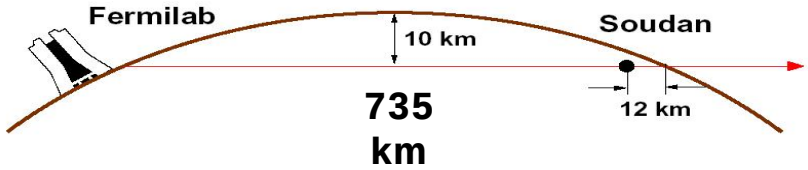
- Introduction to the MINOS experiment
  - Overview of MINOS Physics Goals
  - The NuMI facility and the MINOS detectors
- Start-up of the experiment
  - Commissioning of the neutrino beamline
  - Near detector distributions and comparison with Monte Carlo
- Far detector analysis
  - Selecting Beam neutrino candidates in the Far detector
  - Near-Far extrapolation of the neutrino flux
  - **Oscillation Analysis with 0.93e20 pot**

Introduction to MINOS

The experiment and its Physics Goals

The MINOS Experiment

- **MINOS (Main Injector Neutrino Oscillation Search)** – a long-baseline neutrino oscillation experiment:
  - Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.
  - A Near detector at Fermilab to measure the beam composition and energy spectrum
  - A Far detector deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations



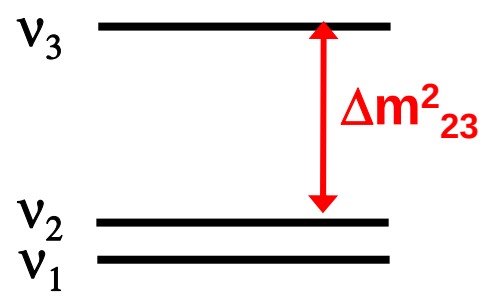
MINOS Physics Goals

- Verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis and make a precise (<10%) measurement of the oscillation parameters Δm^2 and $\sin^2 2\theta$.
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations (not yet seen at this mass-scale)
- Search for/rule out exotic phenomena:
  - Sterile neutrinos
  - Neutrino decay
- Use magnetised MINOS Far detector to study neutrino and anti-neutrino oscillations
  - Test of CPT violation
- Atmospheric neutrino oscillations:
  - First MINOS paper: **hep-ex/0512036, to be published In Phys. Rev. D**

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



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

$$\text{if} \quad \Delta m_{23}^2 >> \Delta m_{12}^2$$

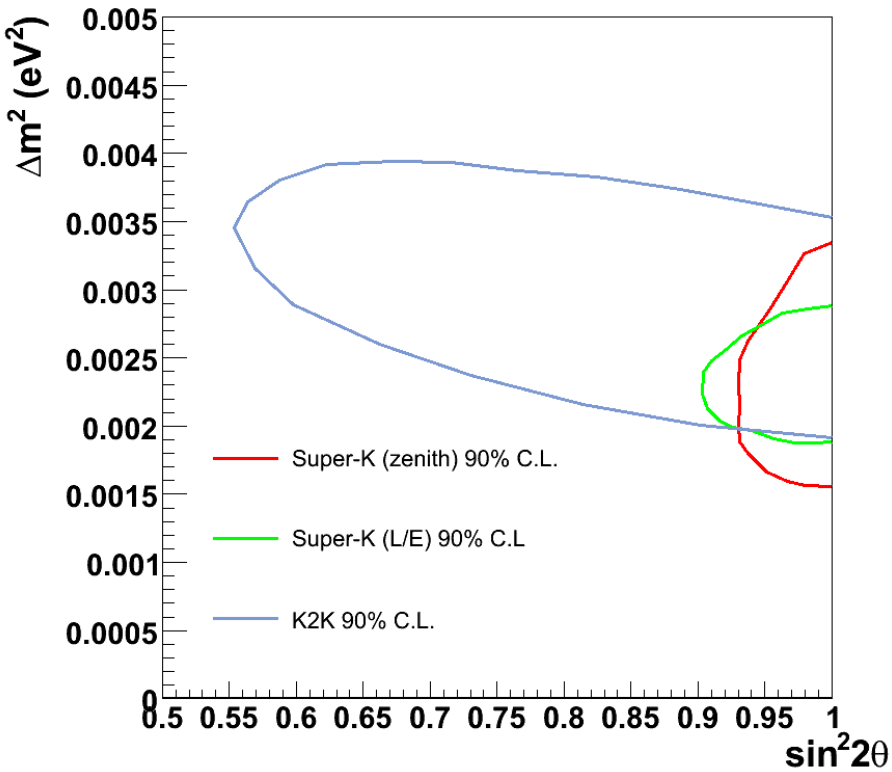
Current knowledge of the 2-3 sector of the MNS mixing matrix

- 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)

- The limits (at 90% C.L.) are:
  - $\sin^2 2\theta > 0.9$
  - $1.9 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

- The analysis presented in this talk, which is for 9.3×10^{19} pot, should provide a measurement of the mixing parameters that is competitive with these results

Allowed regions from Super-K and K2K



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

Overview of the Oscillation Measurement

- In order to perform the oscillation analysis, we need to predict the Far detector unoscillated true neutrino spectrum.

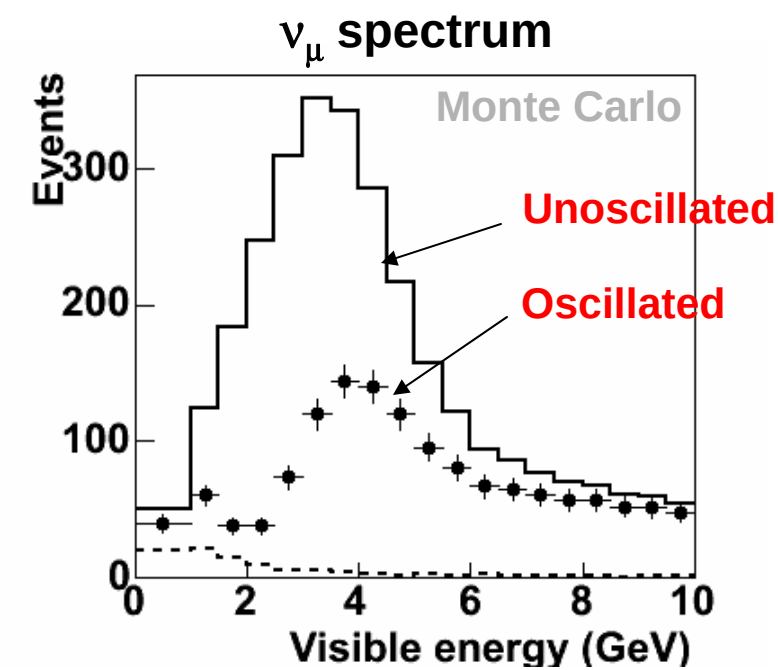
- The goal is to perform this procedure in such a way that we are as insensitive as possible to uncertainties related to beam modelling and cross-sections built-in to our nominal Monte Carlo.

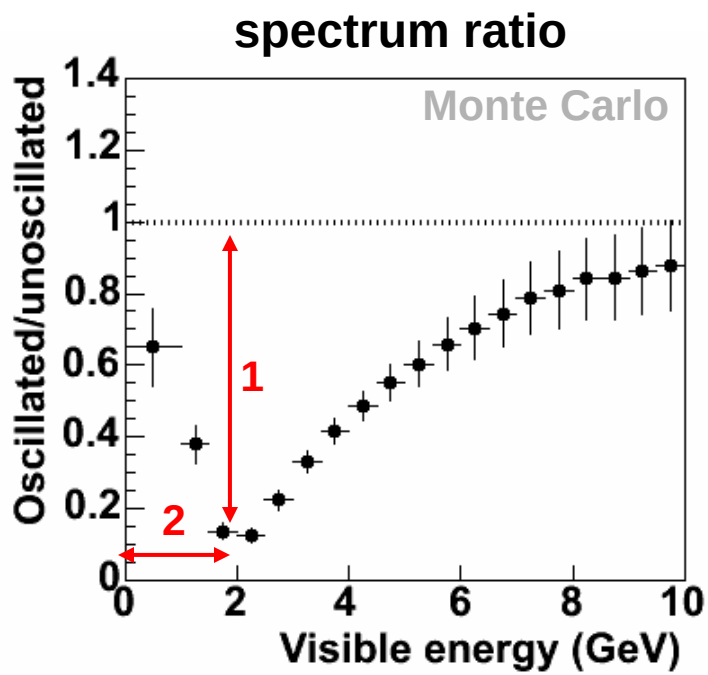
- This is exactly the purpose of the Near detector, and therefore we directly use the Near detector data to perform the extrapolation, using our Monte Carlo to provide necessary corrections due to energy smearing and acceptance.

Example of a ν_μ disappearance measurement

- Look for a deficit of ν_μ events at Soudan…

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



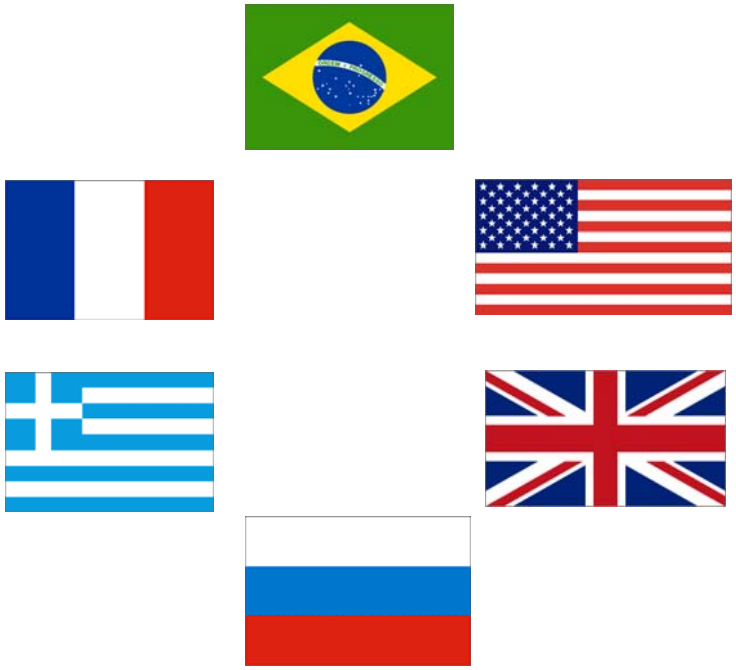


Overview of the MINOS experiment

The NuMI beamline and the MINOS detectors

Beam commissioning and MINOS start-up

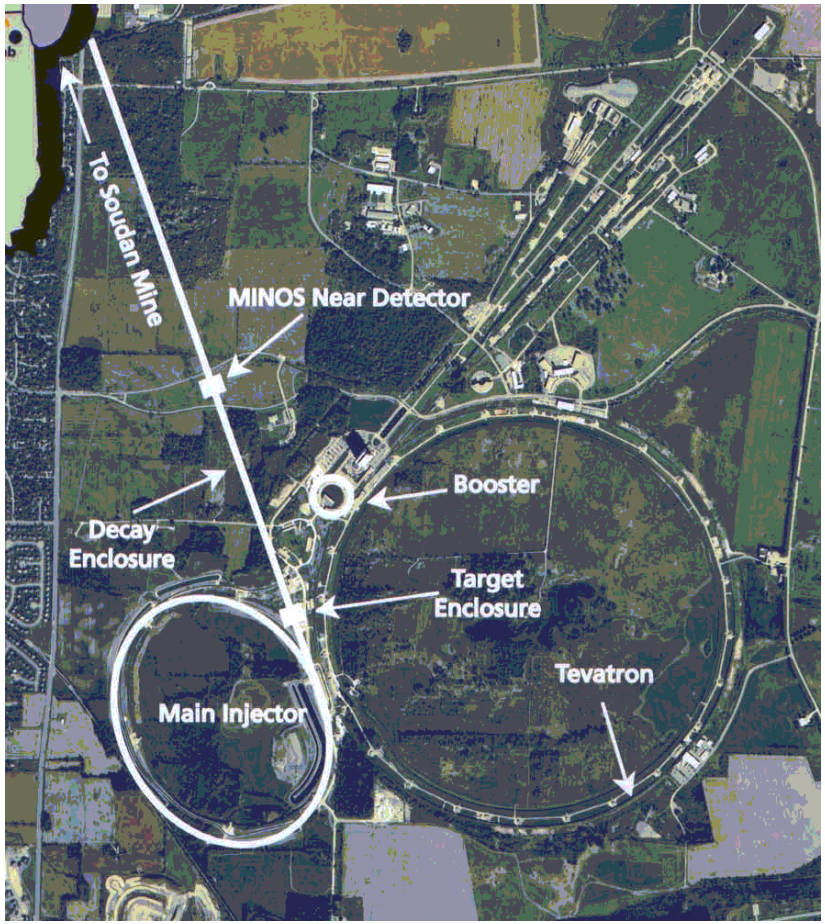
The MINOS Collaboration



32 institutions
175 scientists

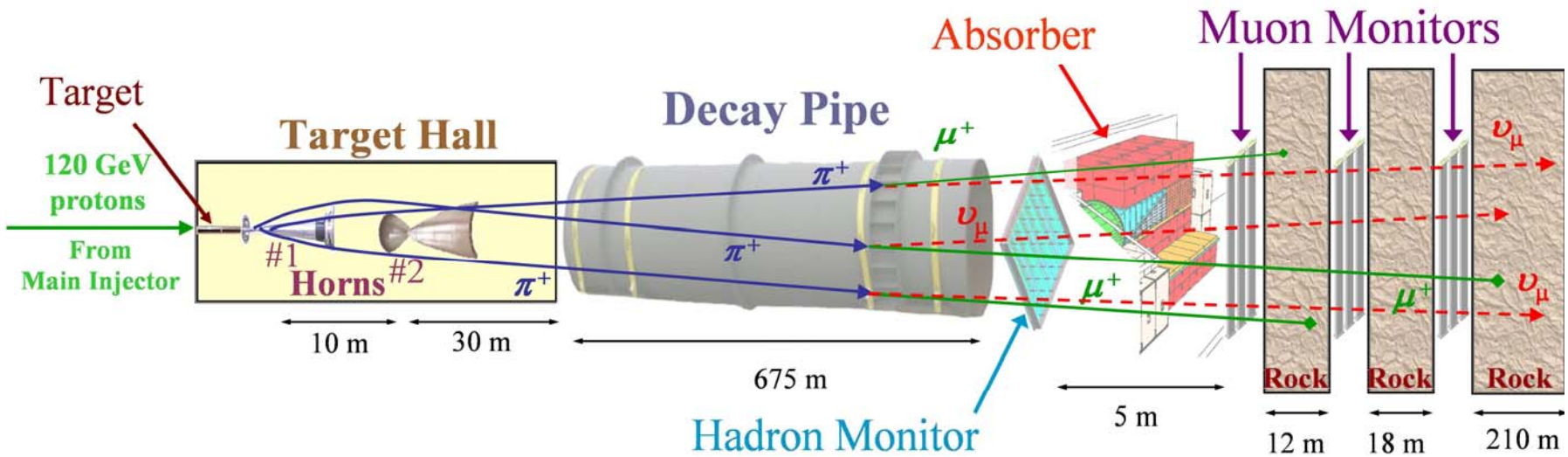
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Western Washington • William & Mary • Wisconsin

The NUMI facility



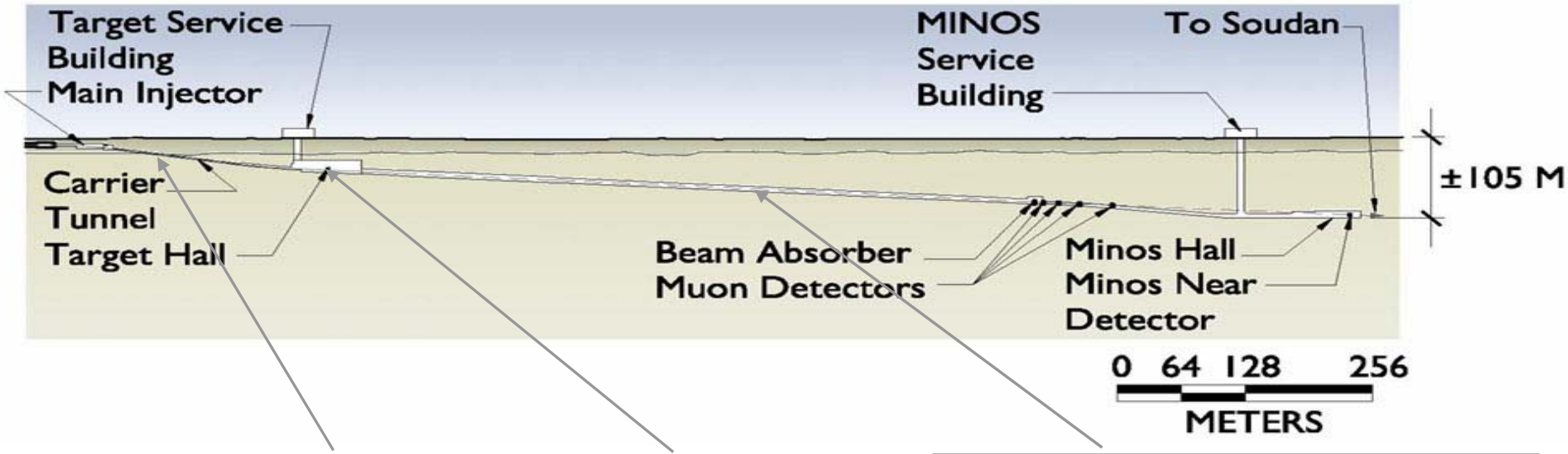
- **Design parameters:**
  - 120 GeV protons from the Main Injector
  - Main Injector can accept up to 6 Booster batches/cycle,
  - Either 5 or 6 batches for NuMI
  - 1.867 second cycle time
  - 4×10^{13} protons/pulse
  - 0.4 MW
  - Single turn extraction (10μs)

Producing the neutrino beam

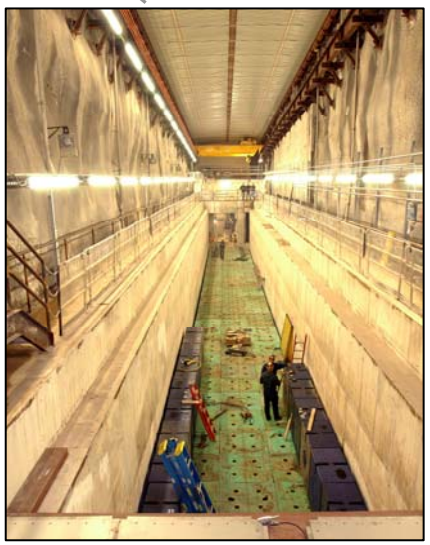


- Moveable target relative to horn 1 – continuously variable neutrino spectrum

The NuMI beamline



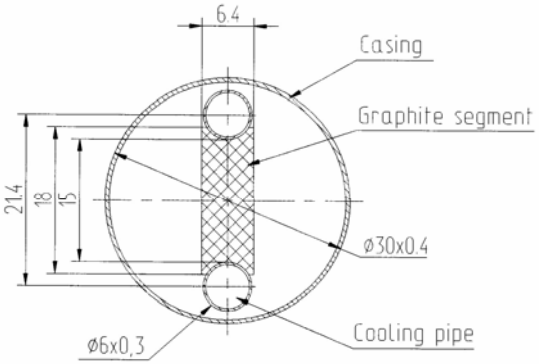
Primary proton line



Target hall

Decay pipe

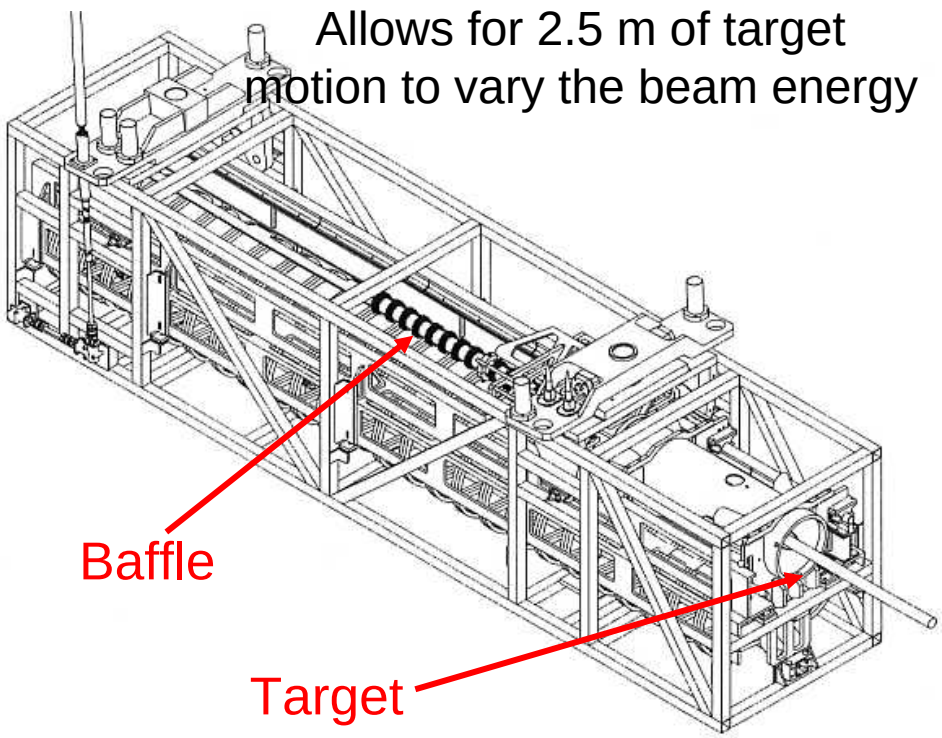
NuMI target



- Target:
  - 47 segments of graphite of 20 mm length and 6.4×15 mm^2 cross section
  - 0.3 mm spacing between segments, for a total target length of 95.4 cm
- Baffle:
  - protects beamline components from beam mis-steering
  - 150 cm long graphite rod with 11mm diameter hole

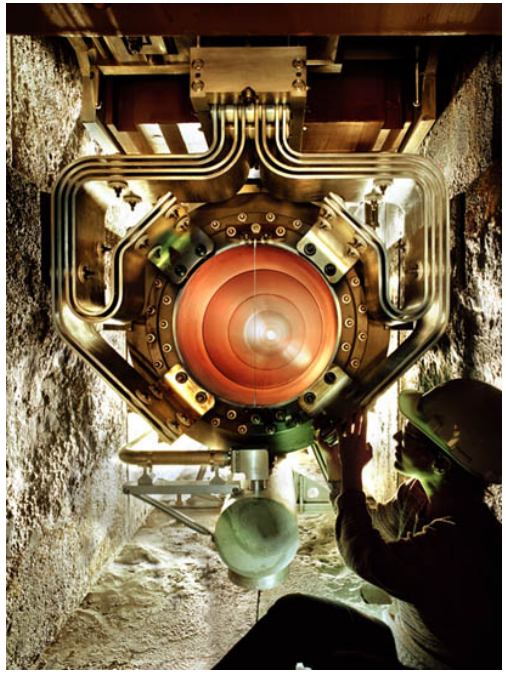
Target/Baffle carrier

Allows for 2.5 m of target motion to vary the beam energy



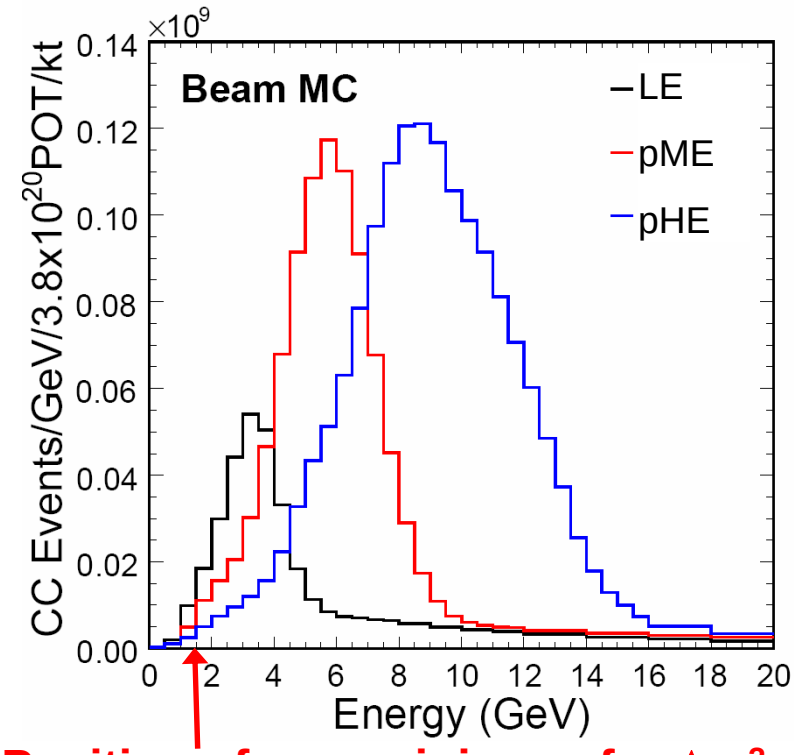
Focussing horns

- Two parabolic focussing horns connected in series.
- Nominal horn current at 200 kA
- Produces 3.0 Tesla peak field



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



Position of osc. minimum for Δm^2=0.0025 eV²

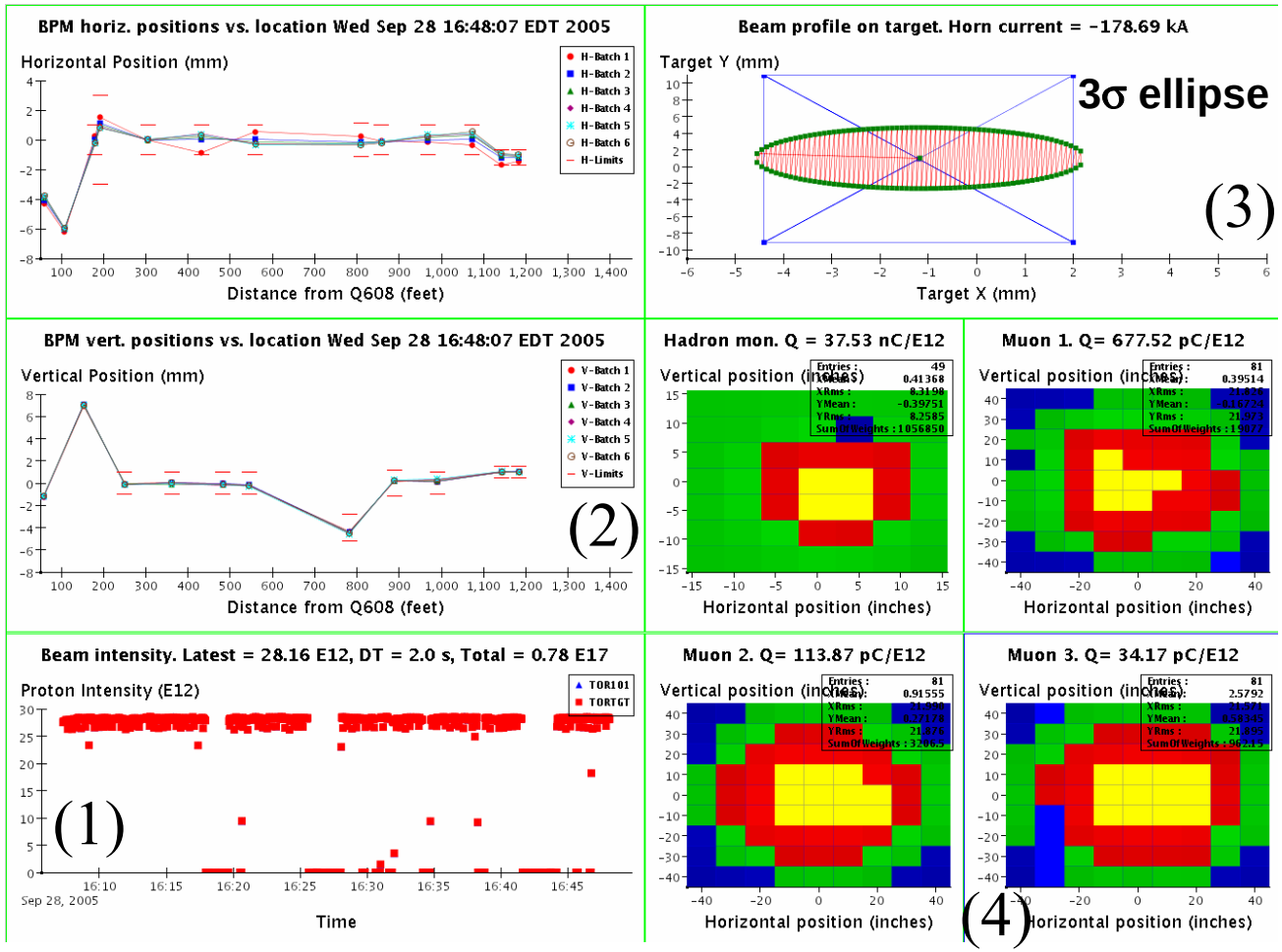
Expected no of events (no osc.) in Far Detector

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

Events in fiducial volume

Monitoring the NuMI beam

- Each spill we monitor:
  - •Intensity (1),
  - •Beam position (2)
  - •Beam profile at the target (3)
  - •hadron and muon profiles at the end of the decay volume (4)
- •This information is then used offline to select good beam quality spills



Detector Technology

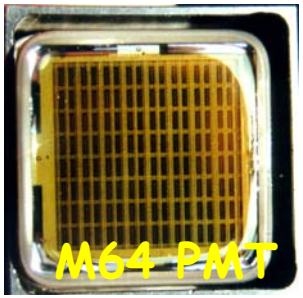
MINOS Near and Far detectors are functionally identical: share same detector technology and granularity:

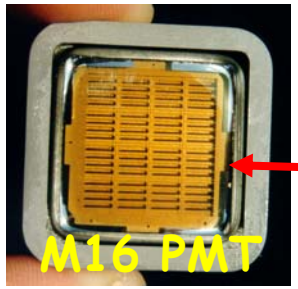
2.54 cm thick magnetised steel plates

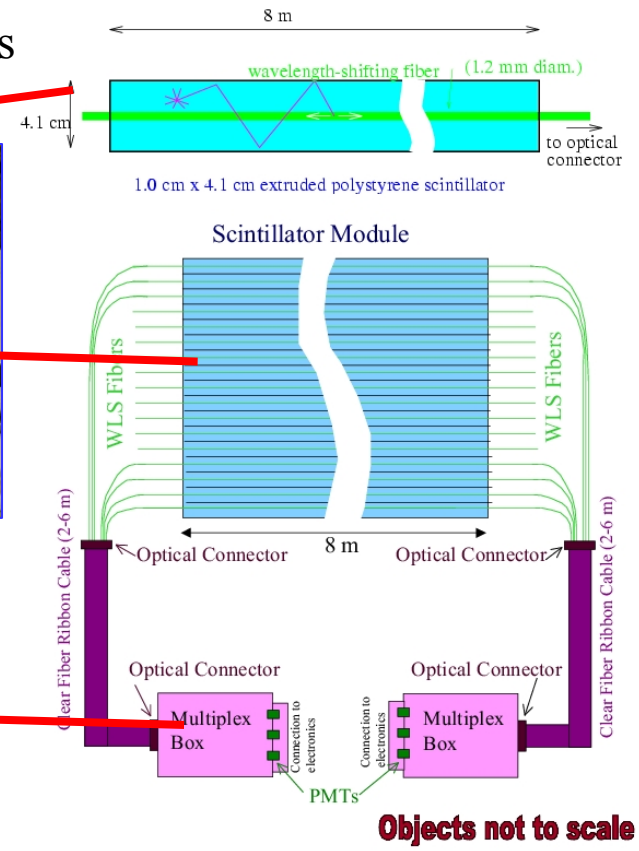
4.1x1cm co-extruded scintillator strips (MINOS-developed technology)

orthogonal orientation on alternate planes – U,V

optical fibre readout to multi-anode PMTs







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

Software triggering in DAQ PCs (Highly flexible : plane, energy, LI triggers in use)

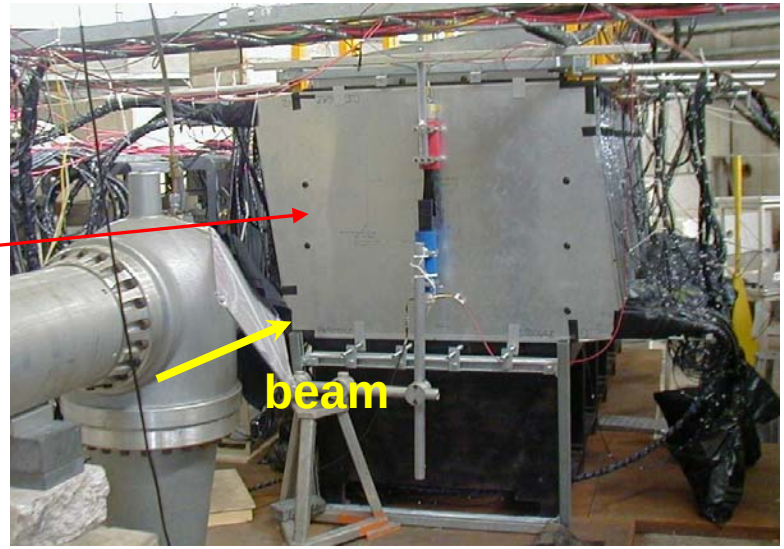
Spill times from FNAL to FD trigger farm

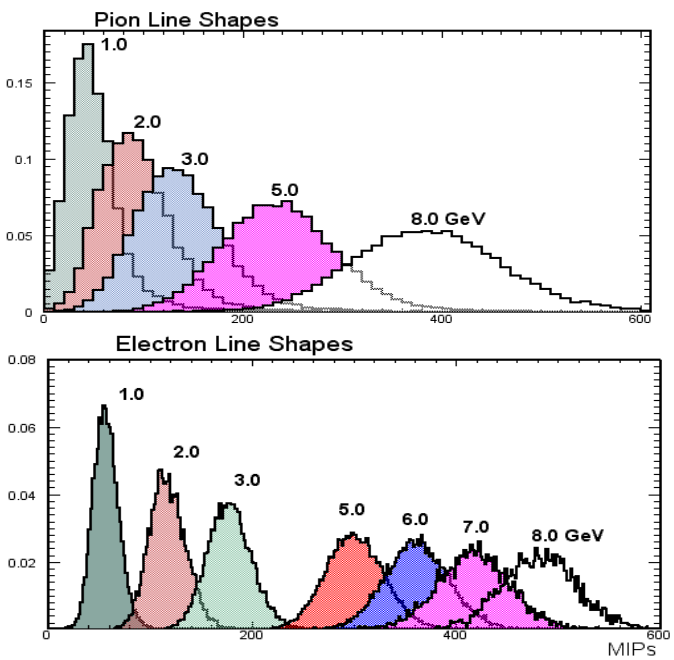
The MINOS Calibration Detector

- Help understand energy response to reconstruct E_ν

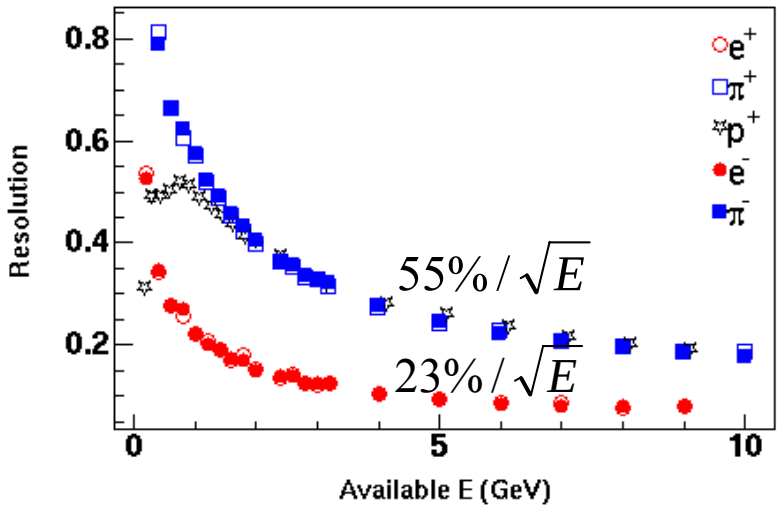
$$E_\nu = p_\mu + E_{had}$$

- Measured in a CERN test beam with a "mini-Minos"
  - operated in both Near and Far configurations
  - Study e/μ/hadron response of detector
  - Test MC simulation of low energy interactions
  - **Provides absolute energy scale for calibration**



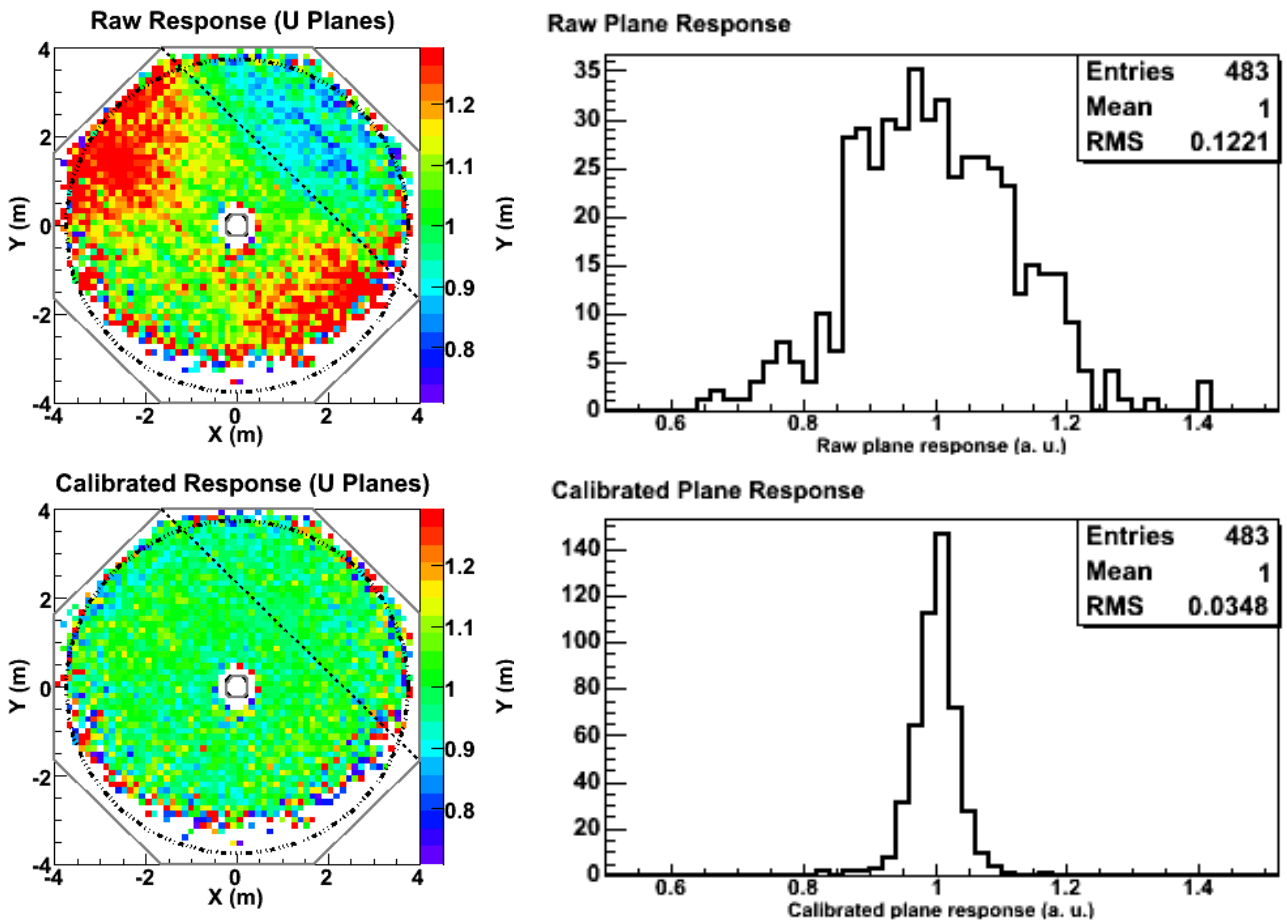


Single particle energy resolution

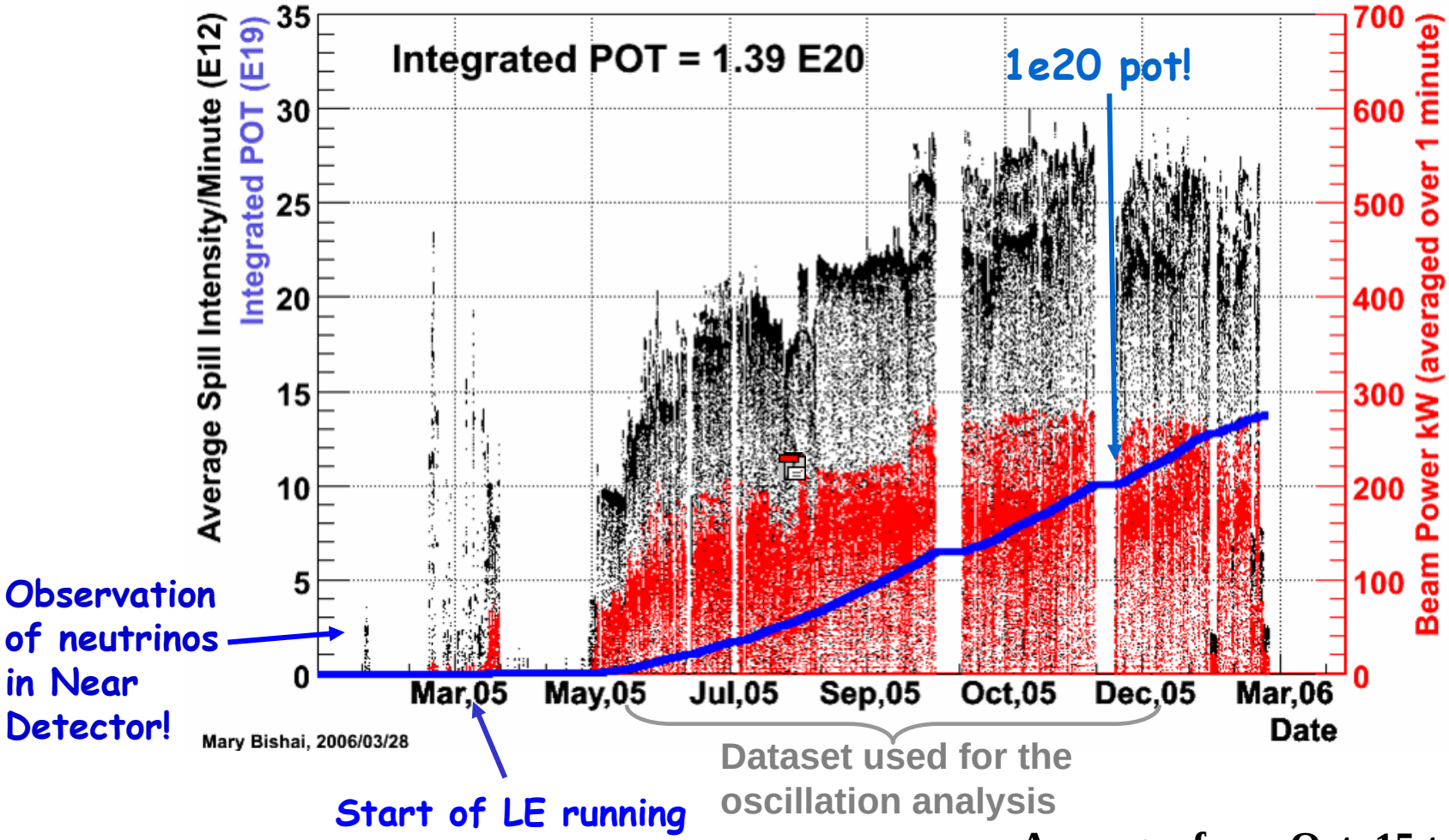


MINOS Calibration system

- 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



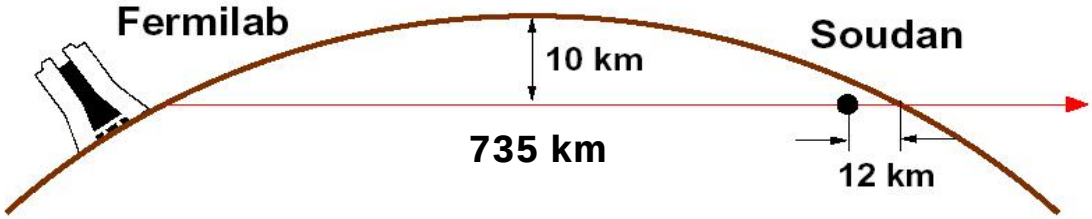
First Year of MINOS running

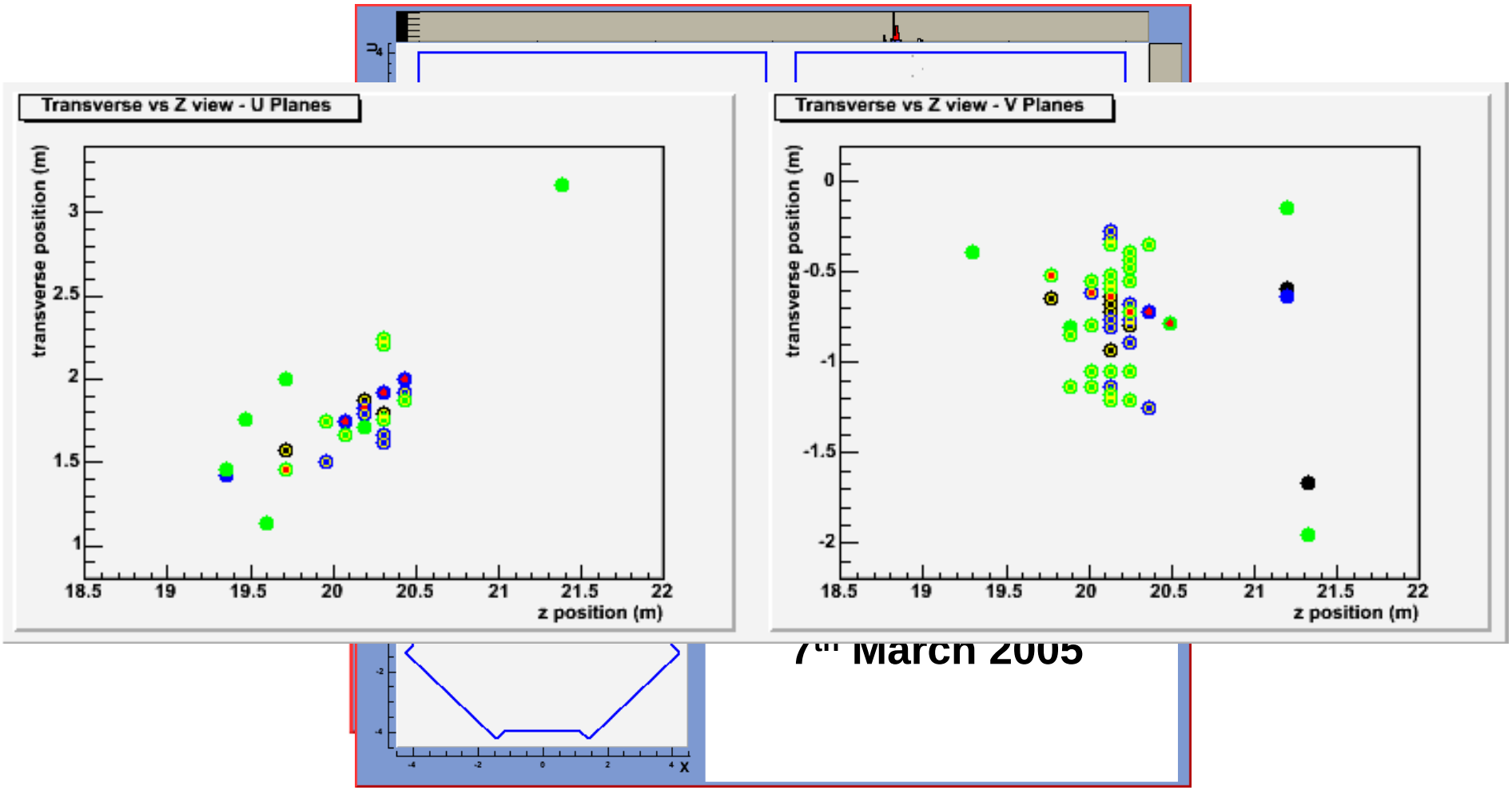


Special thanks to the Fermilab Accelerator Division for providing the sustained high quality beam so essential for our MINOS results. The world record GeV accelerator beam power delivered in our first year of operation gives great promise for the precision MINOS results to follow.

- **Averages from Oct. 15 to Jan 31**
  - **Power: 170 kW**
  - **Proton intensity: 2.3E13 ppp**
  - **Cycle spacing: 2.2 s**

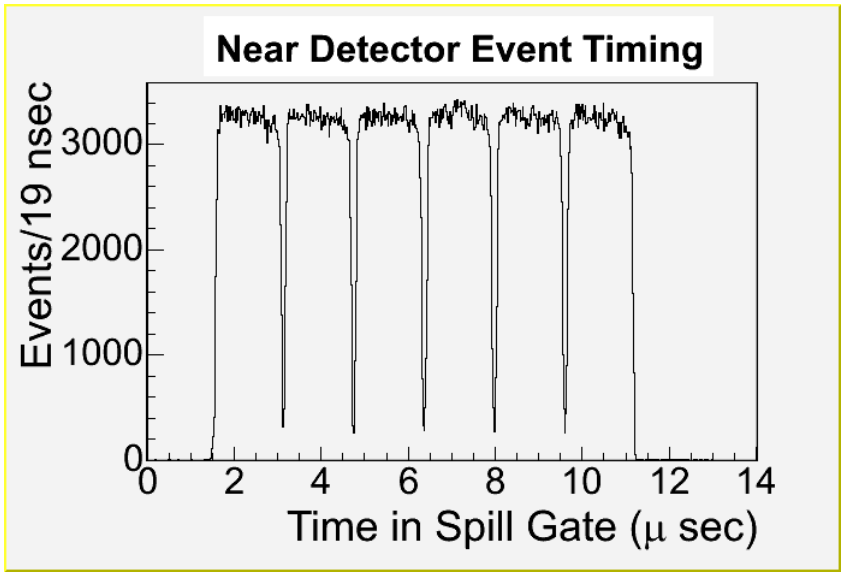
First ND & FD beam neutrinos observed





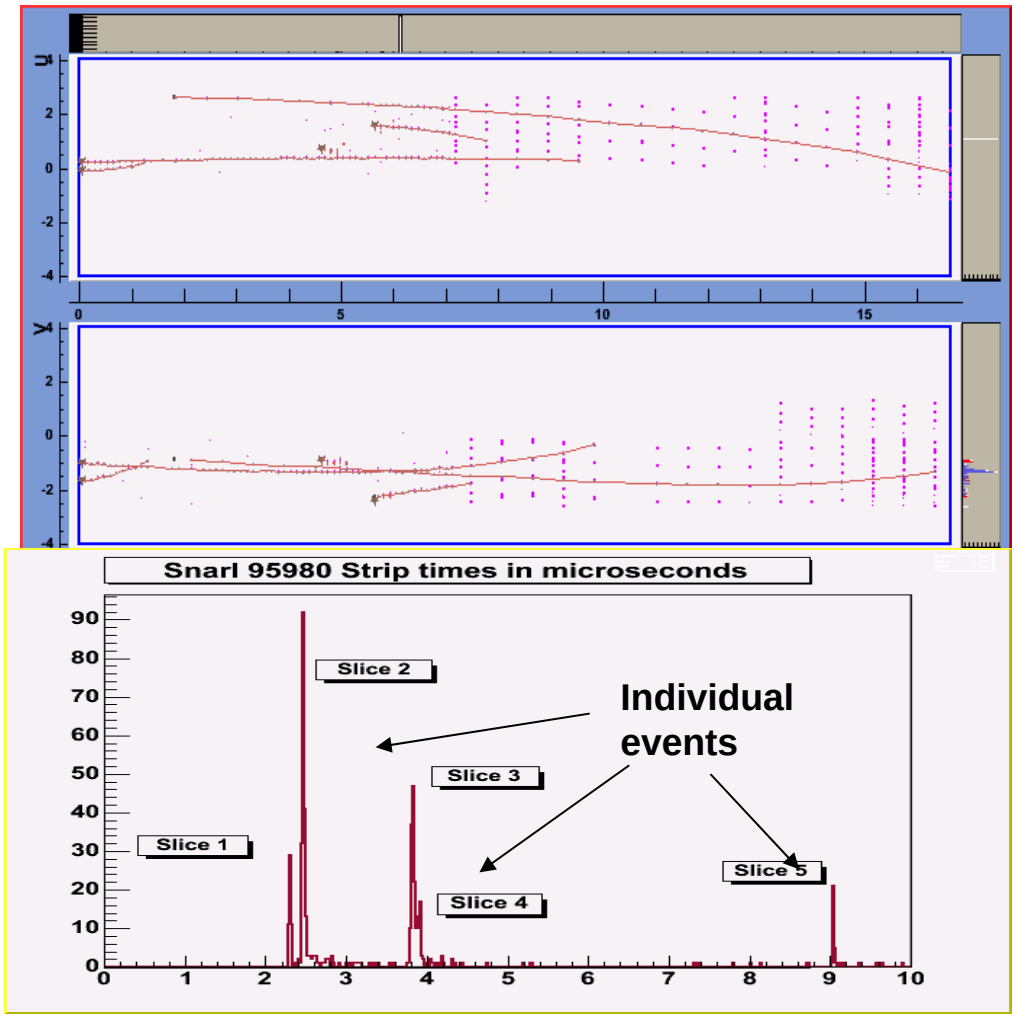
Near detector events

- High rate in Near detector results in multiple neutrino interactions per MI spill
- Events are separated by topology and timing



Batch structure clearly seen!

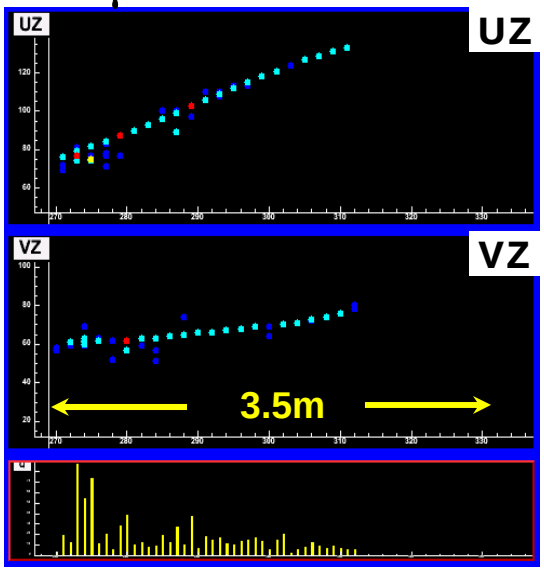
One near detector spill



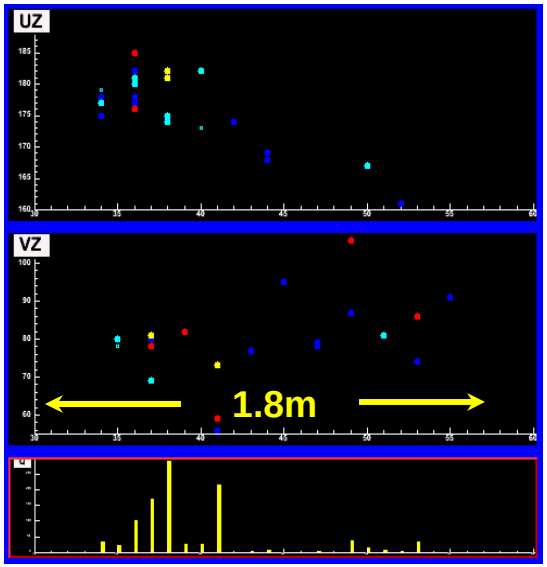
Event topologies

Monte Carlo

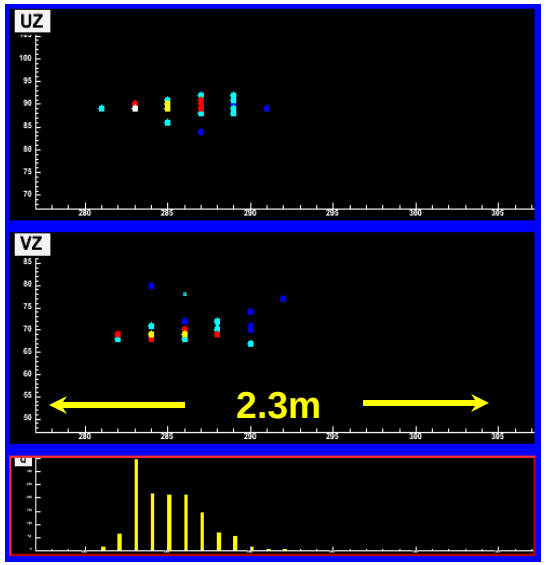
ν_μ CC Event



NC Event



ν_e CC Event



- long μ track+ hadronic activity at vertex

- short event, often diffuse

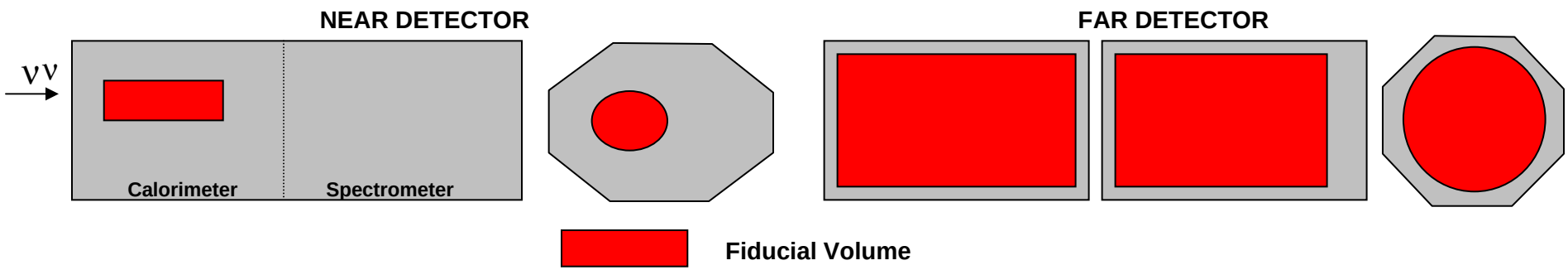
- short, with typical EM shower profile

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

$55\%/\sqrt{E}$ 6% range, 10% curvature

Event selection cuts – Near and Far

- ν_μ CC-like events are selected in the following way:
  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.



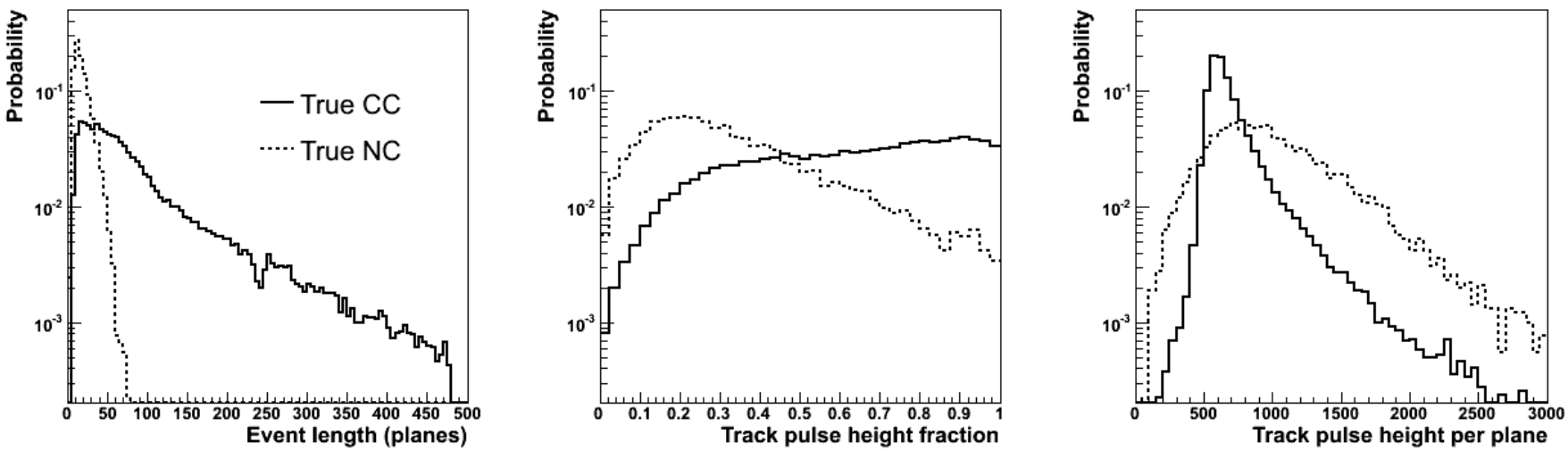
  3. The fitted track should have negative charge (selects ν_μ)
  4. Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.

Selecting CC events

- Events are selected using a likelihood-based procedure, with three input Probability Density Functions (PDFs) that show differences for True CC and NC interactions:
  - **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*)
- The probability that a event with particular values of these three variables is CC or NC (P_μ and P_{NC} respectively) is then the product of the three CC PDFs and the three NC PDFs at those values

Input variables for PDF-based event selection

Monte Carlo

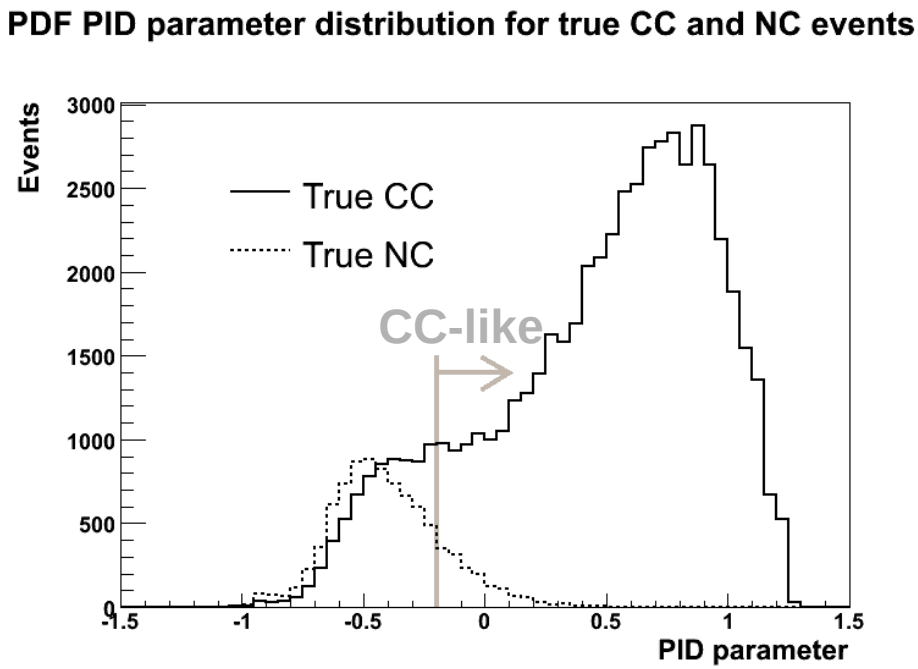


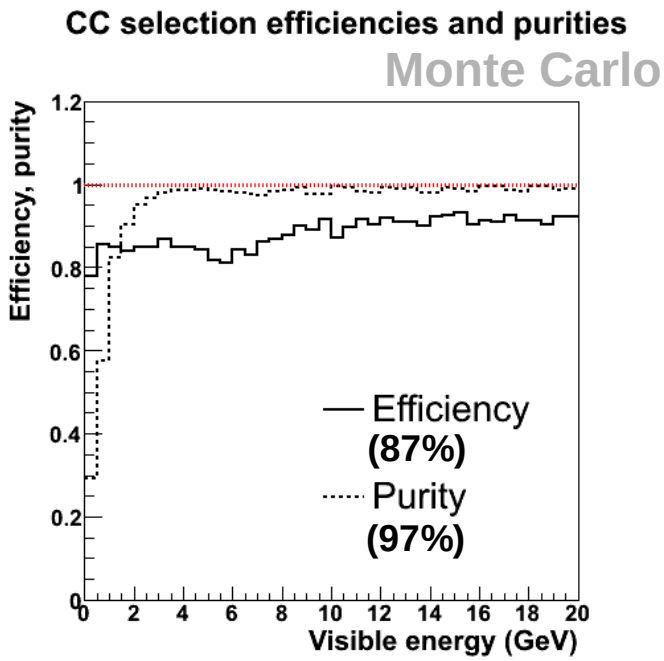
CC selection efficiencies

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

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

- 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



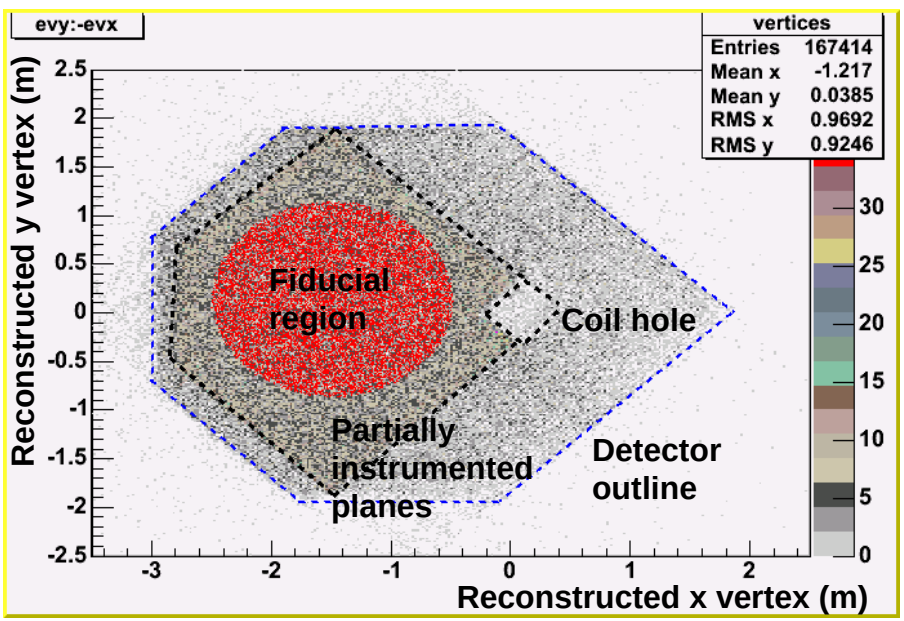


Near detector distributions

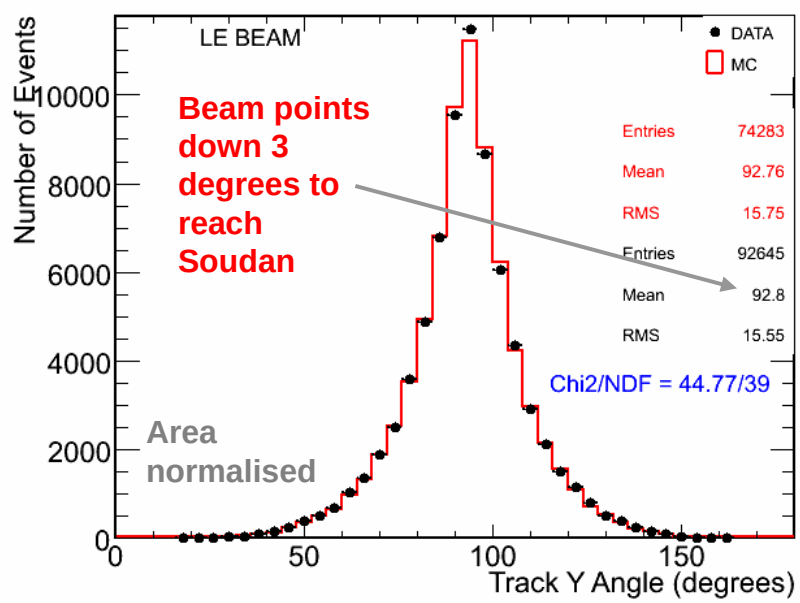
Near Detector distributions

- We observe very large event rates in the Near detector (~1e7 events in the fiducial volume for 1e20 pot)
- This provides a high statistics dataset with which we can study how well we understand the performance of the Near detector and the check the level to which our data agrees with our Monte Carlo predictions

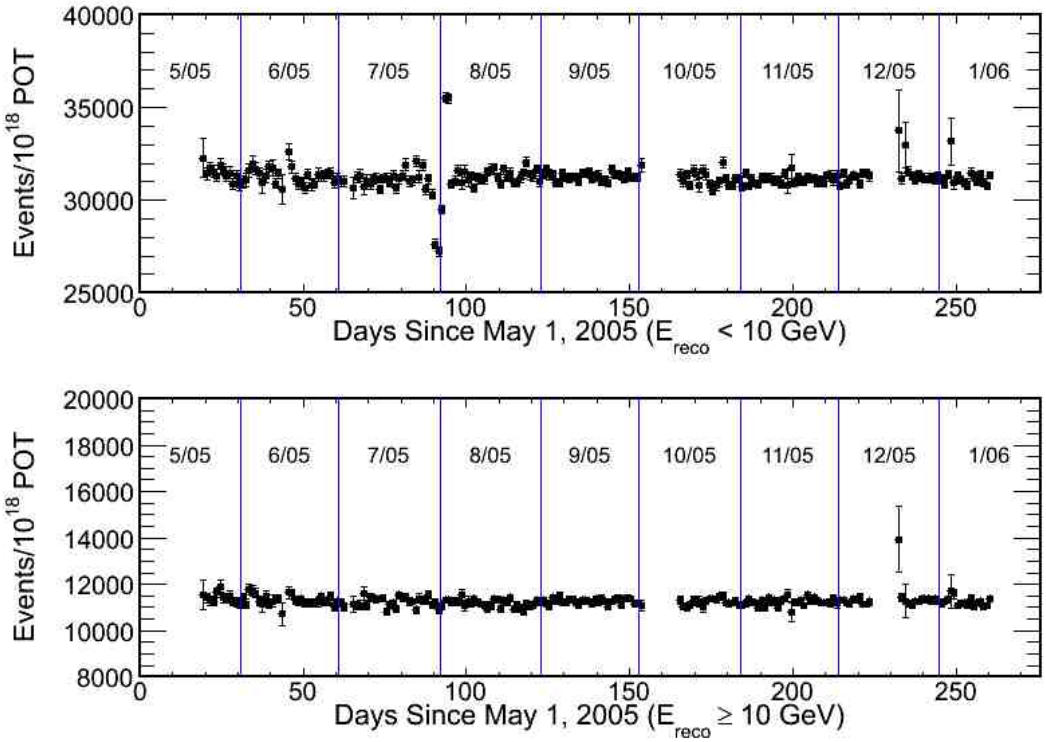
Distribution of reconstructed event vertices in the x-y plane



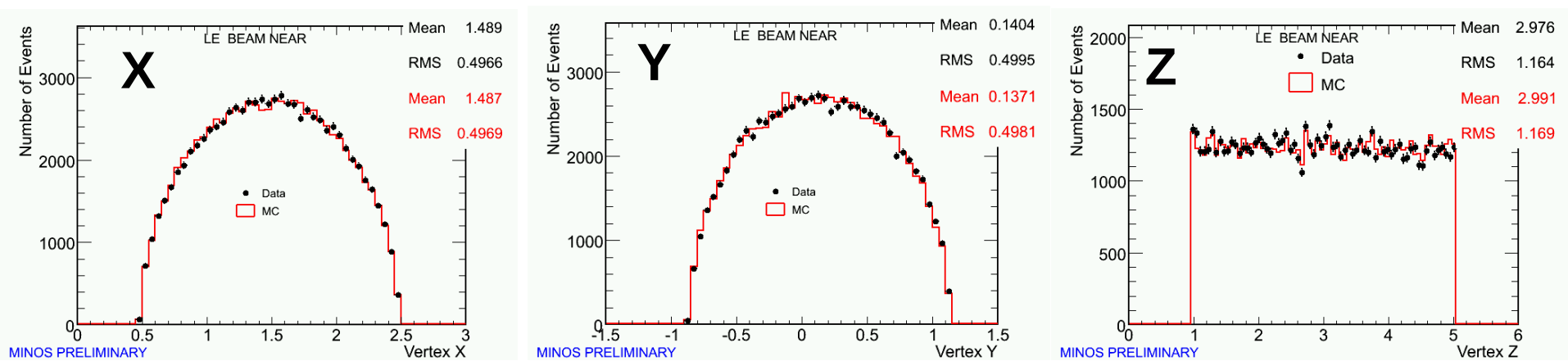
Reconstructed track angle with respect to vertical



Near detector rate and event vertices – LE-10 beam

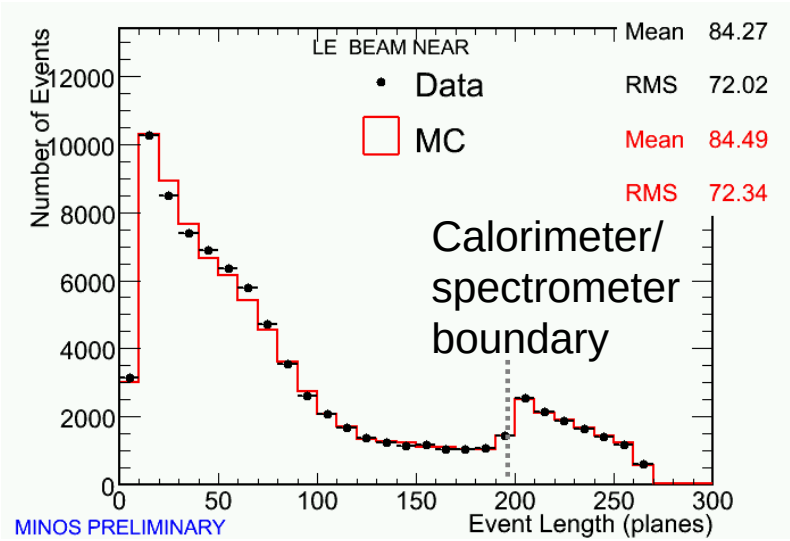


- Event rate is flat as a function of time
- Horn current scans – July 29 – Aug 3

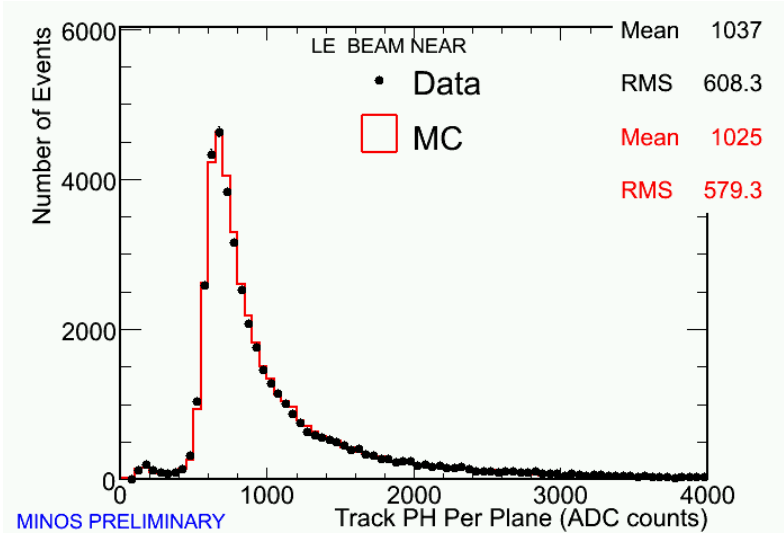


Particle Identification variables LE-10 Beam

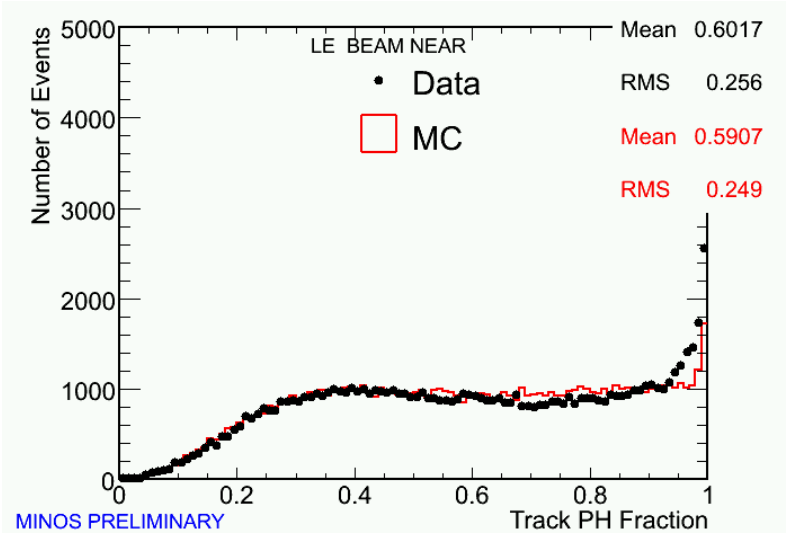
Event length



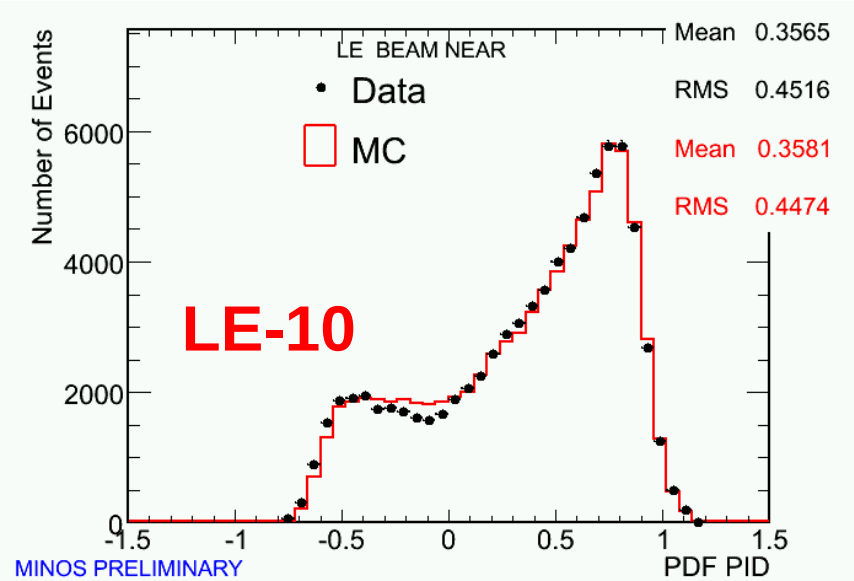
Track PH per plane

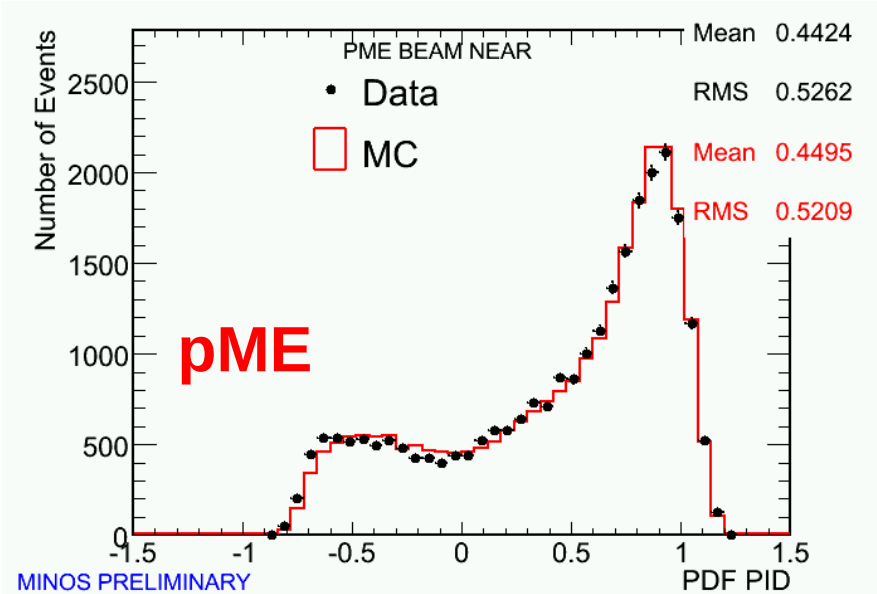


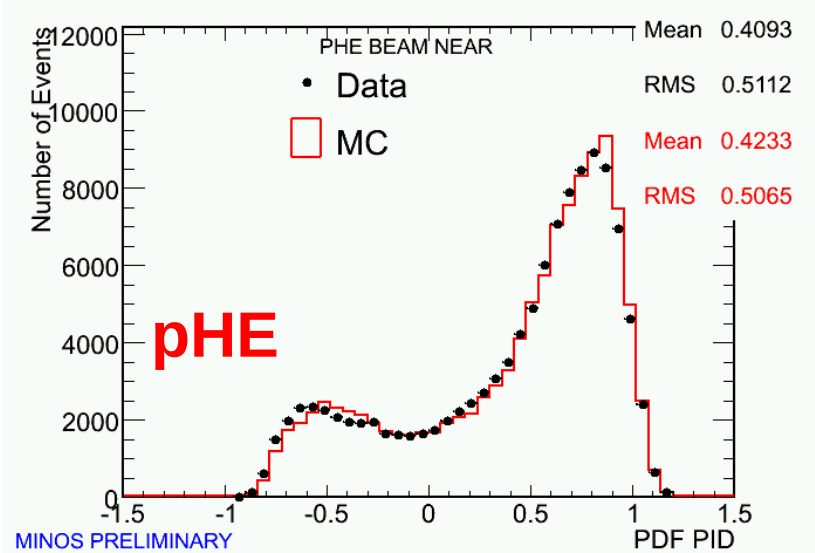
Track PH fraction



PID parameter



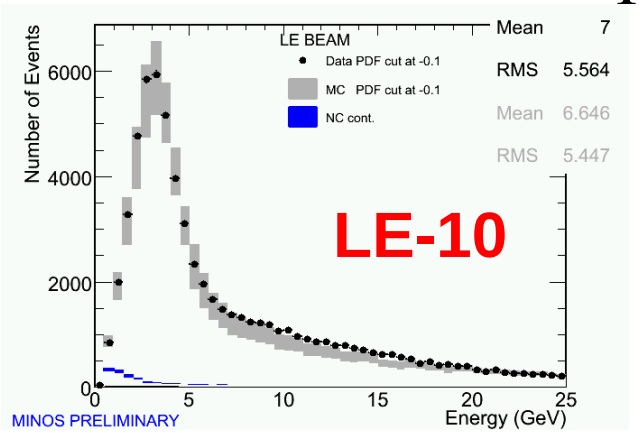


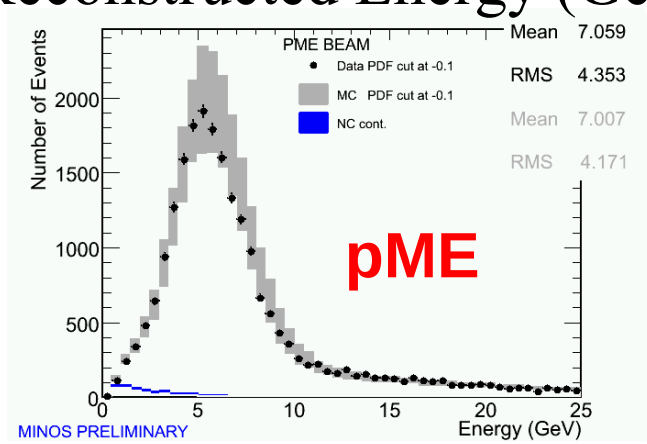


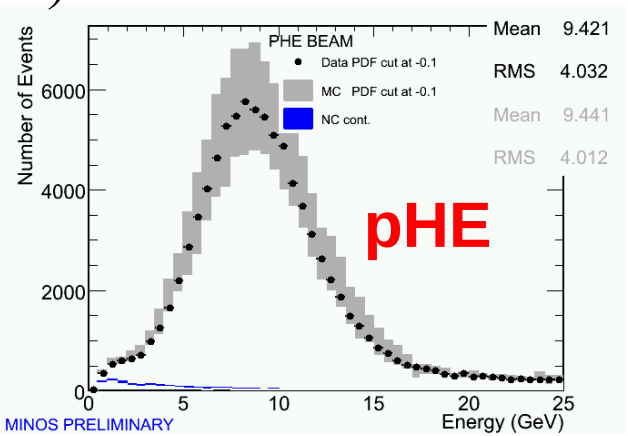
PID cut to select CC-like events is at –0.1

Energy spectra & ratios (CC-like events)

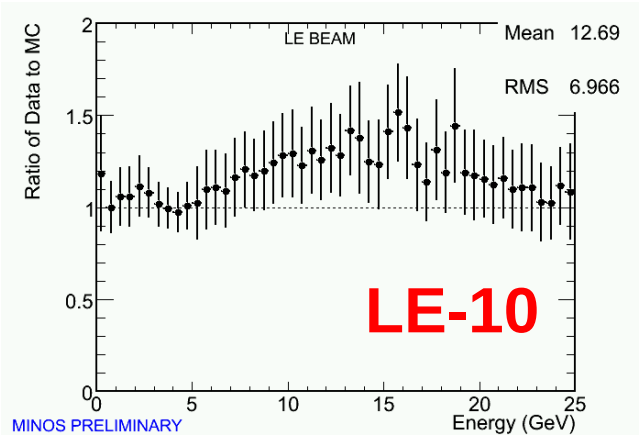
Reconstructed Energy (GeV)

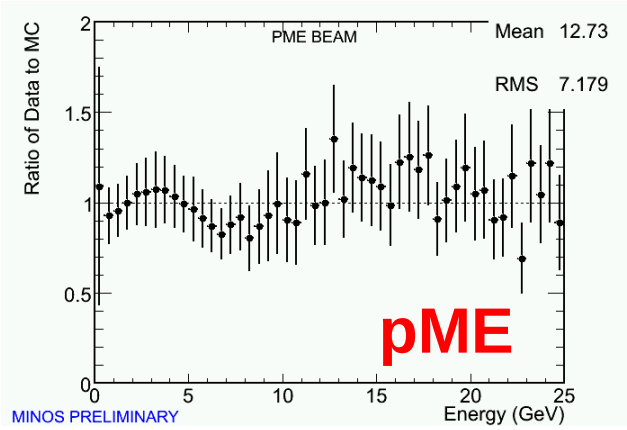


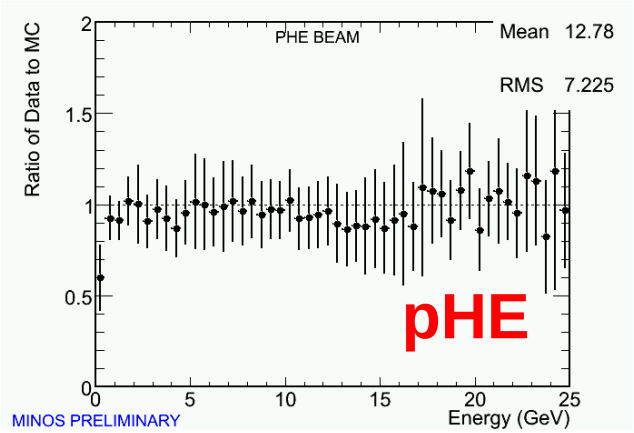




Ratios of Data/MC



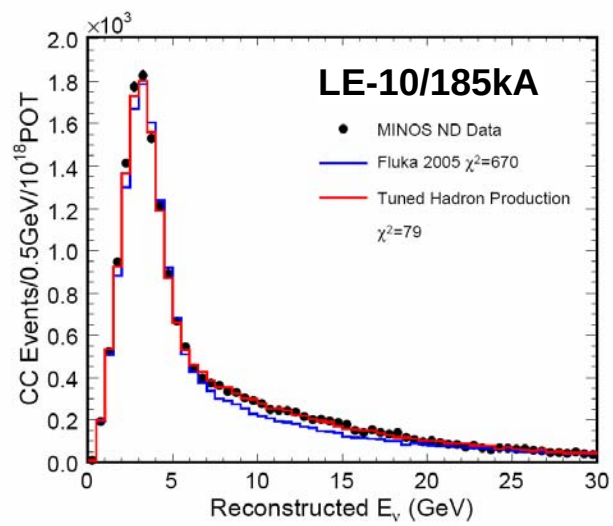


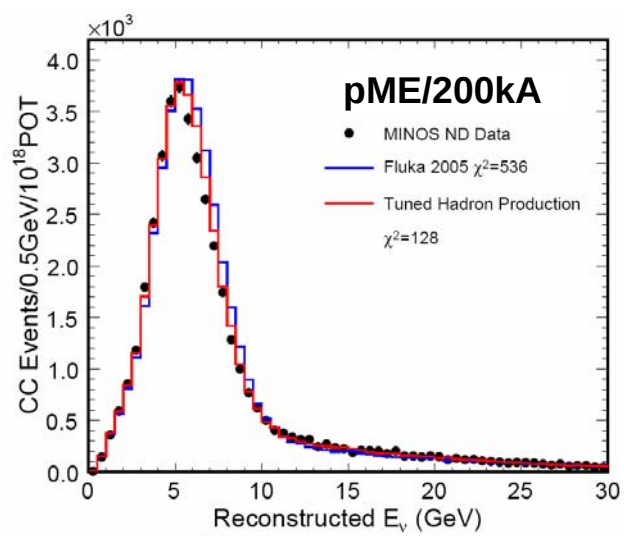


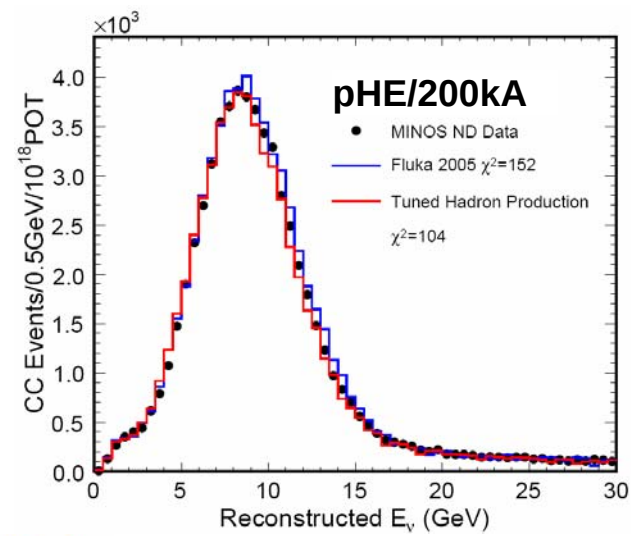
Error envelopes shown on the plots reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties

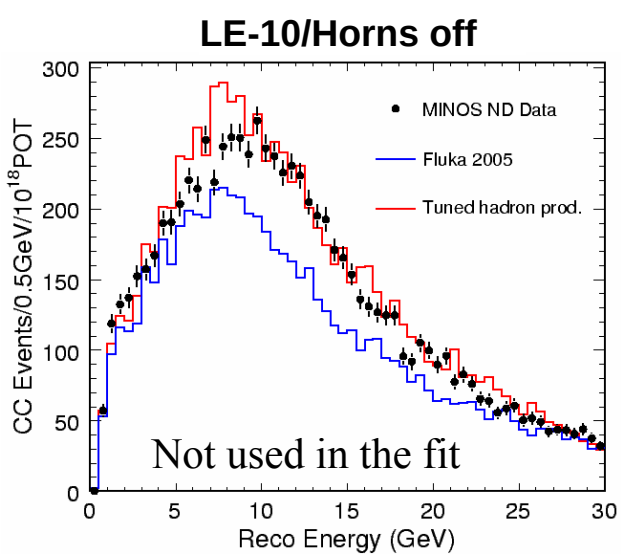
Hadron production tuning

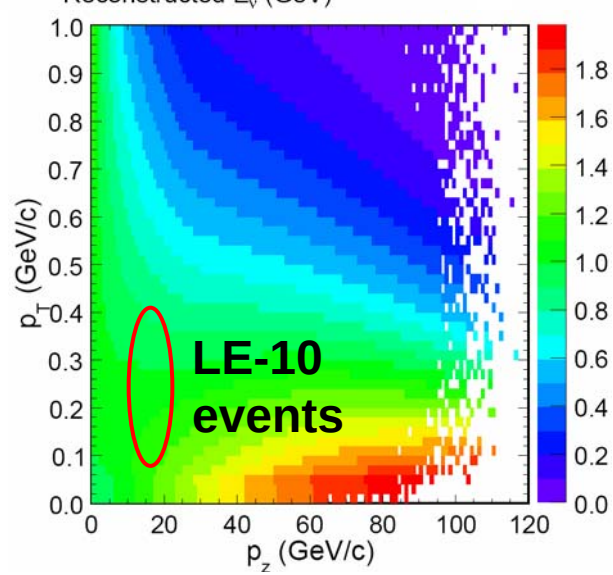
Agreement between data and Fluka05 Beam MC is pretty good, but by tuning the MC by fitting to hadronic x_F and p_T, improved agreement can be obtained.







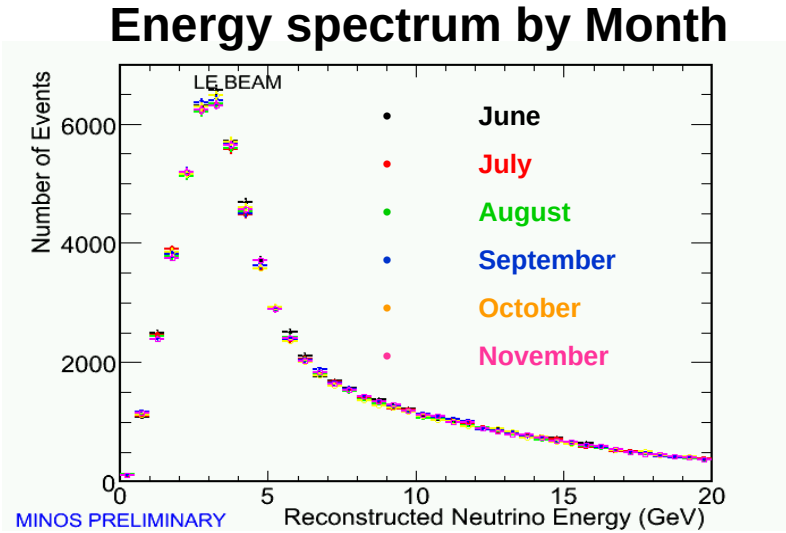


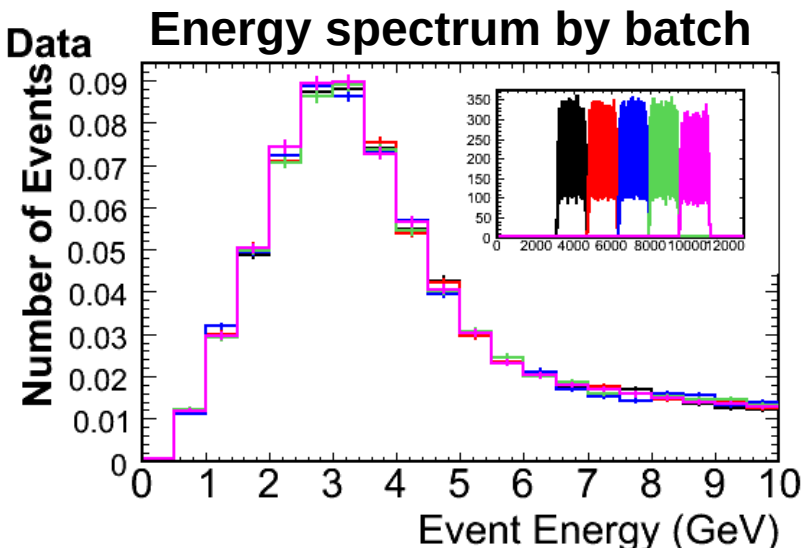


Weights applied as a function of hadronic x_F and p_T.

Stability of the energy spectrum & reconstruction with intensity

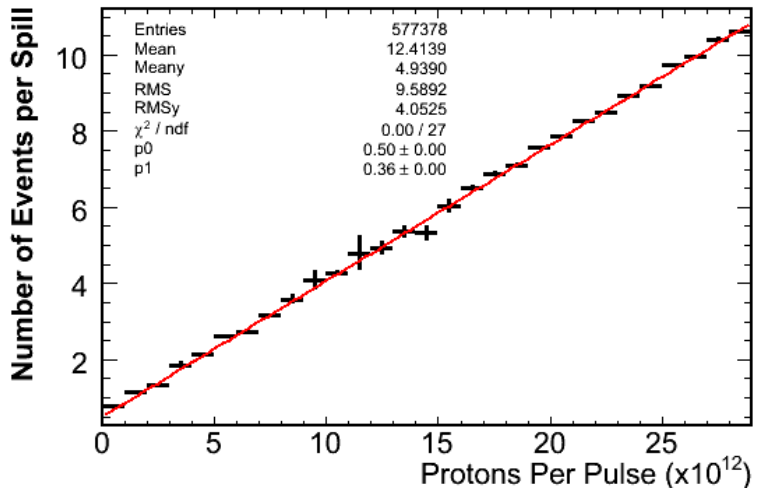
proton intensity ranges from 1e13 ppp - 2.8e13 ppp





- Reconstructed energy distributions agree to within statistical uncertainties (~1-3%)

- Beam is very stable and there are no significant intensity-dependent biases in event reconstruction.



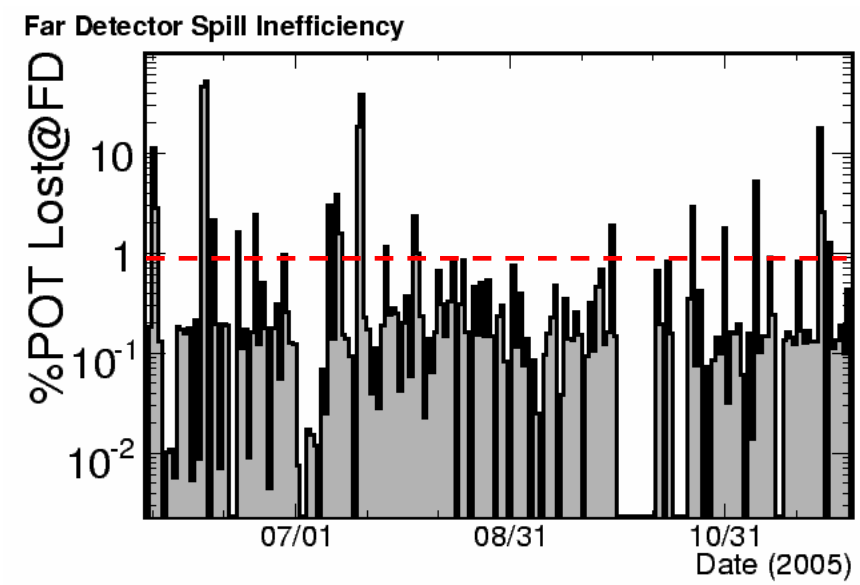
Summary of ND Data/MC agreement

- In general the agreement between data and MC distributions is good
  - **The agreement between low level quantities indicates that there are no obvious pathologies introduced by detector modelling and/or reconstruction.**
  - Agreement between high level quantities is within the expected systematic uncertainties from cross-section modelling, beam modelling and calibration uncertainties (initial agreement improved after applying beam reweighting on the x_F and p_T of parent hadrons in the Monte Carlo)

Far detector Oscillation Analysis with 0.93e20 pot

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%



Special thanks to everyone who helped to maintain such a high livetime during this period!

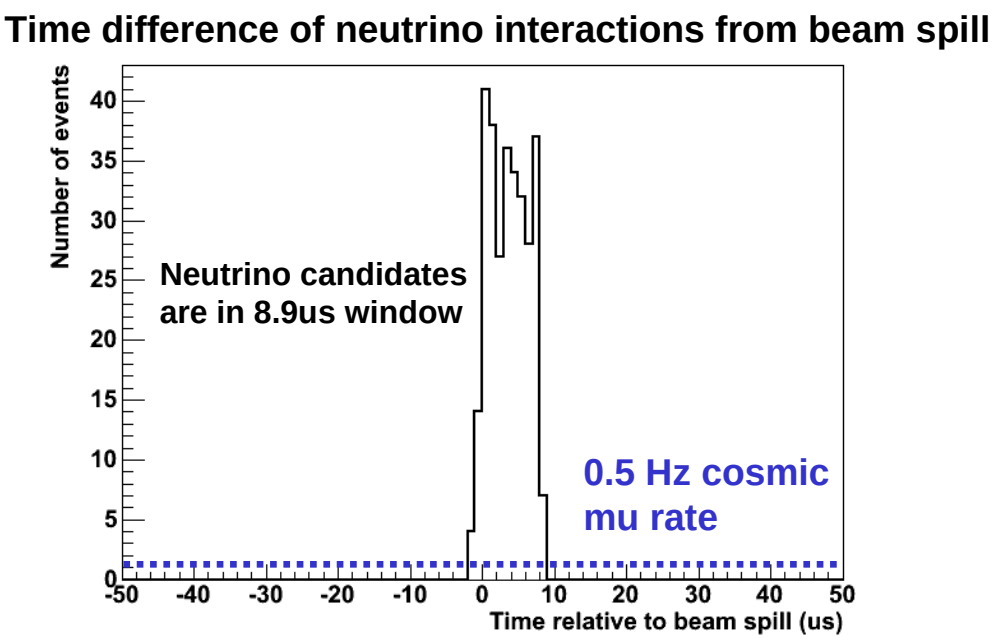
Performing a blind analysis

- 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)



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 in open sample is 1.7 events at 90% C.L.)

Example event – 2 GeV ν_μ CC

Run: 32133, Snarl: 97235, Slice: 1(/1), Event 1(/1)

Reco

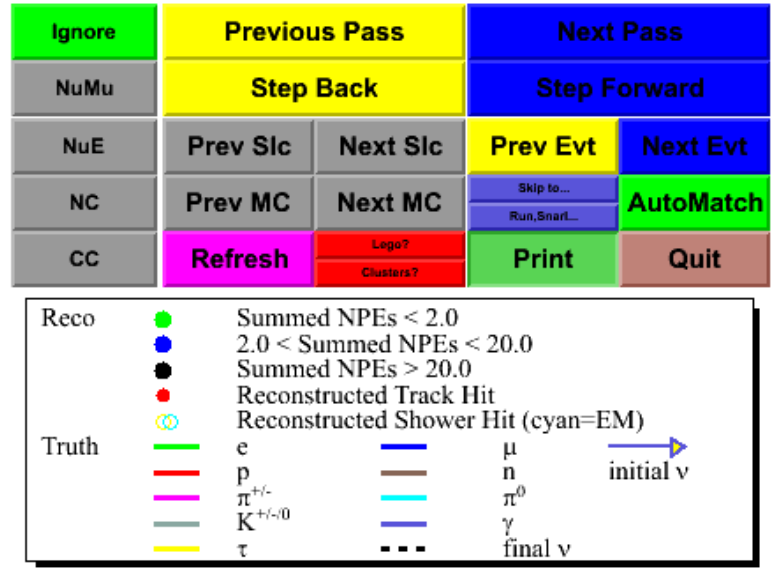
#Trks: 1

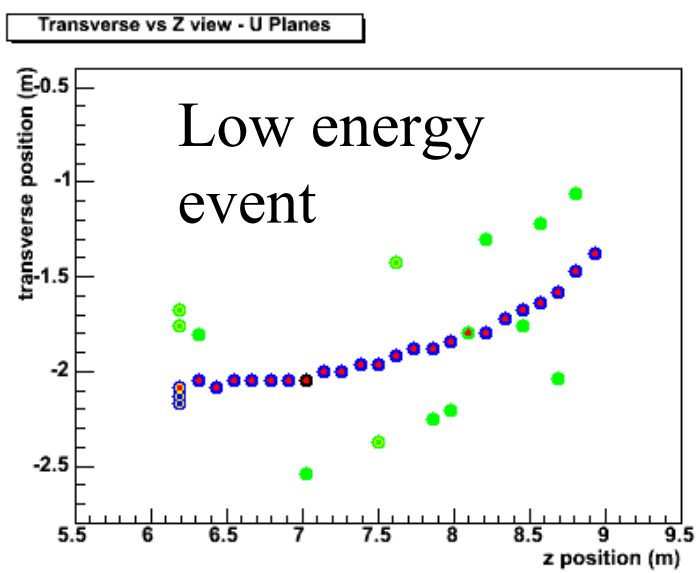
#Shws: 2

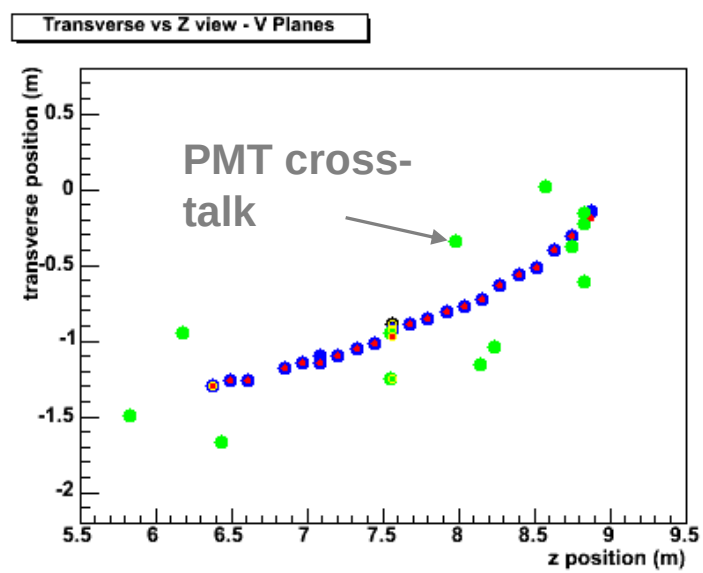
q/p: -0.517 +/- 0.034, p/q: -1.935

TrkRangeEnergy: 2.042 RecoShwEnergy: 0.196

Vtx: -0.52, -2.42, 6.20

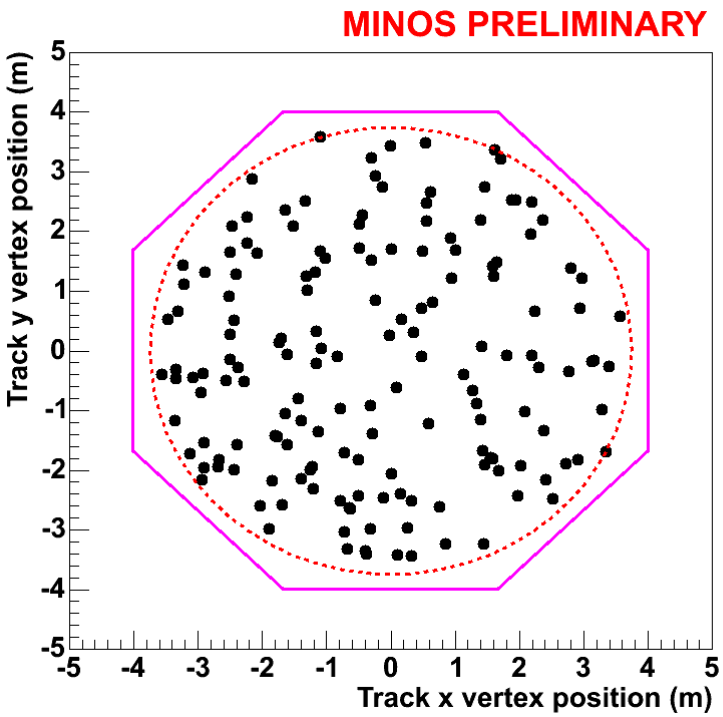


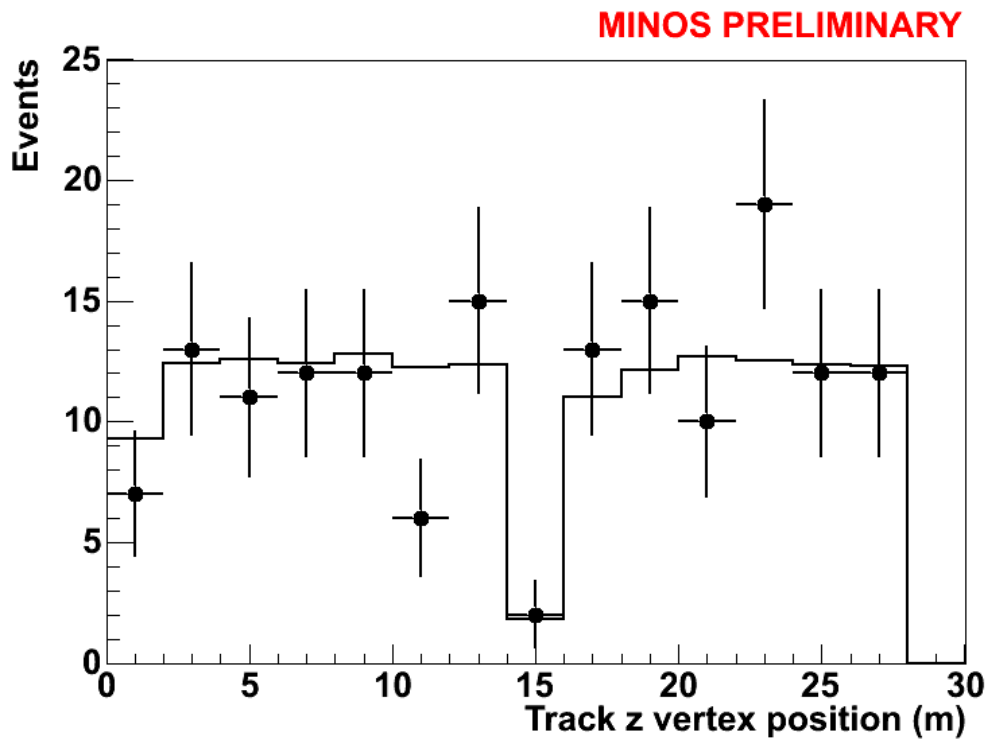




Vertex distributions of selected events

Open dataset

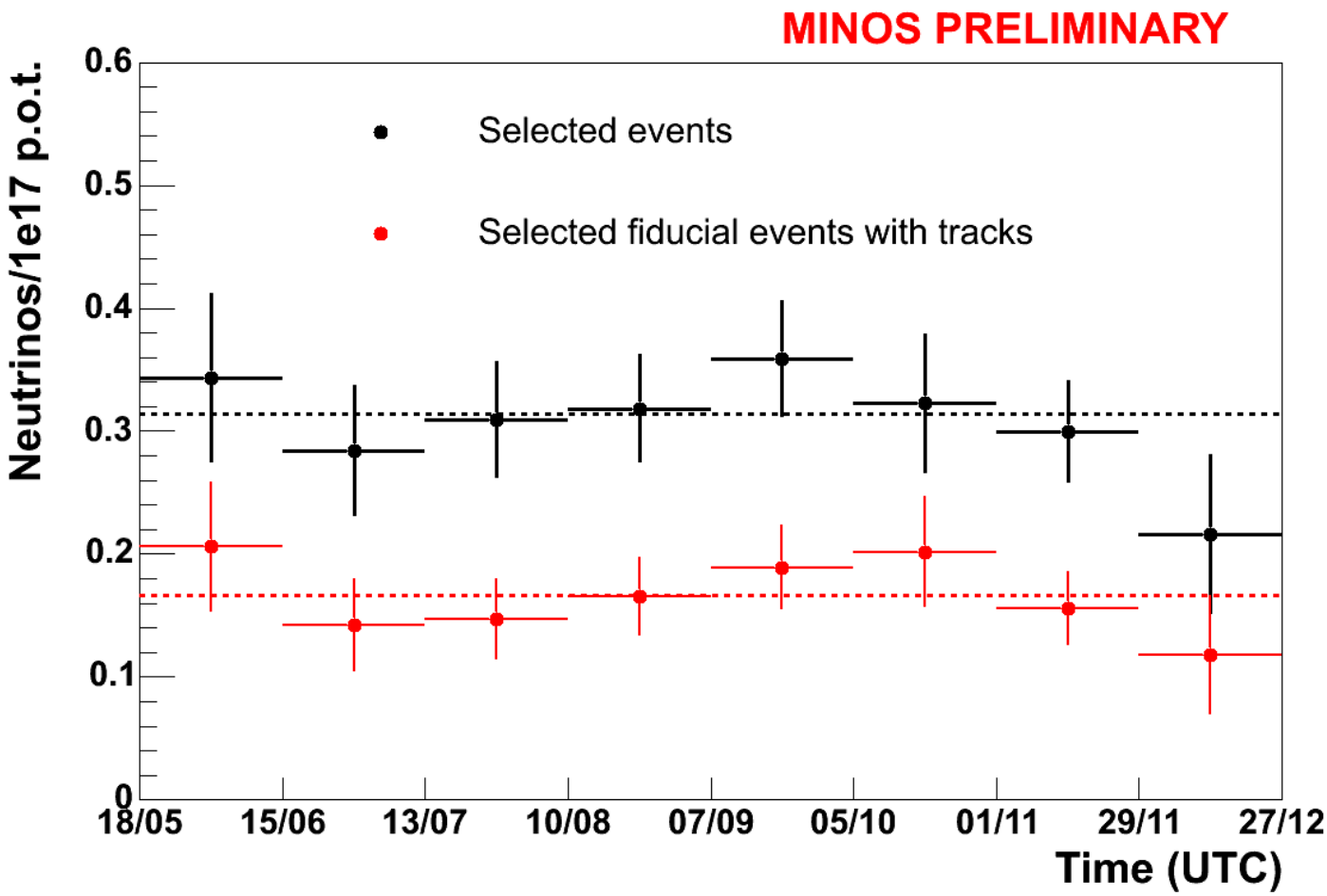




- Distributions consistent with neutrino interactions – no evidence of background contamination.

Selected events as a function of time

Open dataset

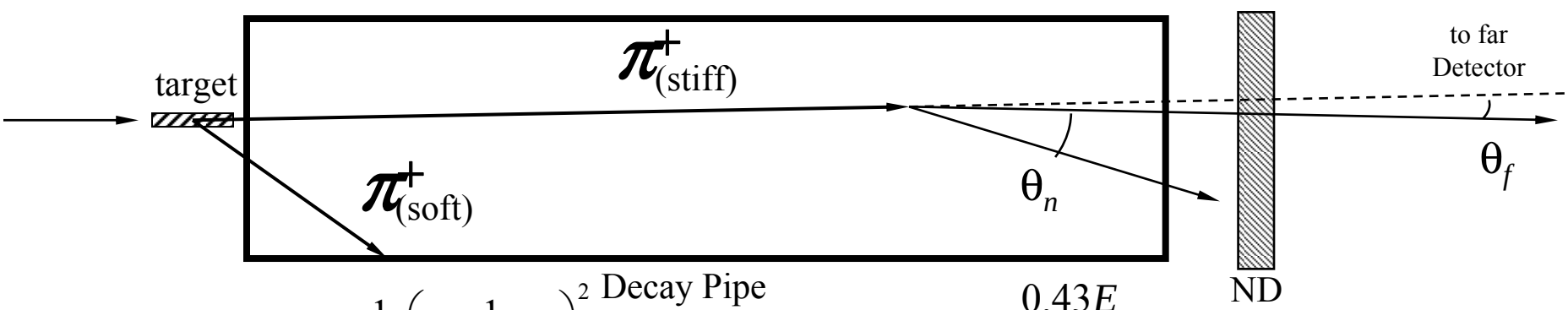


- Neutrino events per P.O.T are flat as a function of time.

Predicting the unoscillated FD spectrum

- 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.**

- Use our knowledge of **pion decay kinematics and the geometry of our beamline** (extended neutrino source, seen as point-like from the Far Detector) **to predict the Far detector energy distribution from the measured Near detector distribution**



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

- This method is known as the "**Beam Matrix**" method.

Schematic Description of the "Beam Matrix"Method

A)

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

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

B)

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

BEAM MATRIX

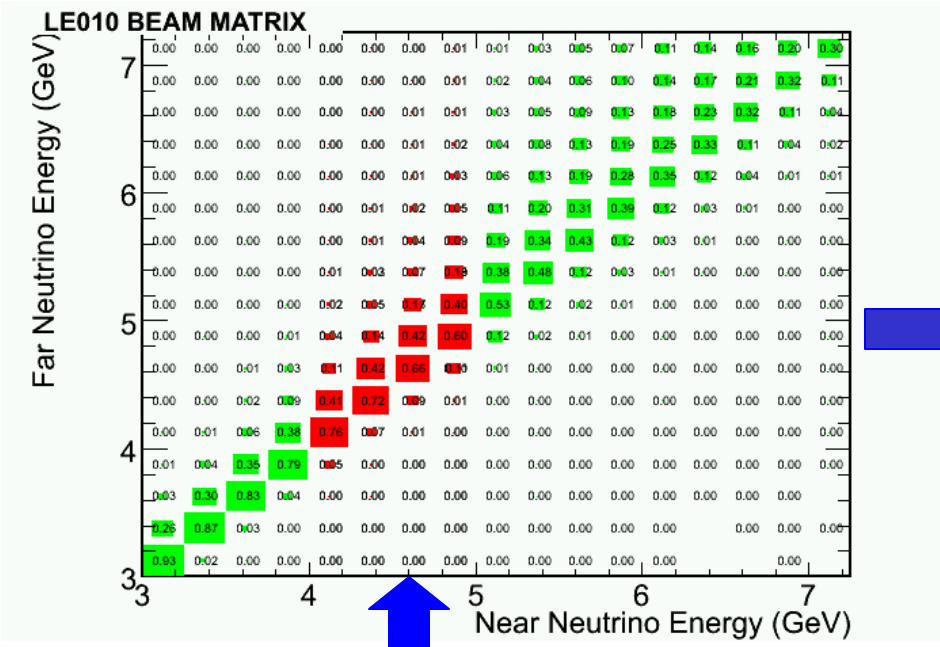
C)

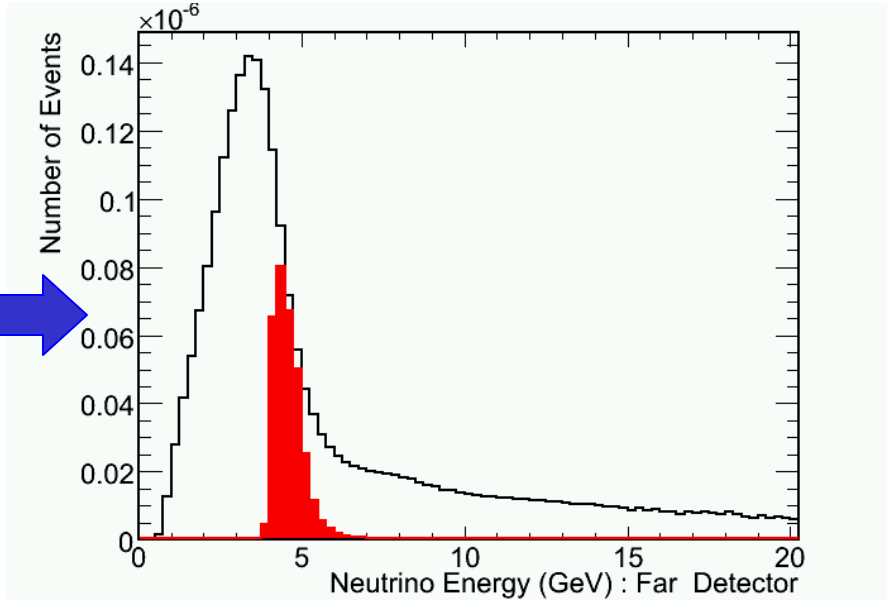
$$E^{True}_{Far\ \text{CC}} \Rightarrow E^{\text{Reconstructed}}_{Far\ \text{CC-like}}$$

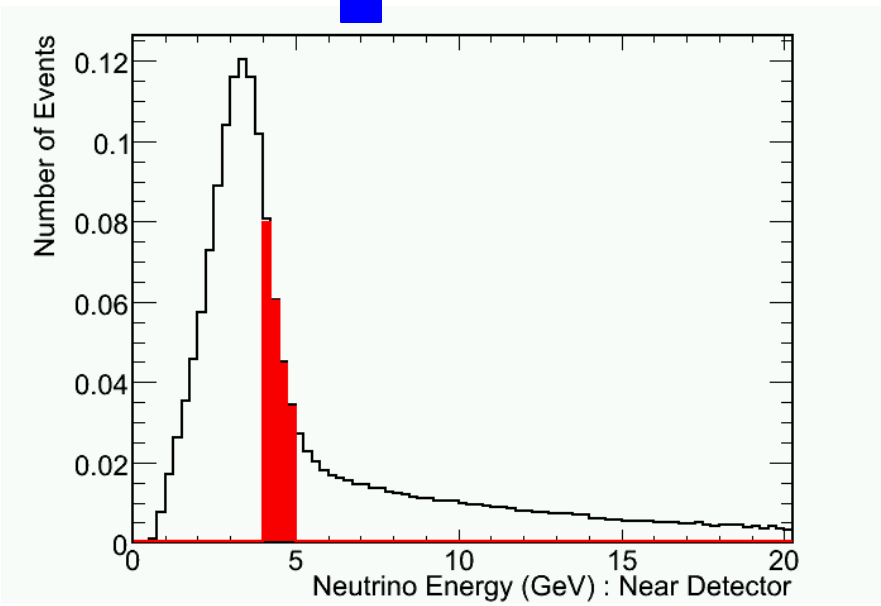
i) Oscillation, True => Reconstructed, Correction for efficiency to obtain CC oscillated spectrum

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

"Beam Matrix"Method : Near to Far extrapolation

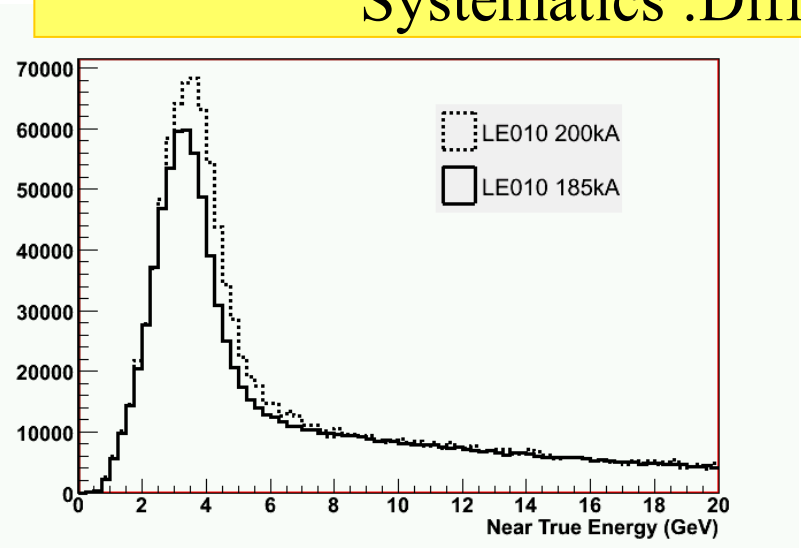






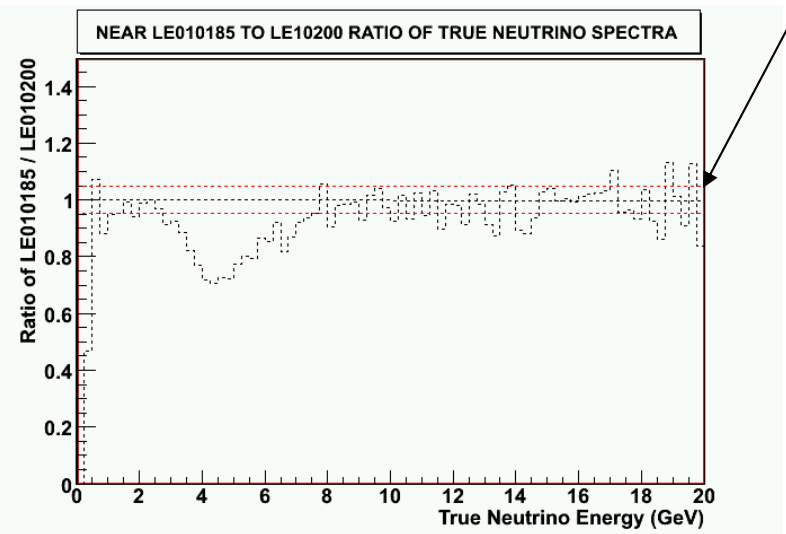
- Beam Matrix encapsulates the knowledge of pion 2-body decay kinematics & geometry.
- Beam Matrix provides a very good representation of how the far detector spectrum relates to the near one.

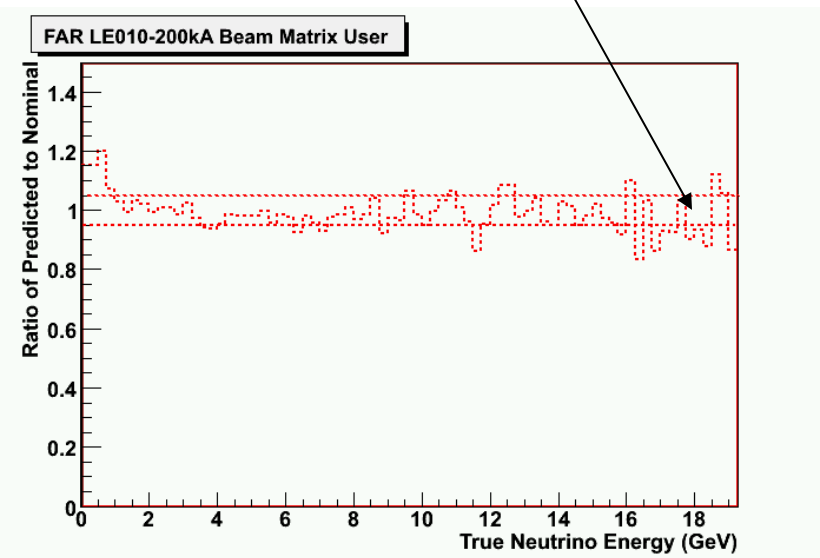
Systematics :Different Beam Matrix used



Method : Use instead of LE010 185 kA GNUMI matrix the LE010 200kA GNUMI matrix.

NOTE :Red dotted bands are ± 5%.

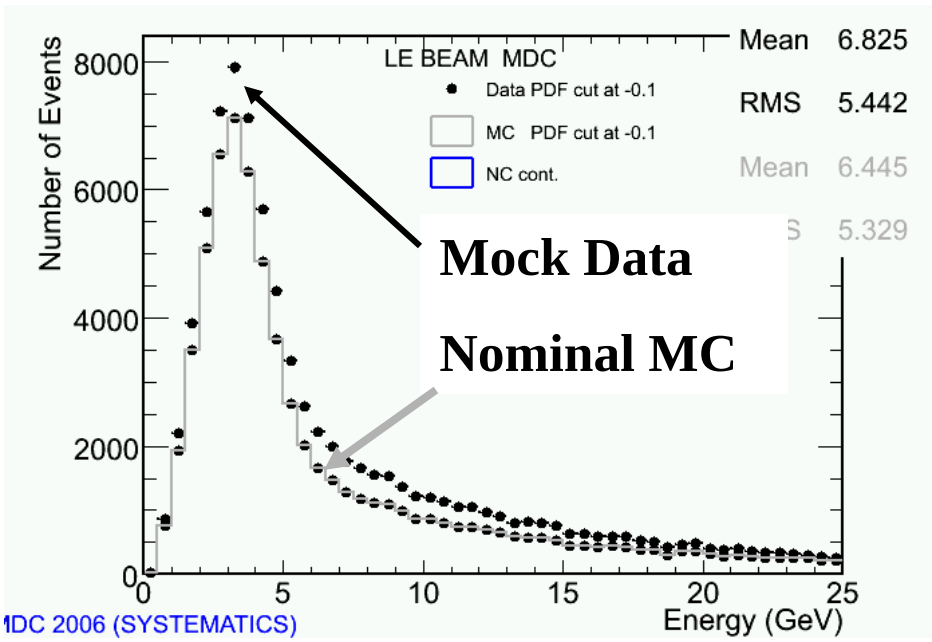


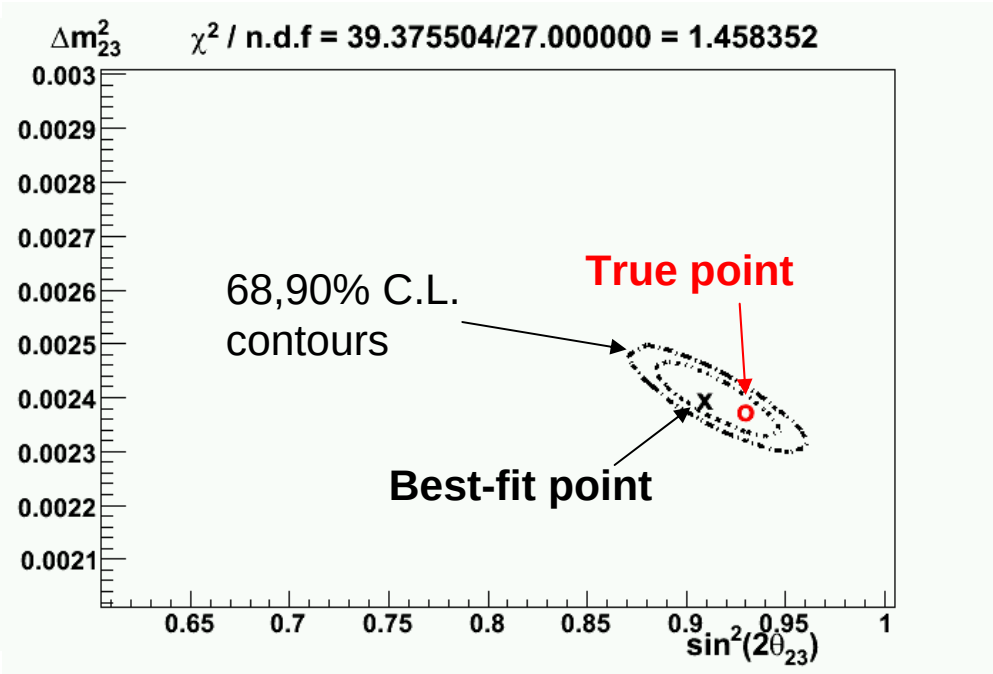


- The different LE010 200 kA matrix corresponds to different beam.
- **The Predicted Far spectrum is within 5% to the "actual" one.**
- **Beam Matrix Method quite robust to beam related uncertainties as well.**

Systematics : Test on 1E22 p.o.t "Mock Data Challenge Set"

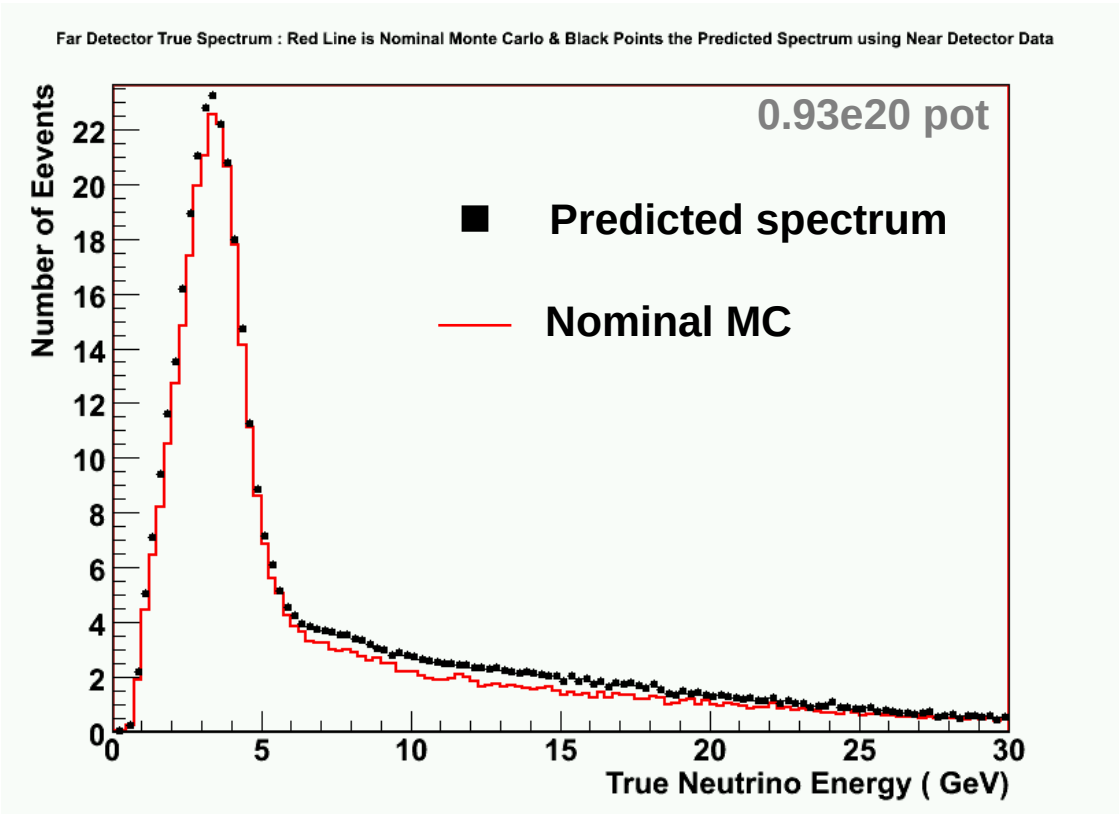
In order to test the robustness of the method, a "fake dataset" was generated with tweaked beam/generator parameters and unknown oscillation parameters.





Beam Matrix Method yields to an accurate estimation of the oscillation parameters despite the large differences between "Mock Data" and Monte Carlo (even for 1E22 protons on target!)

Predicted true FD spectrum



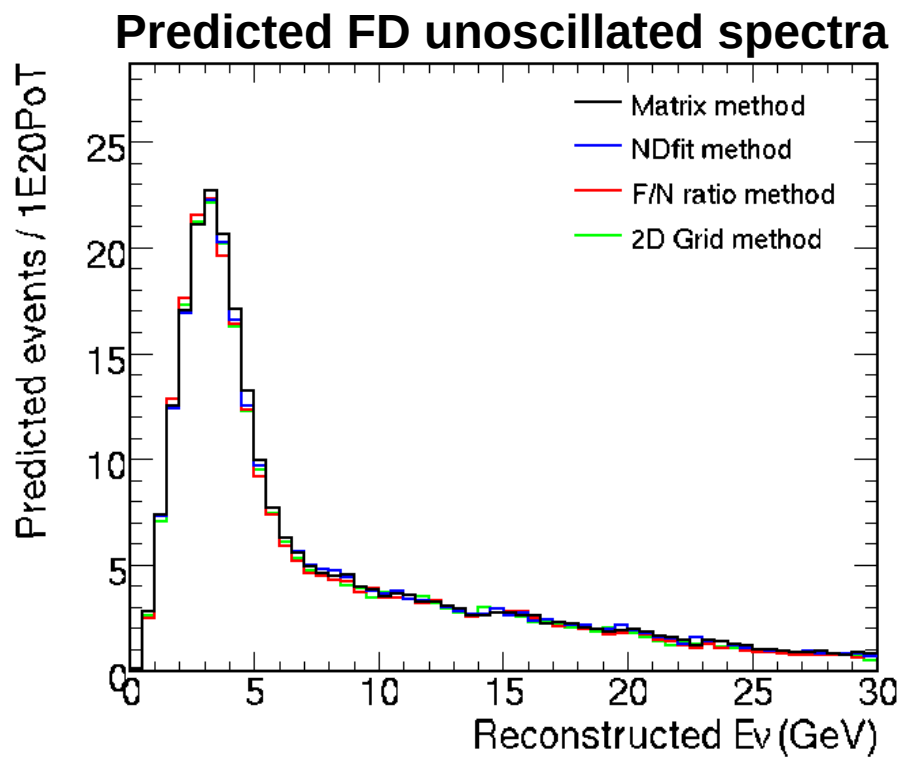
- The predicted FD true spectrum from the Matrix Method is shown on the left.

- **The spectrum is higher than the nominal FD MC in the high energy tail. This is as expected, given that the ND Data visible energy distribution is also higher than the nominal MC in this region.**

Alternative methods for predicting the FD spectrum

- We have investigated three other methods of deriving the FD spectrum from the ND data:
  - Extrapolation using the Far/Near ratio from the MC
  - Two independent methods of fitting to the ND data in order to derive systematic parameters that are used to reweight the FD Monte Carlo
    - These are termed "NDfit" and "2d Grid Fit" respectively

- These methods have quite different sensitivities to systematic errors, therefore comparing the results obtained with all four is a good check of the robustness of our oscillation measurement



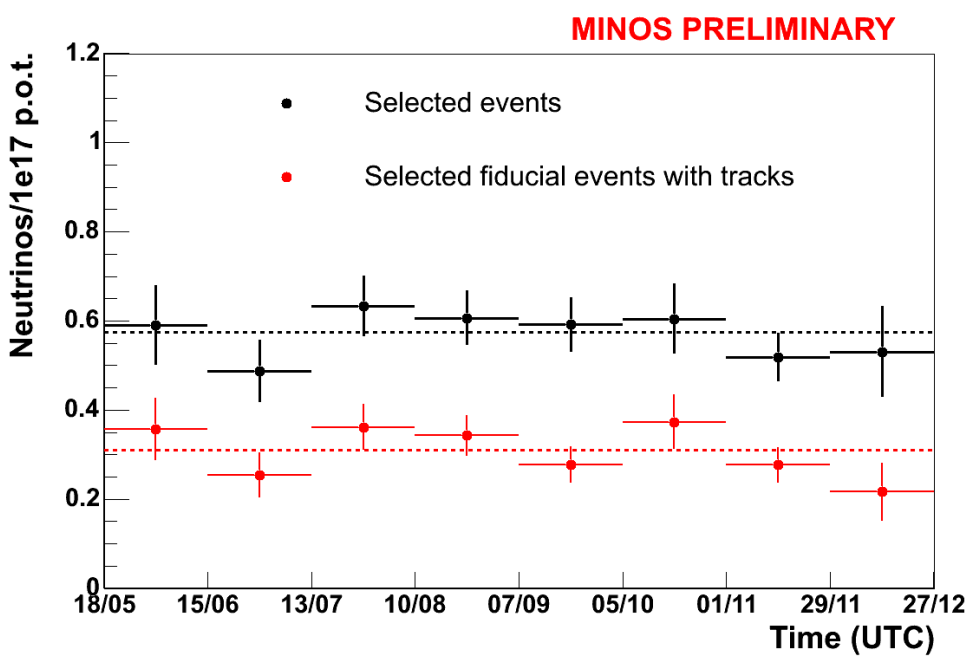
•In what follows, I will present the contours and best-fit distributions for the Matrix method analysis, and will overlay the best-fit points for the other methods on the primary contour.

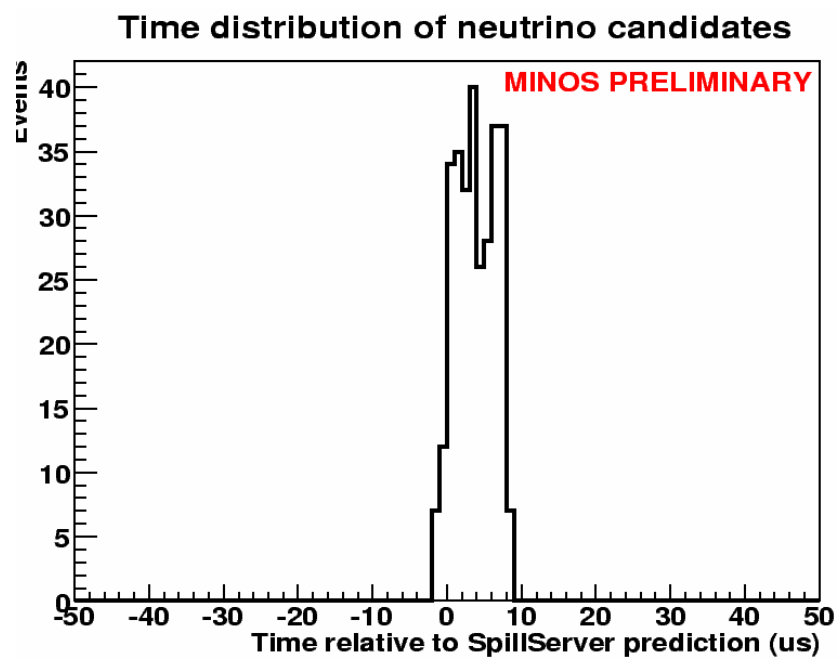
Box opening

- **After extensive checks on the open dataset, the collaboration decided that we had sufficient confidence in the FD data.**
- **Our analysis methods had been fully validated on MC datasets.**
- **Therefore we could proceed to open the box and look at the full dataset (March 4th 2006)**

Full dataset

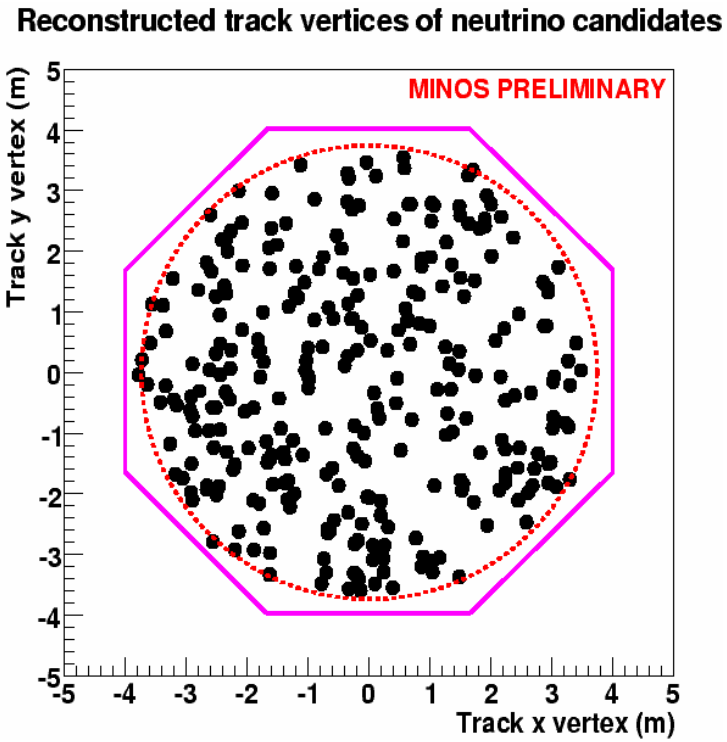
Far Detector Data

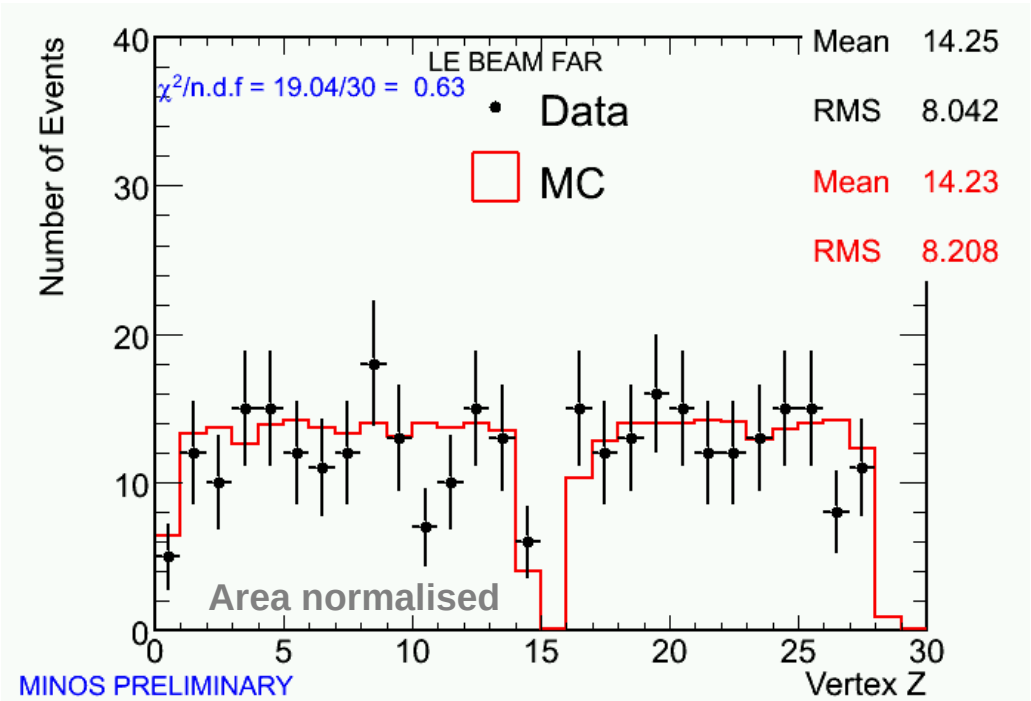




Vertex distributions of selected events

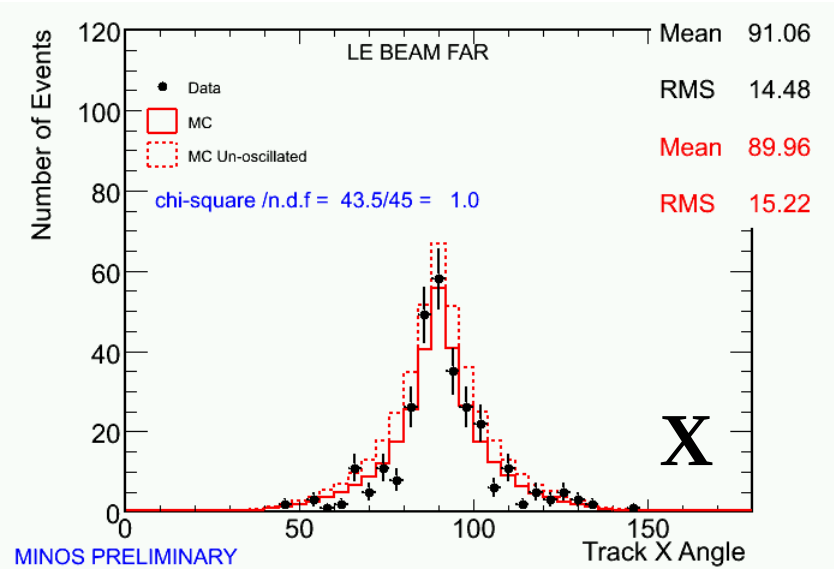
Full dataset

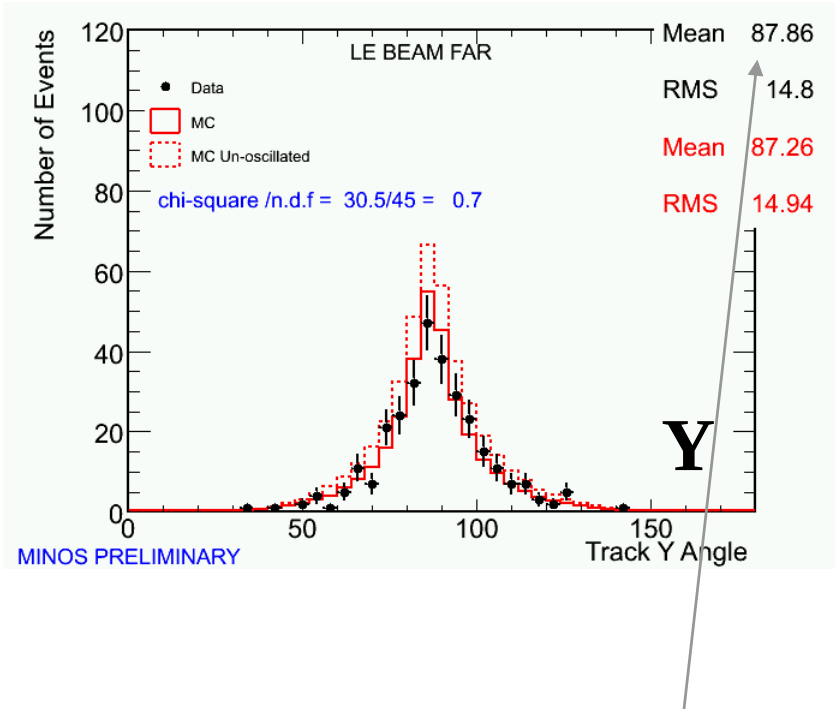


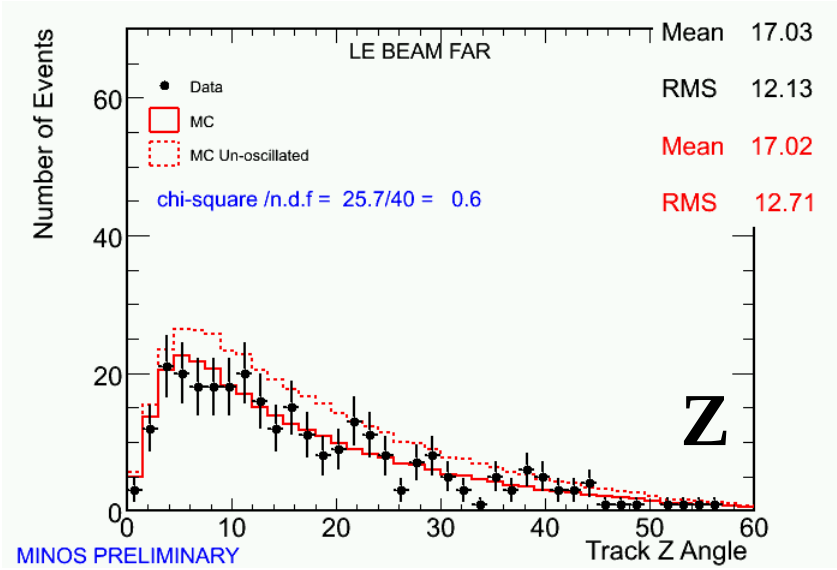


- 296 selected events with a track – no evidence of background contamination.
- Distribution of selected events consistent with neutrino interactions (uniform distribution of event vertices)

Track angles



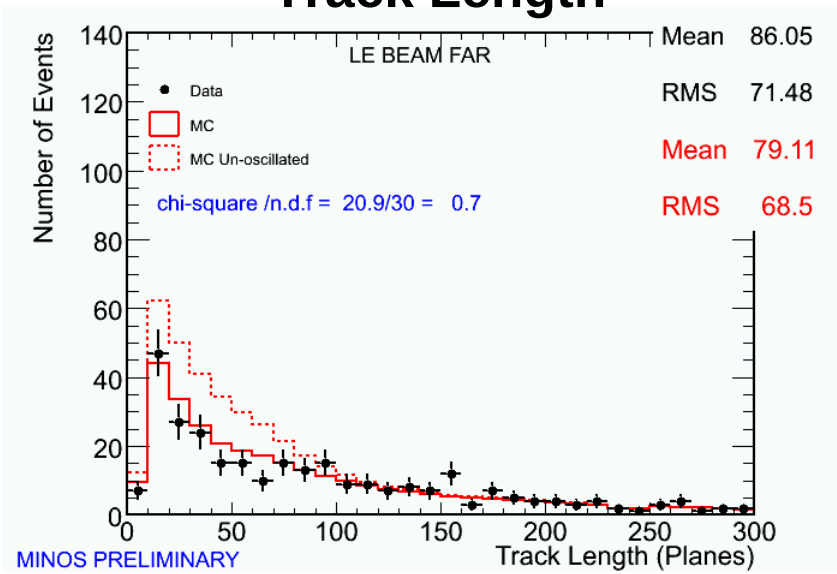




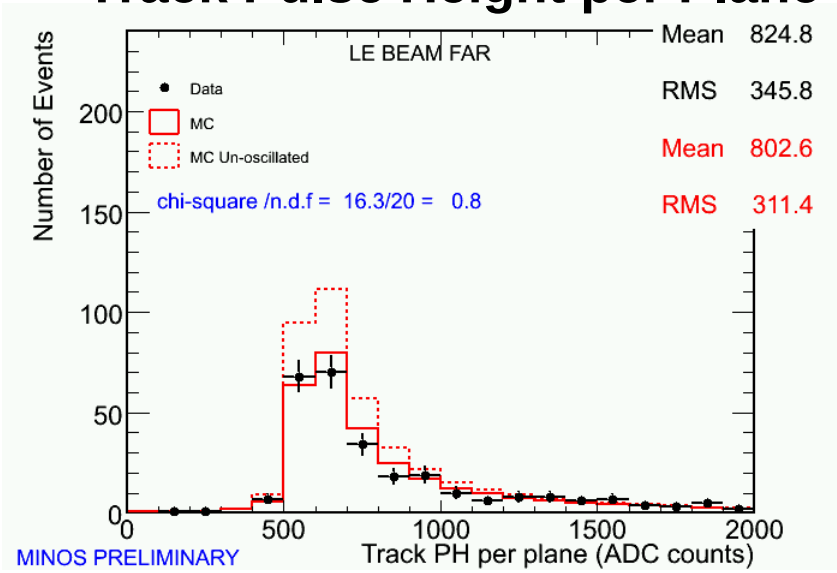
- Notice that beam is pointing 3 degrees up at Soudan!

Track quantities & PID parameter

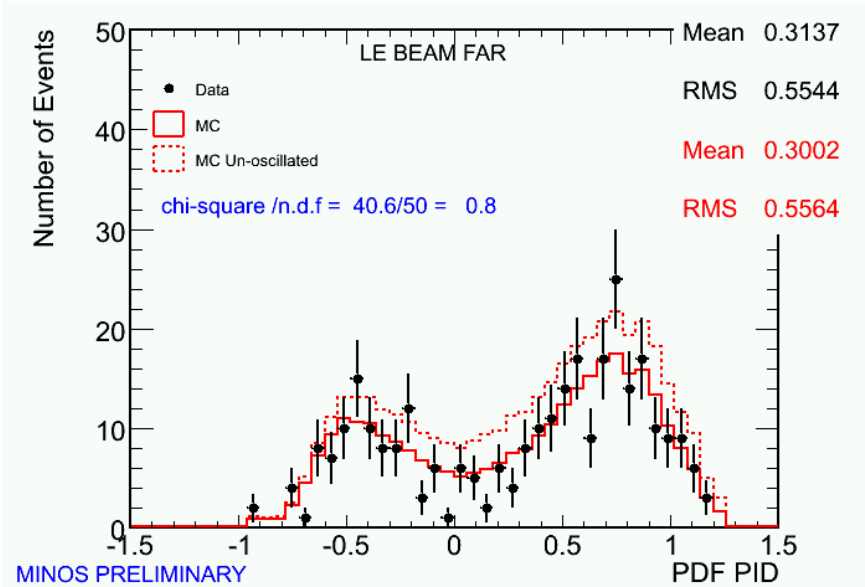
Track Length



Track Pulse Height per Plane



Particle Identification Parameter



Breakdown of selected events

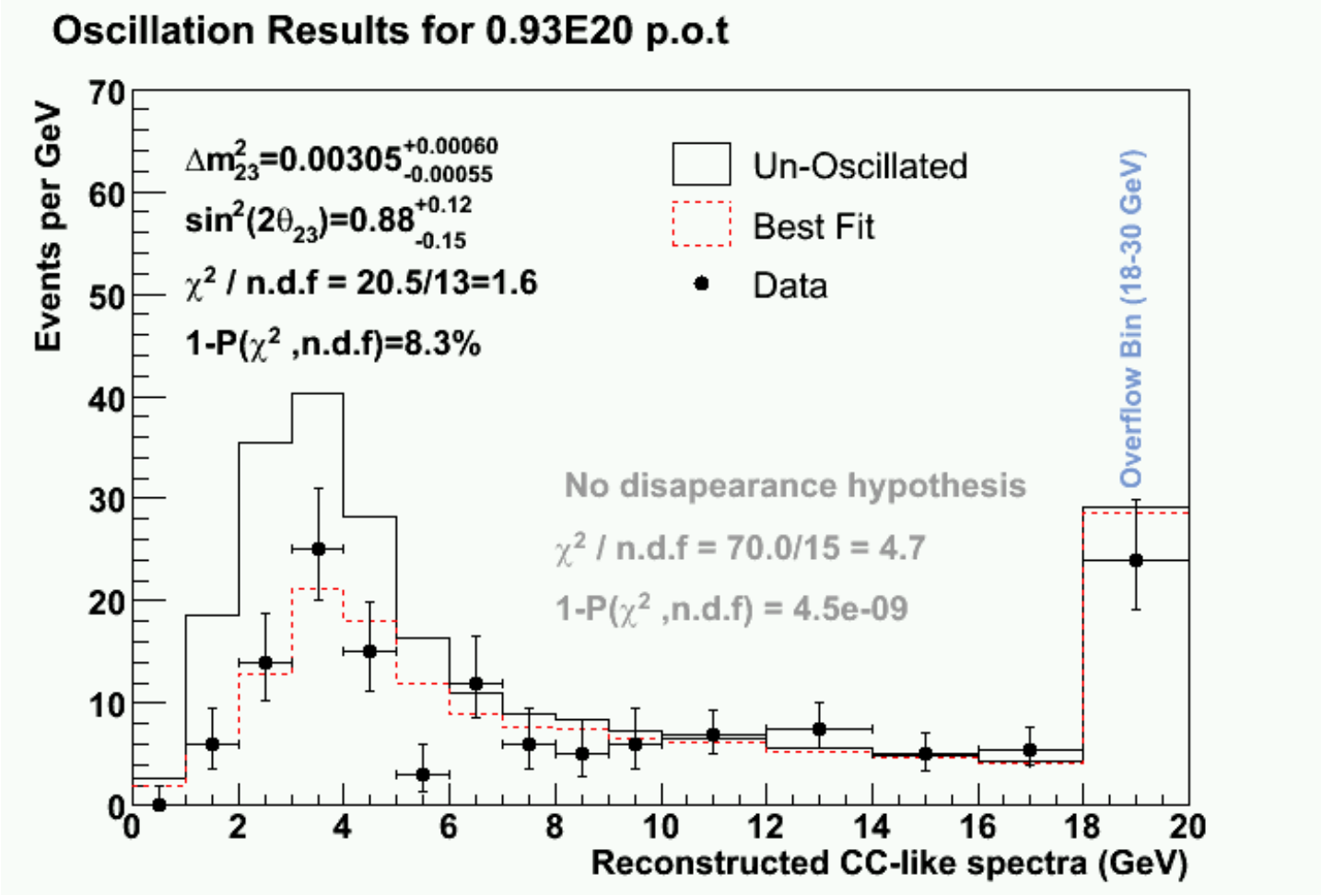
Cut	Events	efficiency
All events in fiducial vol	331	-
Events with a track	296	89.1%
Track quality cuts	281	95.3%
PID cut (CC-like)	204	72.9%
Track charge sign cut (negative muons only)	186	91.2%
Reconstructed energy < 30 GeV	166	89.2%

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 this effect is 5 standard deviations**

Best-fit spectrum

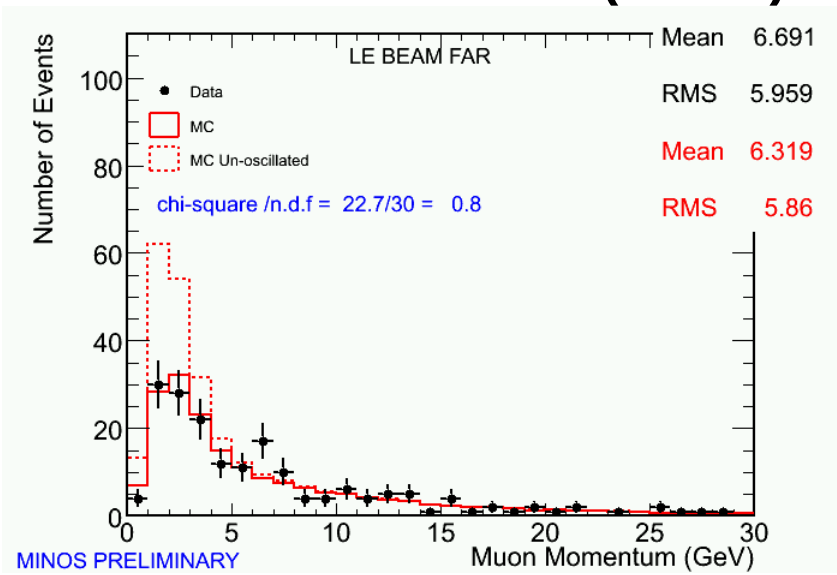


$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i)$$

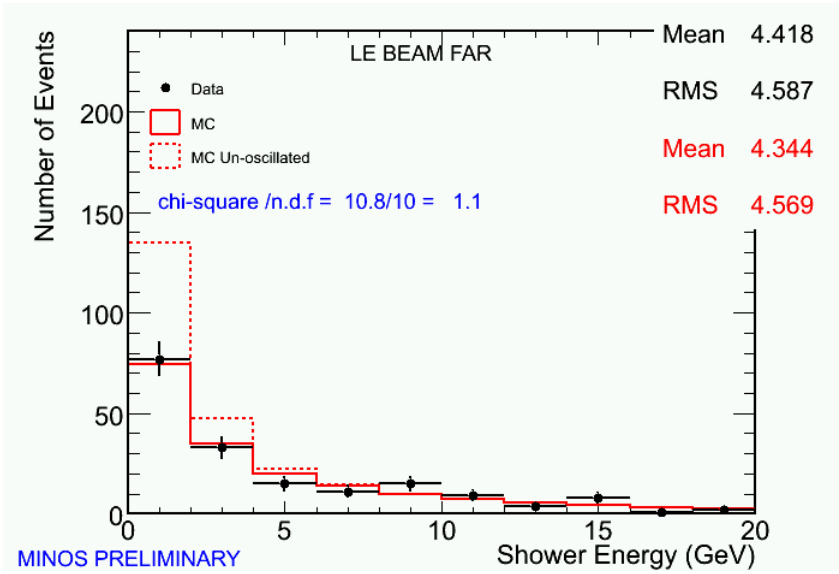
- Measurement errors are 1 sigma, 1 d.o.f.

Physics distributions

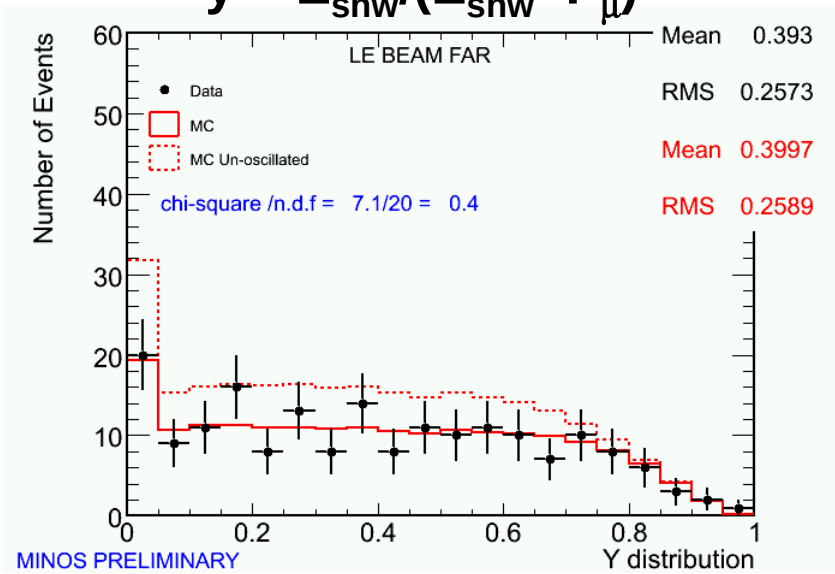
Muon Momentum (GeV/c)



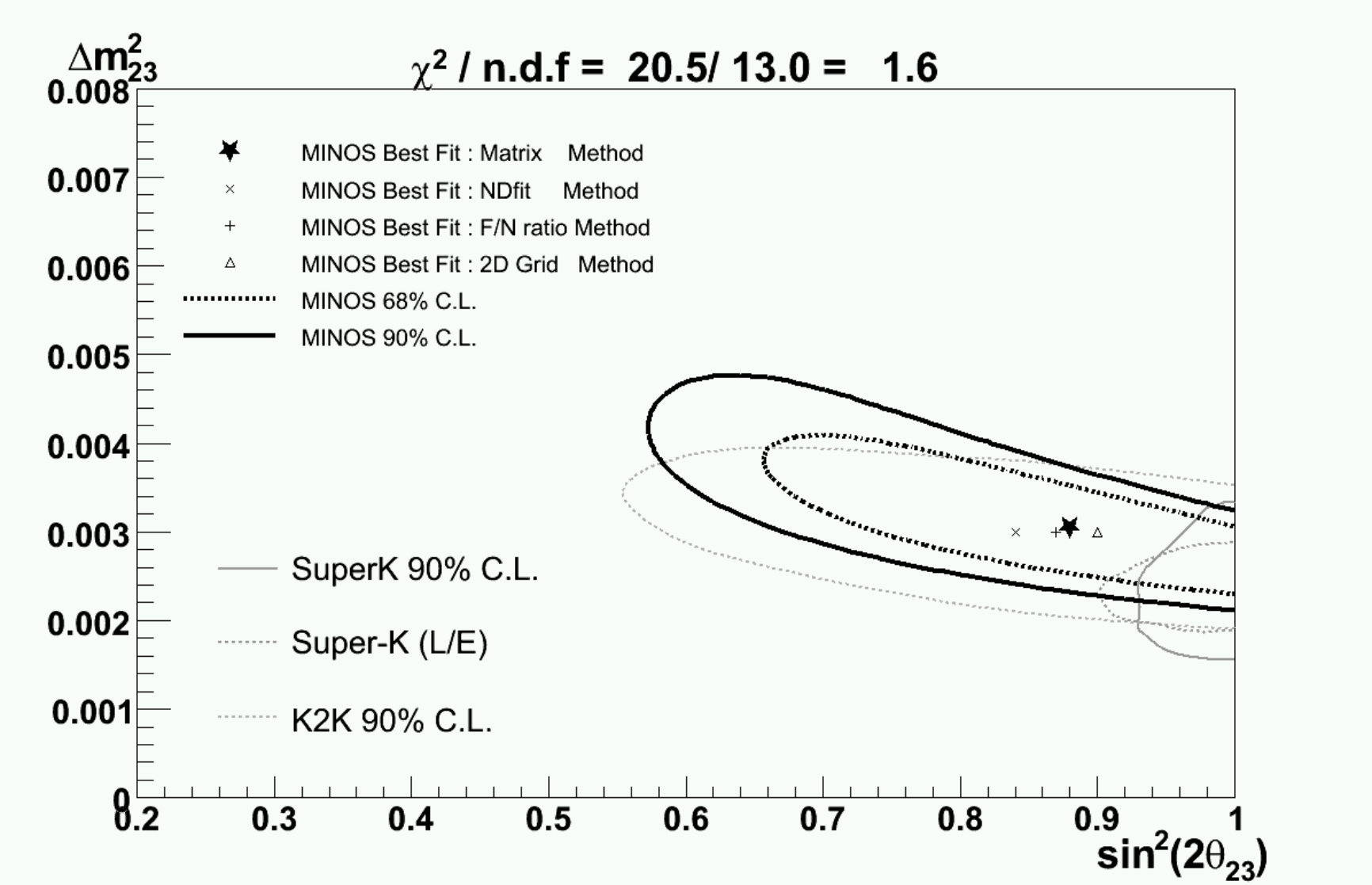
Shower Energy (GeV)



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

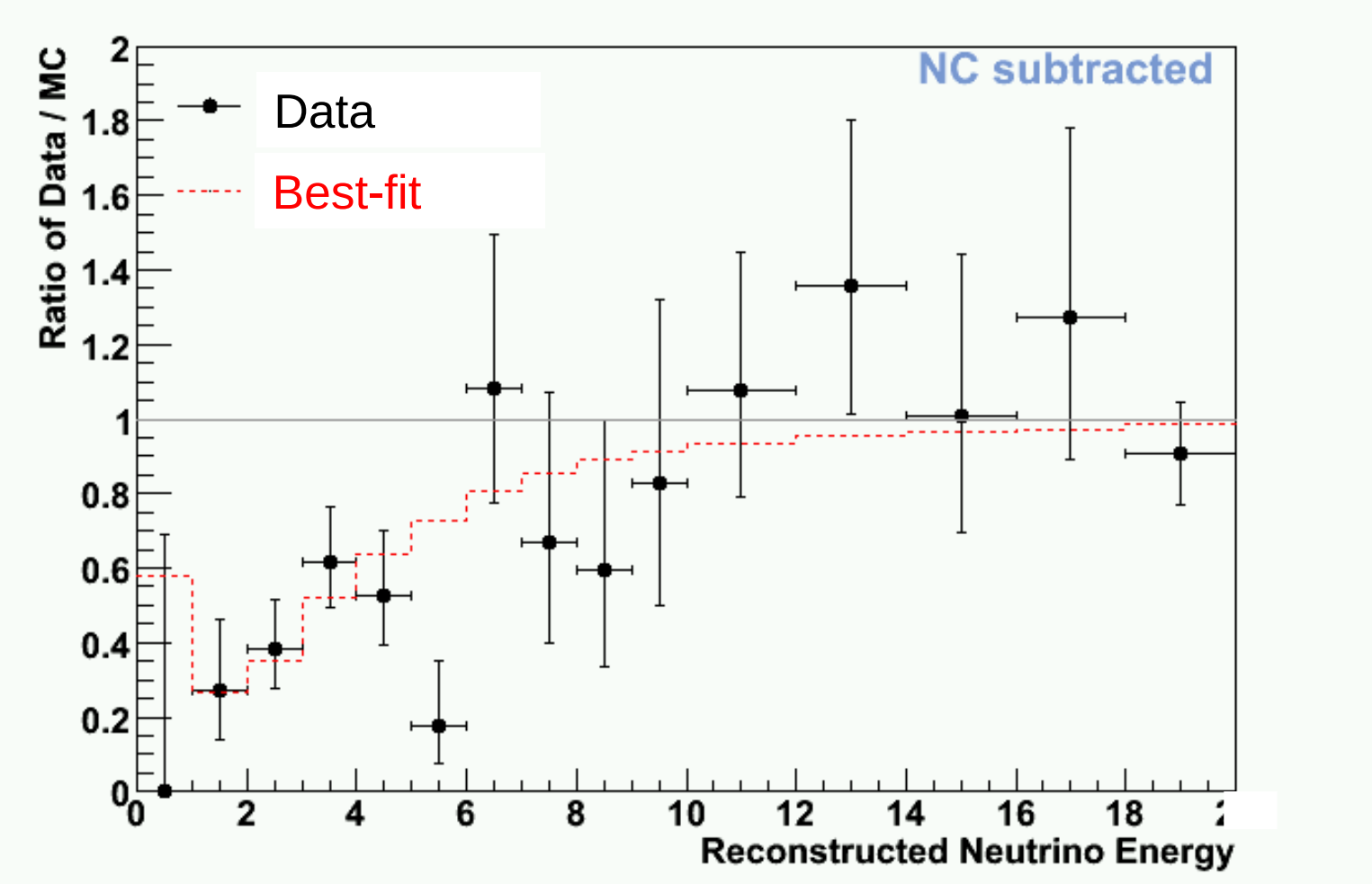


Allowed regions



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

Ratio of Data/MC



- Data is quite well-described by the best-fit oscillation hypothesis

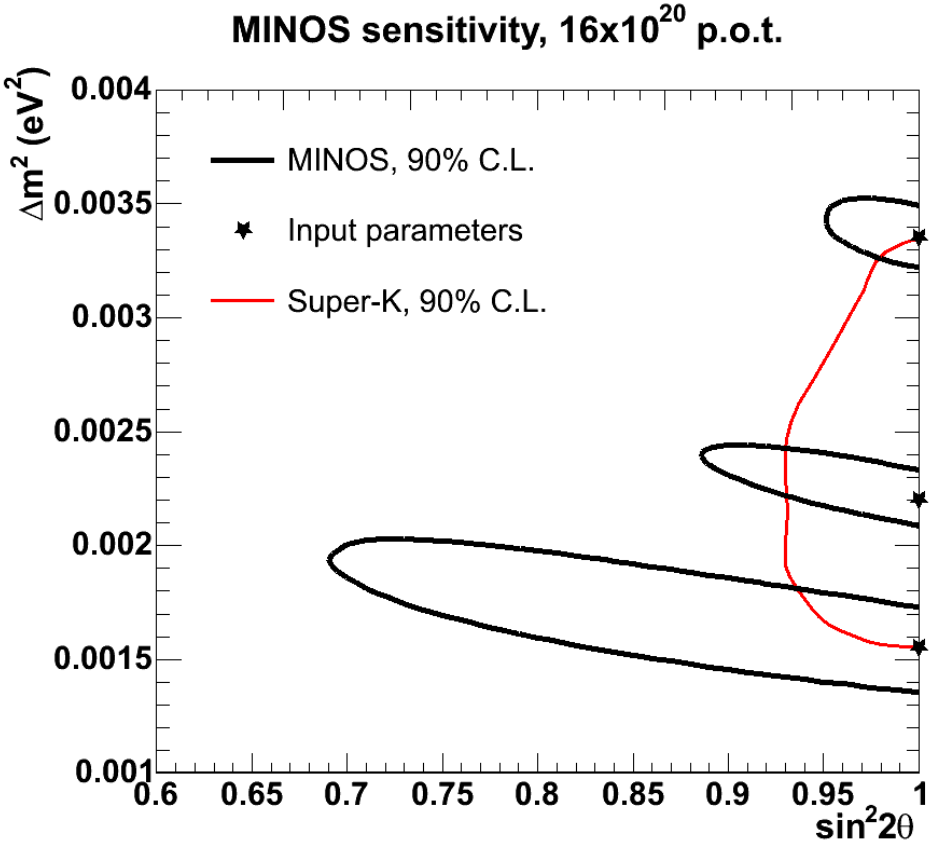
Systematic errors

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

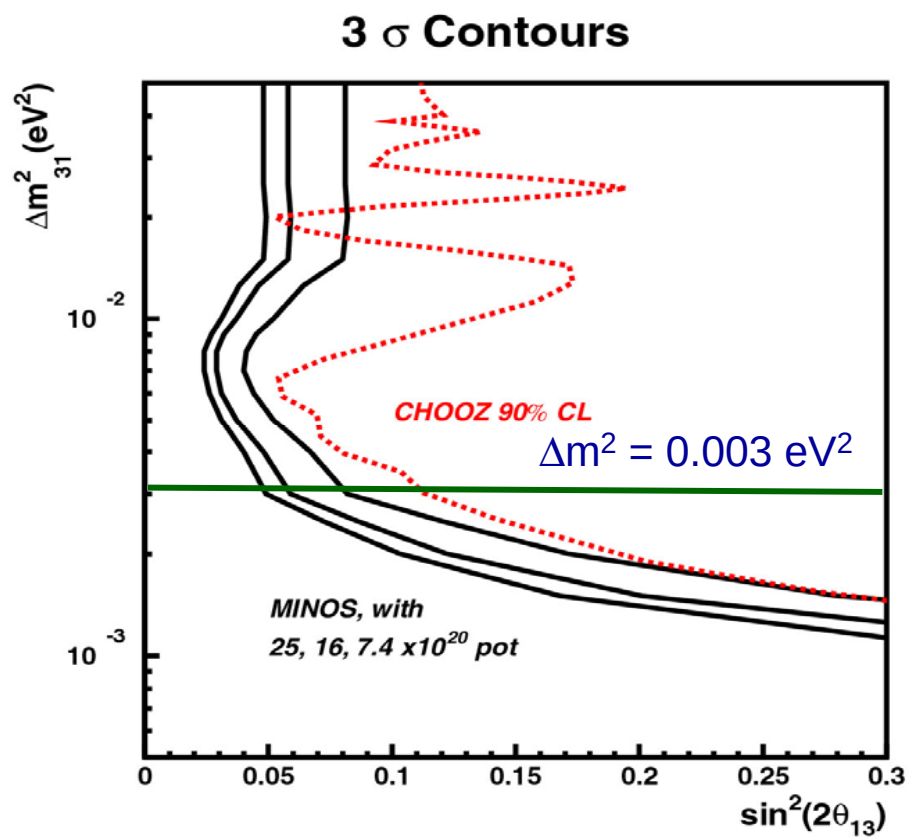
Uncertainty	Δm^2 shift (eV^2)	$\sin^2 2\theta$ shift
Normalisation +/- 4%	0.63e-4	0.025
Muon energy scale +/- 2%	0.14e-4	0.020
Relative Shower energy scale +/- 3%	0.27e-4	0.020
NC contamination +/- 30%	0.77e-4	0.035
CC cross-section uncertainties	0.50e-4	0.016
Beam uncertainty	0.13e-4	0.012
Intranuclear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

Projected sensitivity of MINOS

ν_μ disappearance



$\nu_\mu \rightarrow \nu_e$



•With increased statistics, we should be able to make a very precise measurement of Δm^2_{23} and also search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations well-below the current exclusion limit

•In addition, by making a precise measurement of the CC spectrum, we should be able to test/rule out alternate models such as neutrino decay.

Summary and Conclusions

- In this talk I have presented the first accelerator neutrino oscillation results from a 0.93×10^{20} pot exposure of the MINOS far detector.
- **Our result disfavours no oscillations at 5 σ and is consistent with ν_μ disappearance with the following parameters:**

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

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

- 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.

Acknowledgements

- **On behalf of the MINOS Collaboration, we would like to express our gratitude to the many Fermilab groups (Accelerator division, Technical division, PPD, Computing division, Business services, Laboratory services, ES&H, FESS) who provided technical expertise and support in the design, construction, installation and operation of the experiment.**

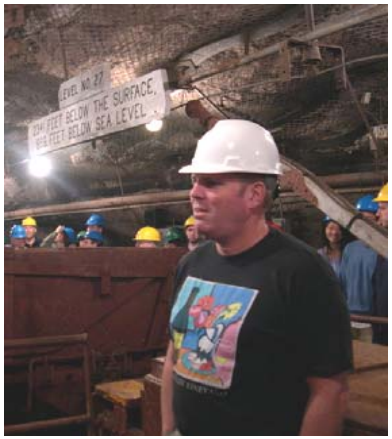
- **We would also like to gratefully acknowledge financial support from the following institutions: DOE, NSF, University of Minnesota, PPARC(UK)**

Palace of King Minos, Knossos, Crete

Dedication

Lynn Miller

Michael Murtagh

Julia Thompson

Doug Michael