First MINOS Results from the NuMI Beam

C. James, MINOS Run Coordinator
for the MINOS Collaboration

FNAL Program Review, May 2006

The MINOS Experiment

- MINOS

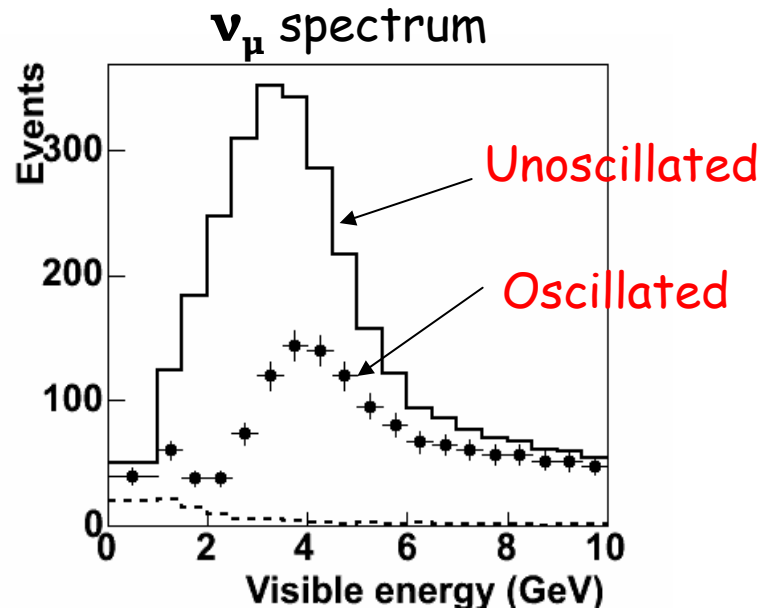
Main Injector Neutrino Oscillation Search

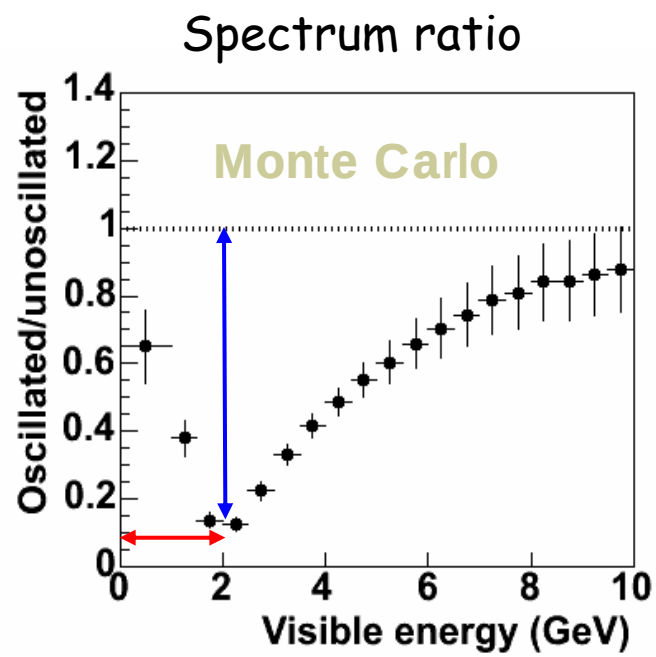
- Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.
- Near Detector at Fermilab to measure the beam composition and energy spectrum
  - Develop CC muon neutrino event selection
  - Examine Near detector distributions and comparison with Monte Carlo
- Far Detector deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations
  - "blinded" data-set
  - Near-Far extrapolation of the neutrino flux
  - Oscillation Analysis with 0.93×10^{20} POT

The Oscillation Measurement

- To perform the oscillation analysis, we need to predict the neutrino spectrum seen by the Far Detector in the absence of oscillations.
- Want to minimise uncertainties related to beam modeling and cross-sections (nominal values are built-in to our Monte Carlo.)
- Use the Near Detector data to correct the nominal Monte Carlo
  - beam spectrum
  - neutrino cross-sections
- Look for a deficit of ν_μ events at Soudan

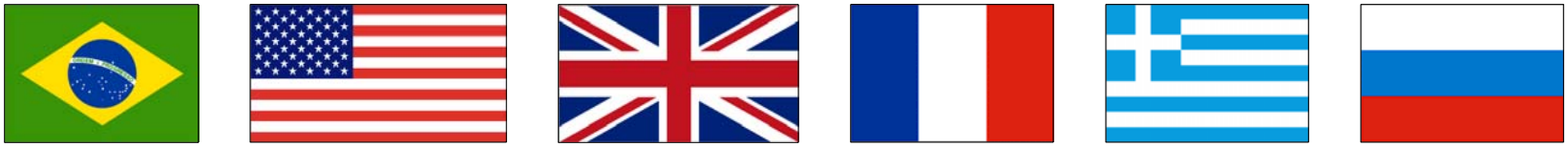
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$





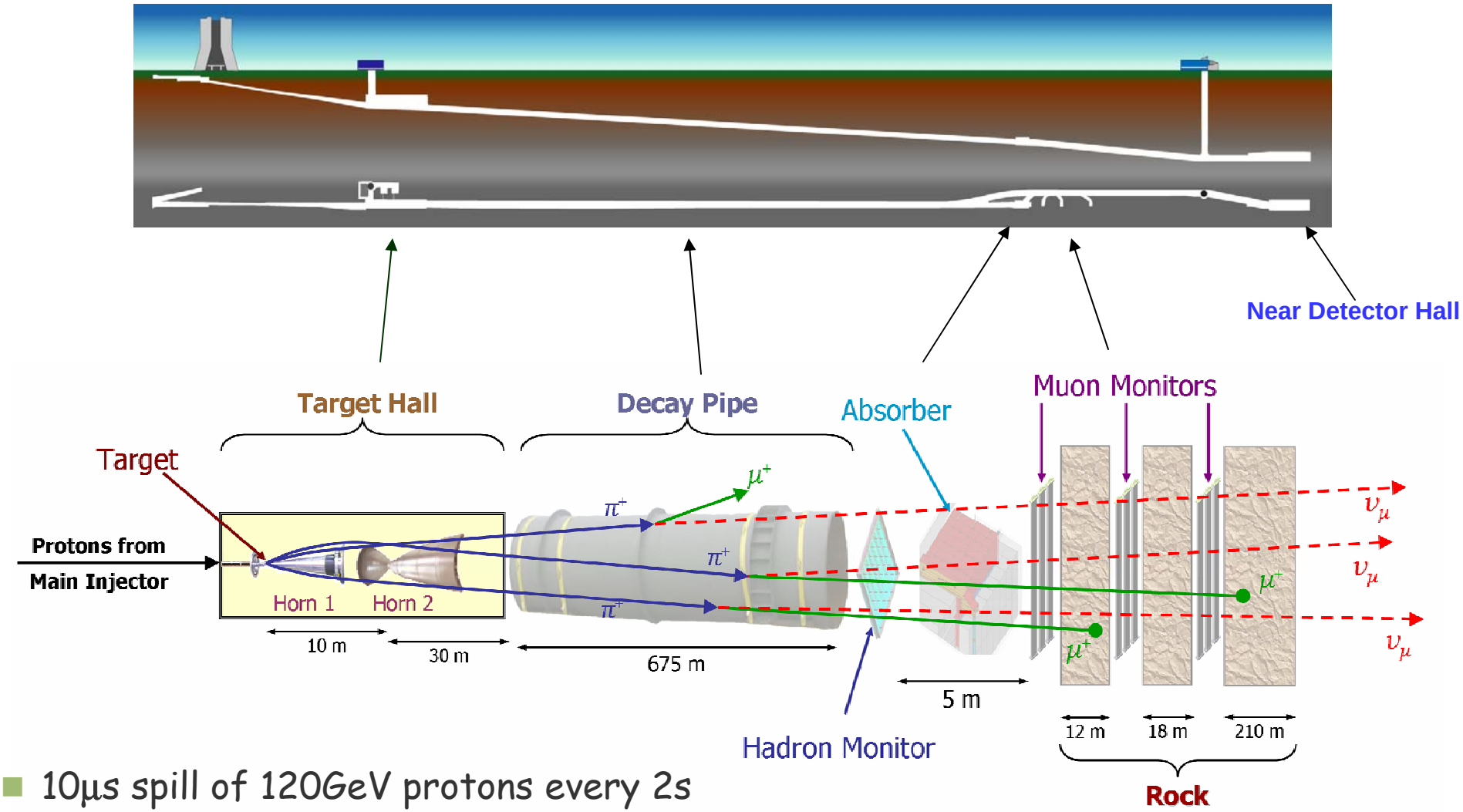
MINOS Collaboration

- 32 institutions, 175 scientists
- The FNAL MINOS group numbers 32
  - 29 senior staff and 3 post-docs
    - 16 in Particle Physics Division
    - 4 in Computing Division
    - 12 in Accelerator Division
  - 7 FTE involved in current data analysis



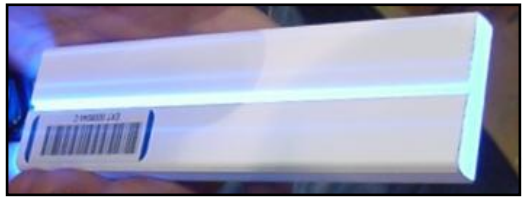
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas
College de France • Fermilab • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Duluth • Minnesota-Twin Cities • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex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

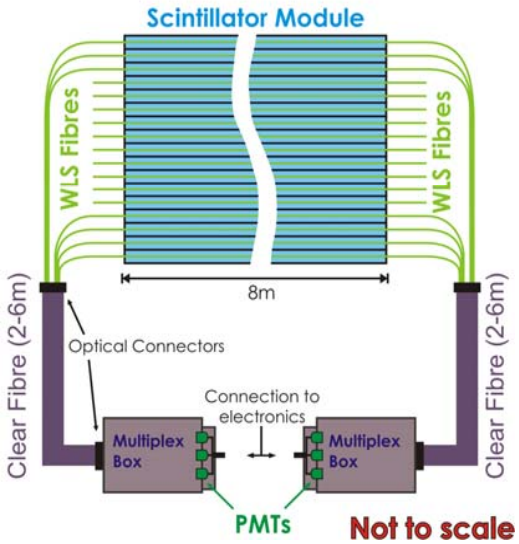
NuMI Beam Facility



- 10μs spill of 120GeV protons every 2s
- 0.2 MW average beam power
- 20 $\times 10^{12}$ protons per pulse (ppp)

MINOS Detectors





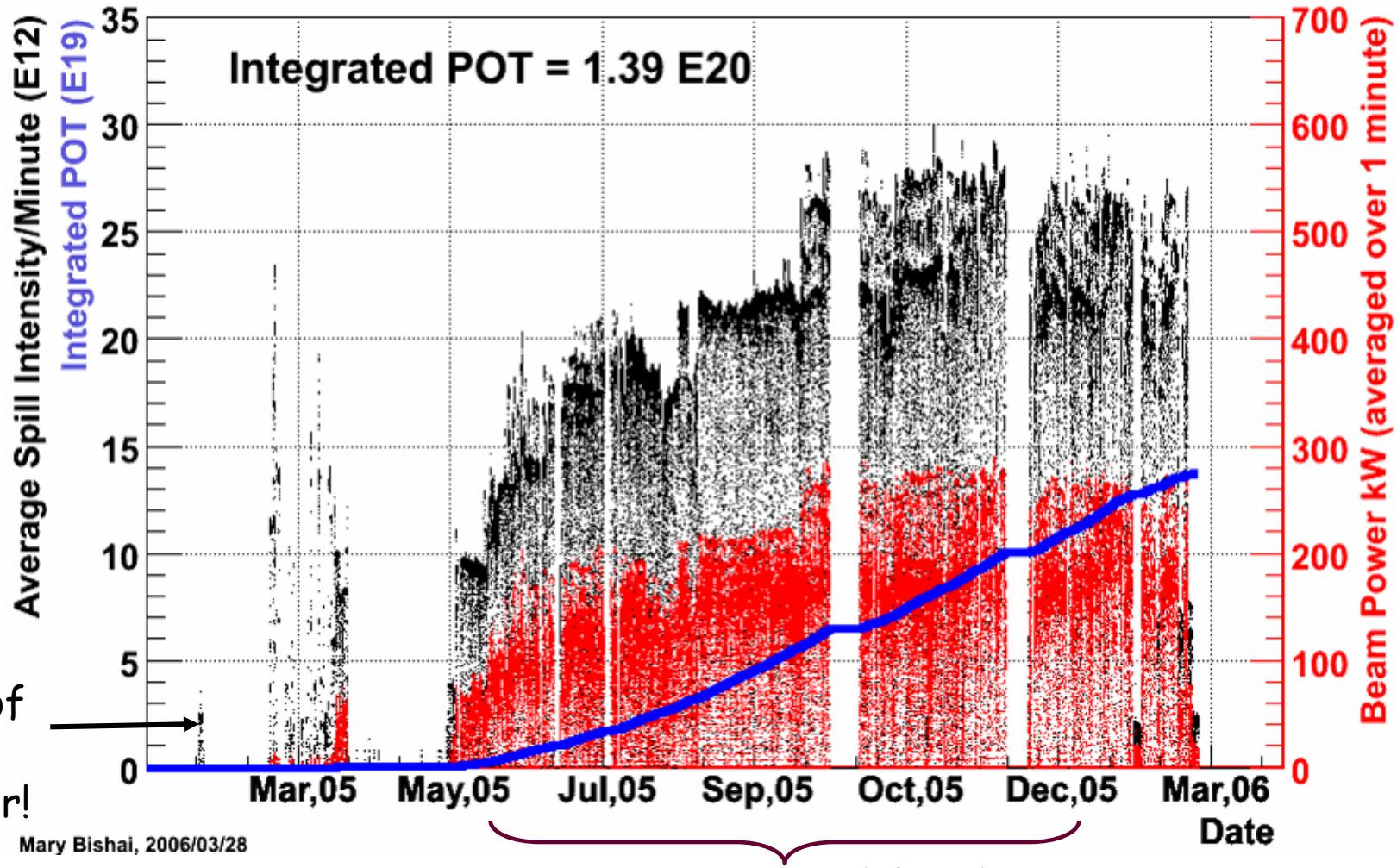
- 1 km from target
- 1 kton
- 282 steel planes
- 153 scintillator planes
- Live-time during beam: 95%

- 735 km from target
- 5.4 kton
- 484 steel/scintillator planes
- Live time during beam: 98.9%

- 2.54cm thick magnetised steel plates
- co-extruded scintillator strips
- orthogonal orientation on alternate planes – U,V
- optical fibre readout to multi-anode PMTs
- Magnetised to 1.2 T
- GPS time-stamping to synchronise FD data to ND/beam

First Year of NuMI Beam

2.3×10^{13} protons/pulse averaged for 15 Oct to 31 Jan (2.2 s cycle)

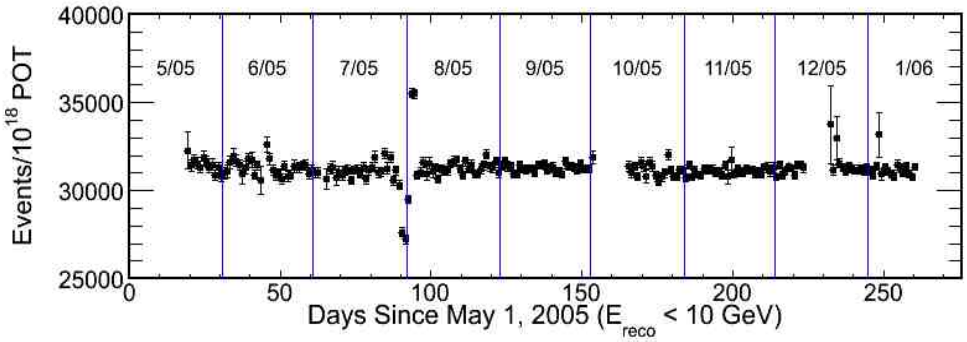


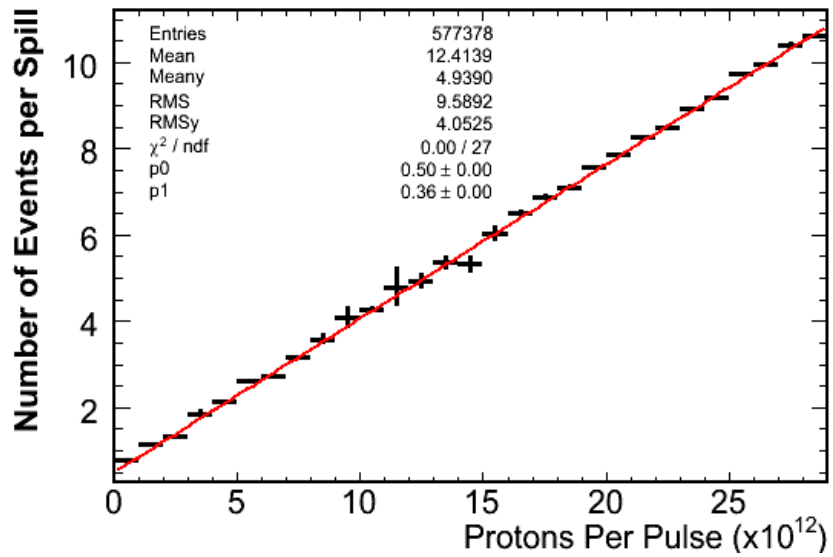
Observation of neutrinos in Near Detector!

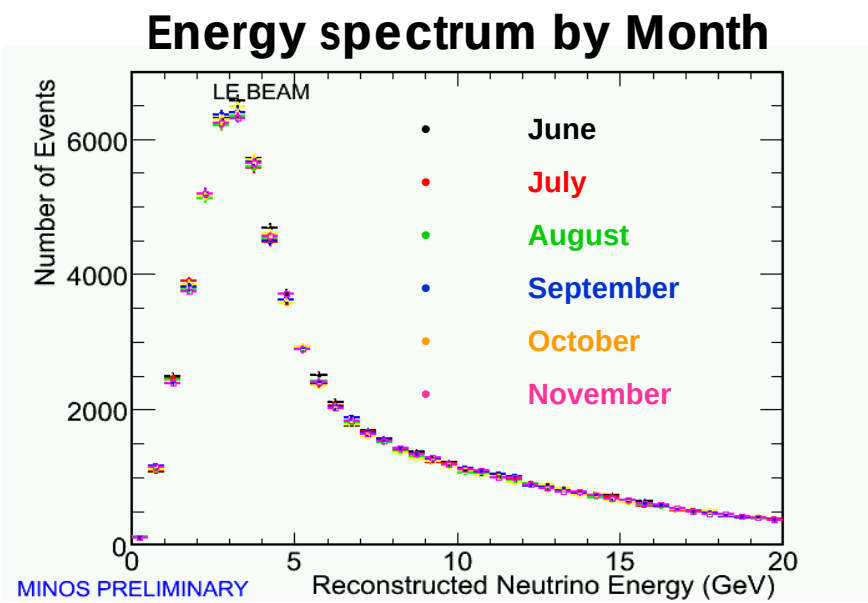
Dataset used for the oscillation analysis

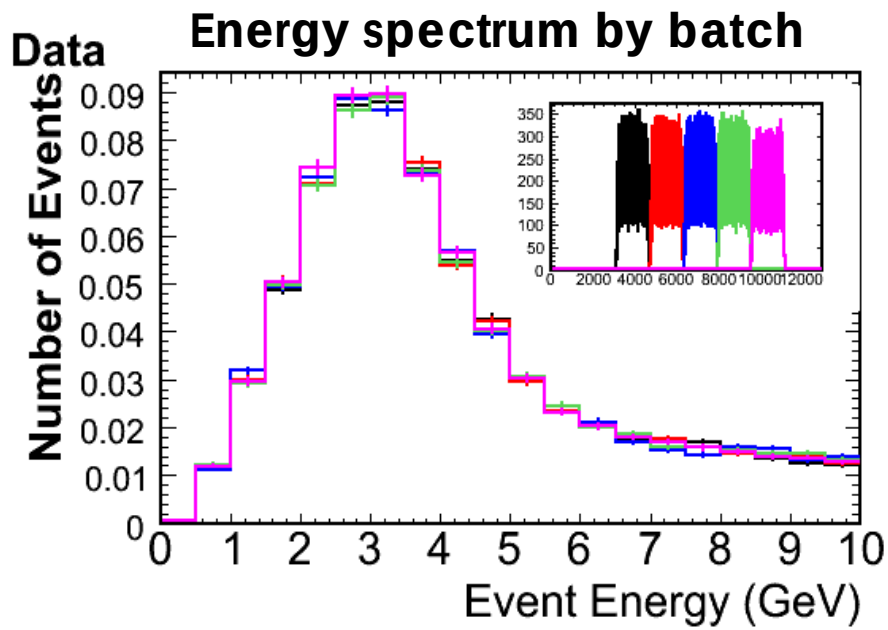
Beam & Near Detector stability

- Over time, and at different intensities





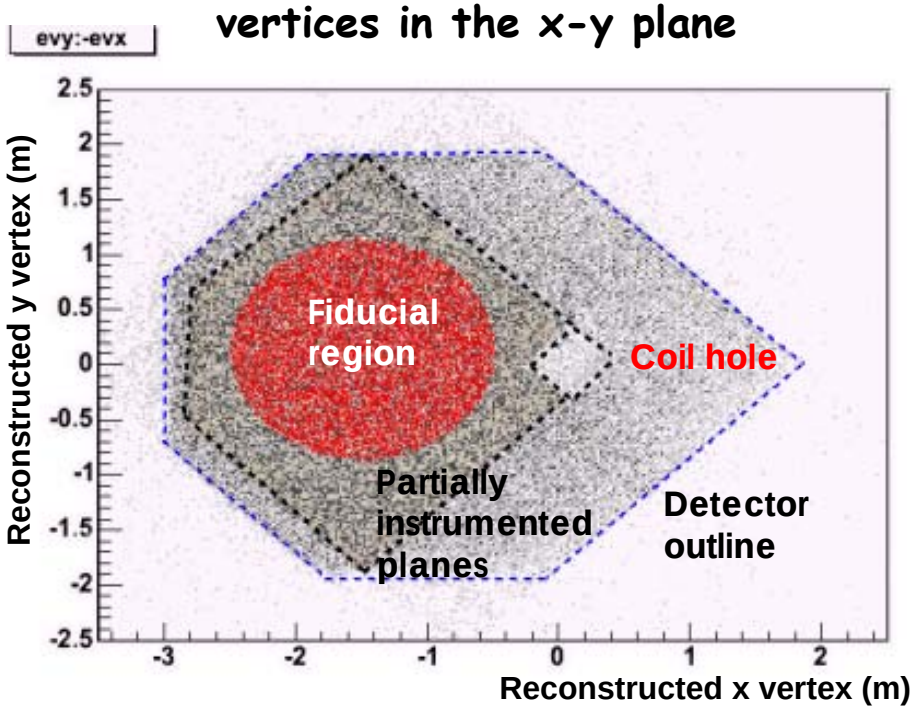




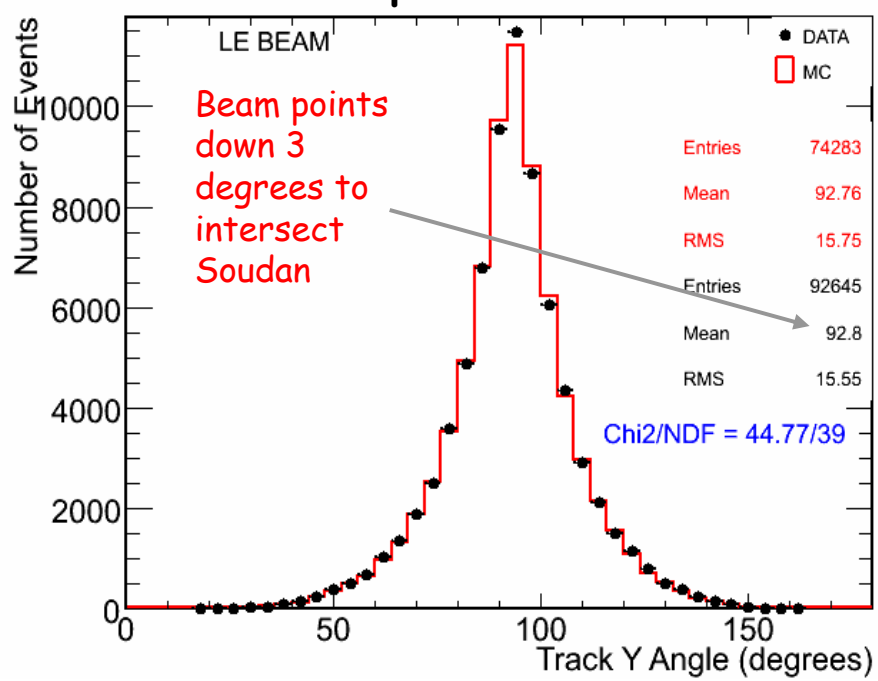
Near Detector Data

- We observe very large event rates in the Near detector (~10^7 events in the fiducial volume for 10^{20} POT)
  - This provides a high statistics dataset with which we can study how well we understand the performance of the Near Detector and check the level to which our data agrees with our Monte Carlo predictions

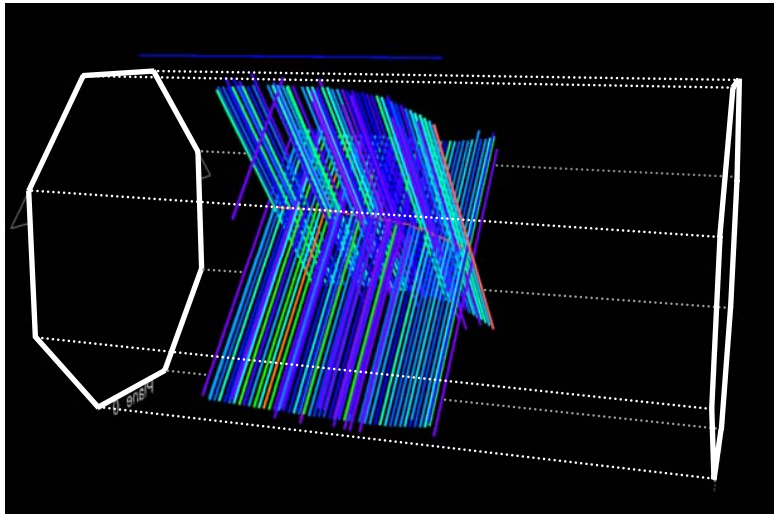
Distribution of reconstructed event vertices in the x-y plane

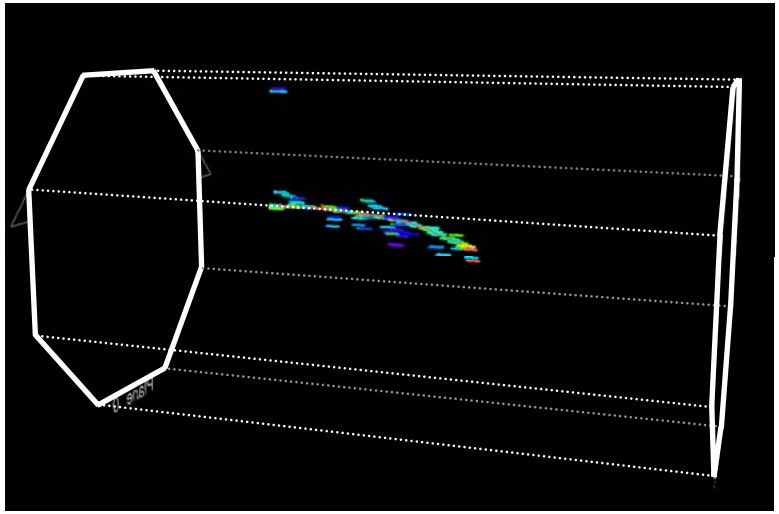


Reconstructed track angle with respect to vertical



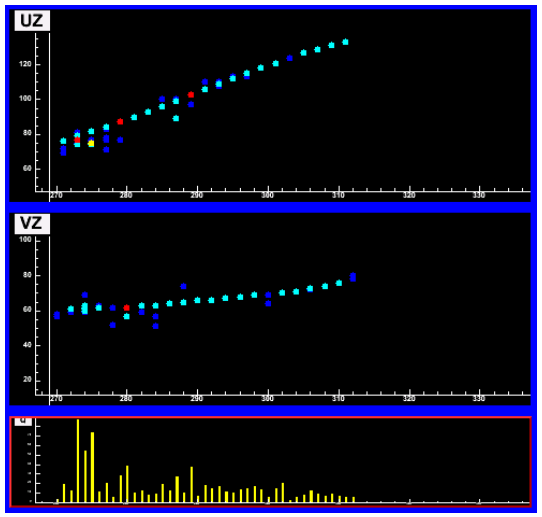
Events look like - - -





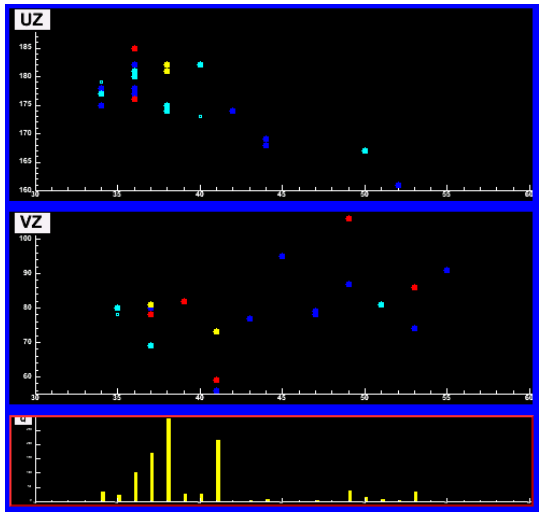
Monte Carlo

ν_μ CC Event



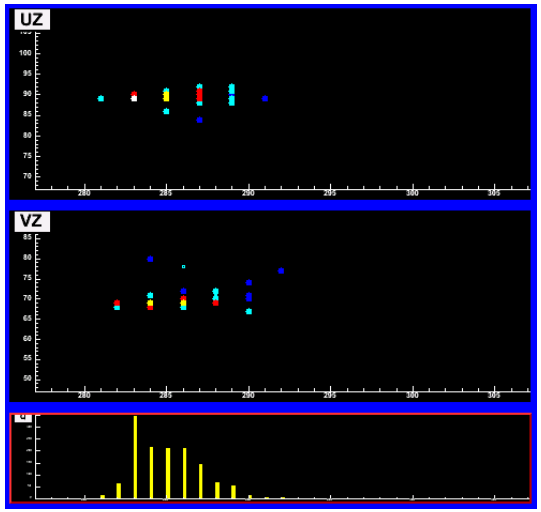
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

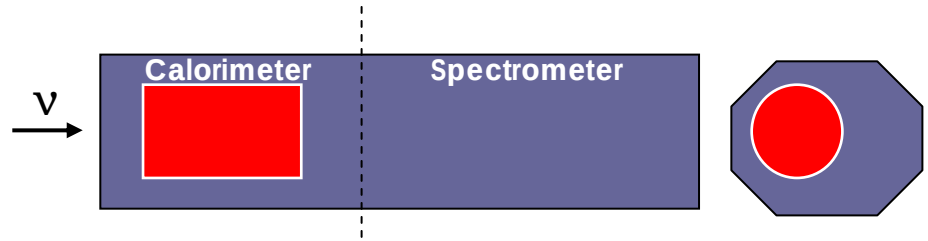
Event Selection

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

1. The reconstructed track vertex should be within the fiducial volume of the detector:
2. The fitted Event must contain at least one good reconstructed track
3. 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.

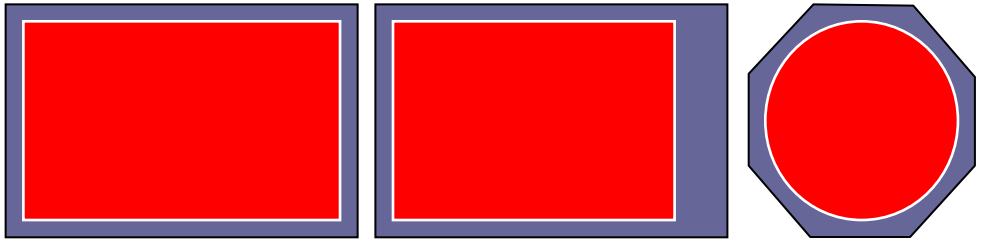
NEAR:

1m < z < 5m (from detector front)
R < 1m from beam center



FAR:

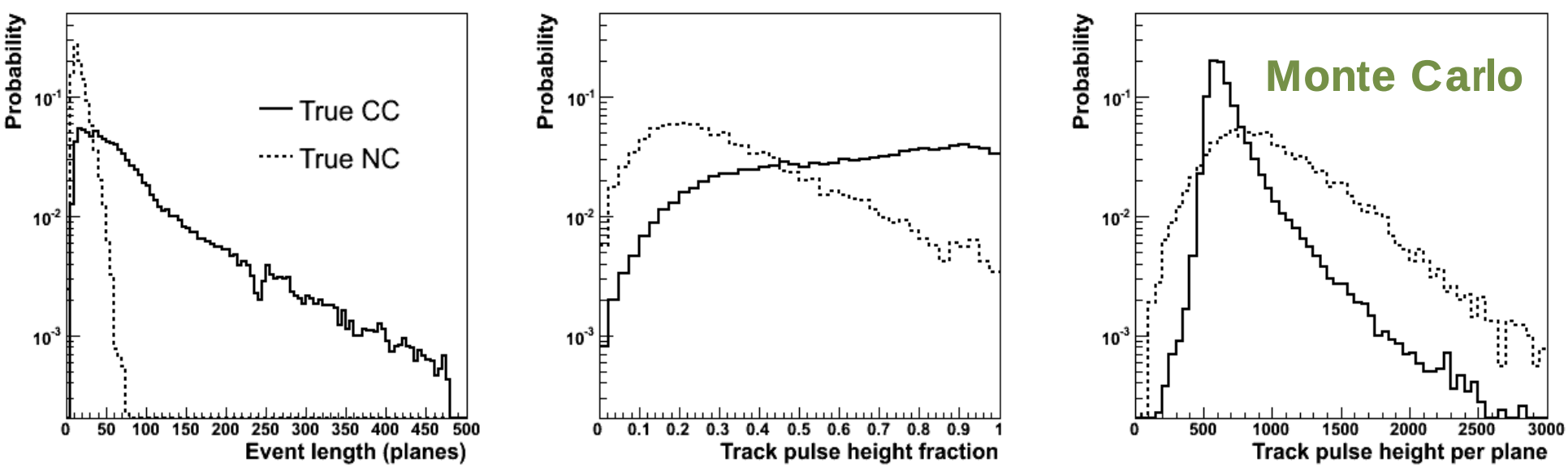
z > 50cm from front face
z > 2m from rear face
R < 3.7m from detector center



Selecting CC Events

- Events selected by likelihood-based procedure, with 3 input Probability Density Functions (PDFs), which show differences between 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*)
- Define P_μ (P_{NC}) as the product of the three CC (NC) PDFs, at the values of these variables taken by the event

Input variables for PDF-based event selection

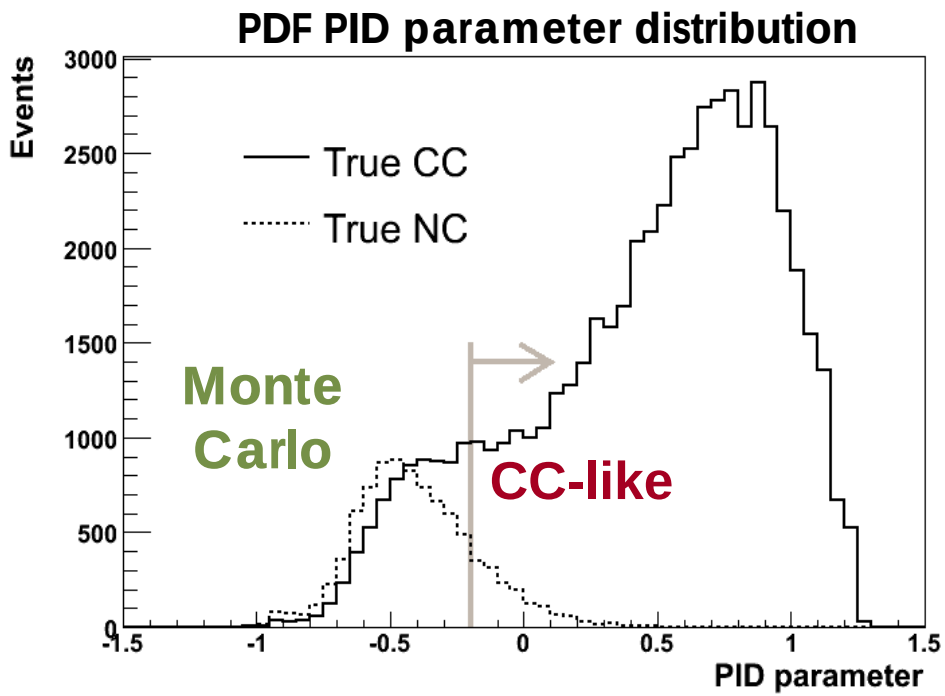


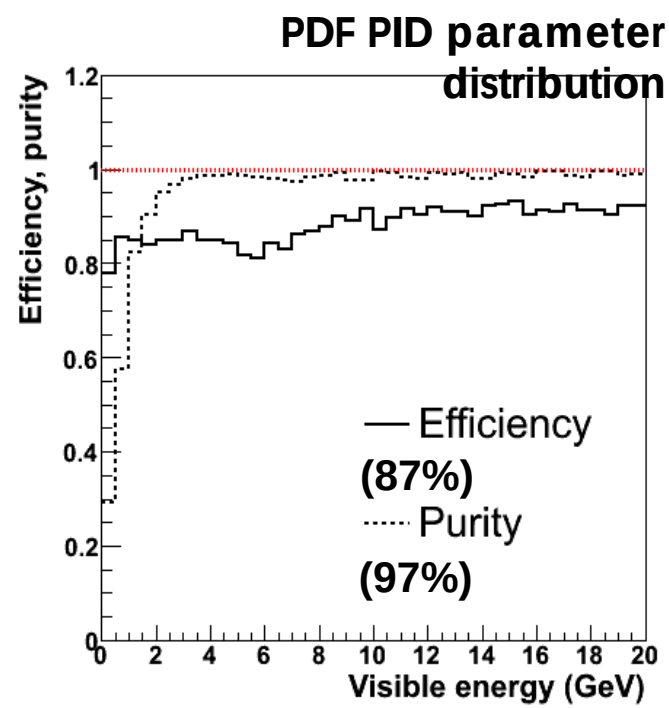
Selecting CC Events

- Particle ID (PID) parameter is defined:

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

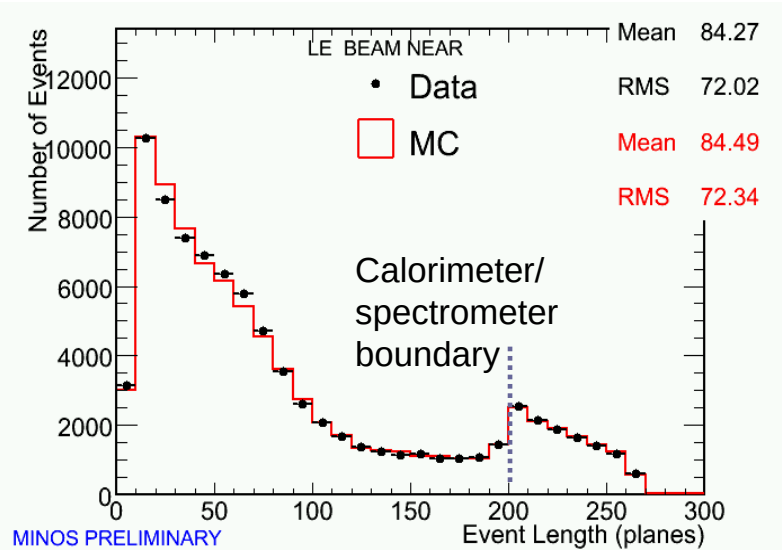
- *CC*-like events are defined by *PID* > –0.2 in the FD (> –0.1 in the ND)
  - NC contamination limited to low energy bins (below 1.5 GeV)
  - Selection efficiency is quite flat as a function of visible energy



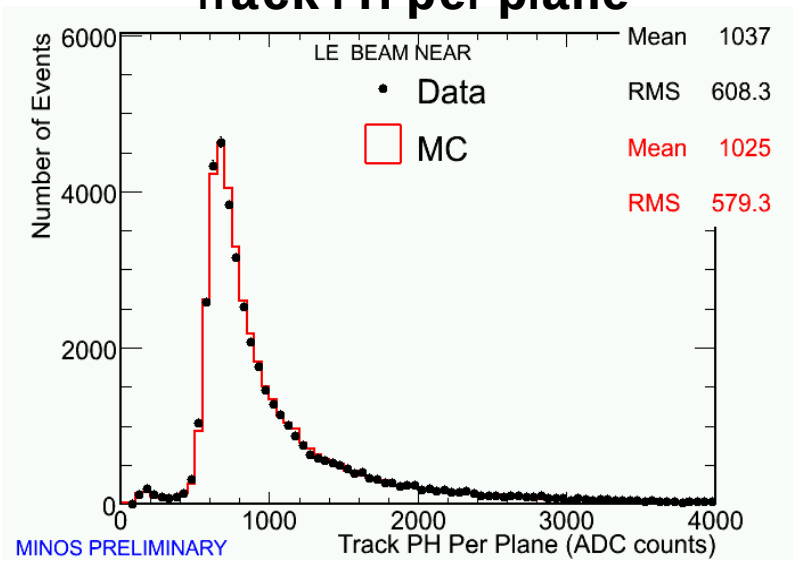


Near Detector data

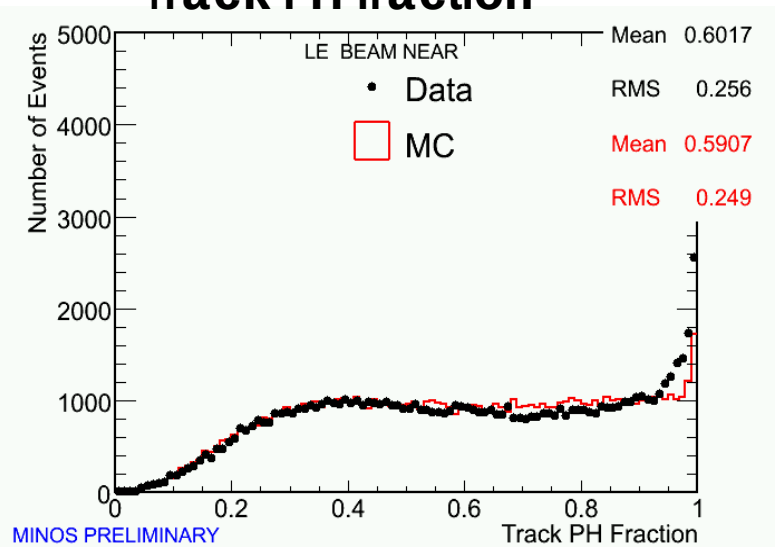
Event length



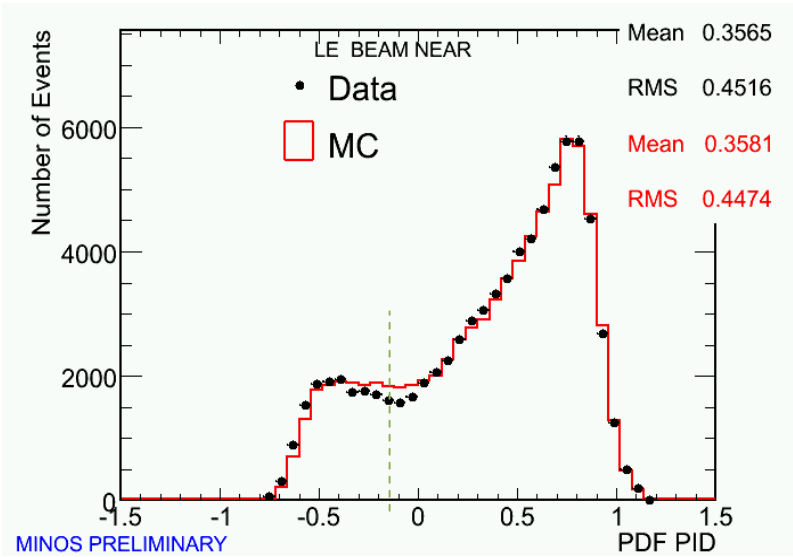
Track PH per plane



Track PH fraction

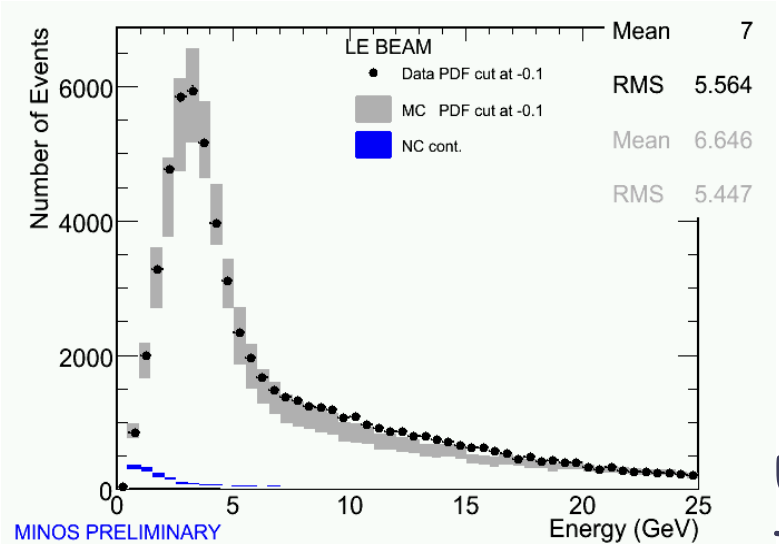


PID Parameter



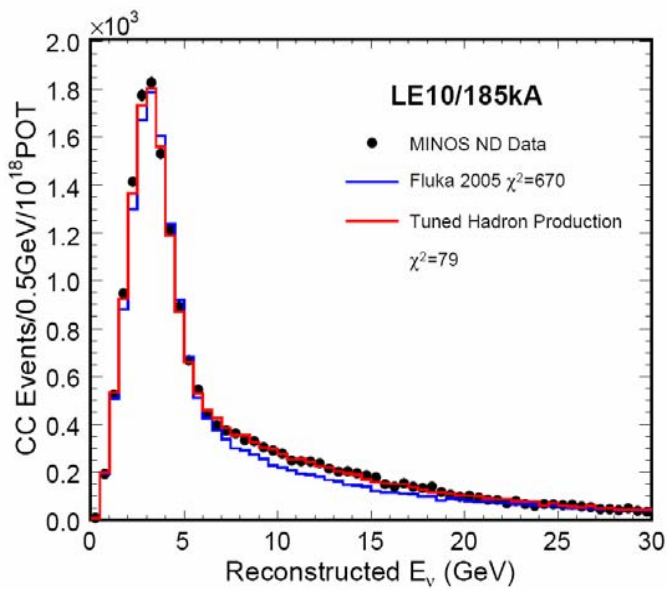
Neutrino Spectrum in Near Detector

Error envelope reflects uncertainties due to cross-section modeling, beam modeling and calibration uncertainties

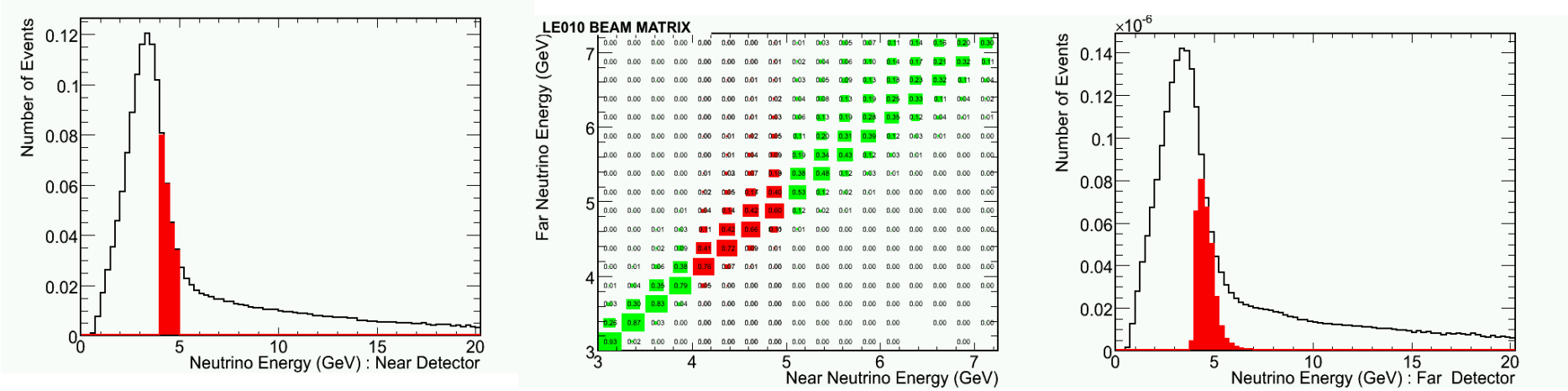


Use the Monte Carlo to transform from this Reconstructed energy spectrum to the True energy spectrum

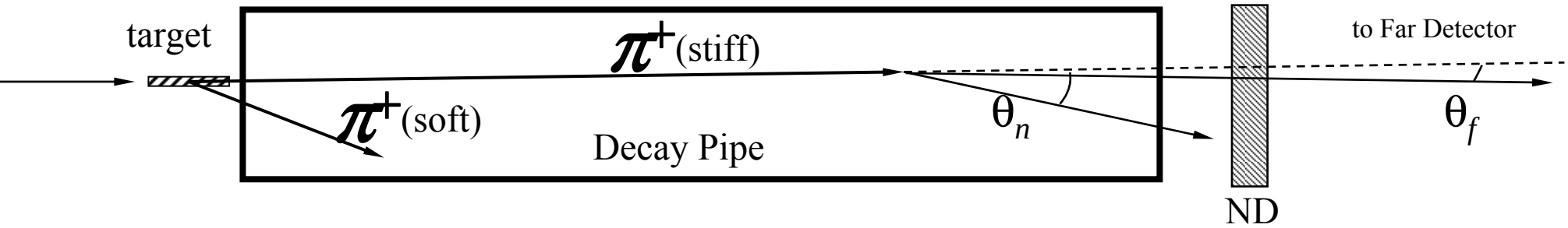
Agreement between data and Fluka-05 Beam MC is pretty good, but by tuning the MC by fitting to hadronic x_F and p_T, improved agreement can be obtained.



Predict the Far Spectrum (unoscillated)

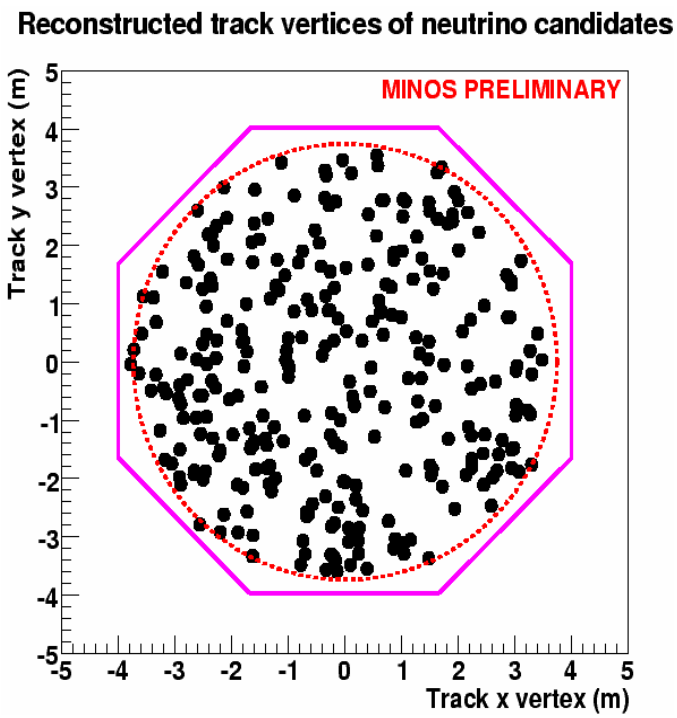


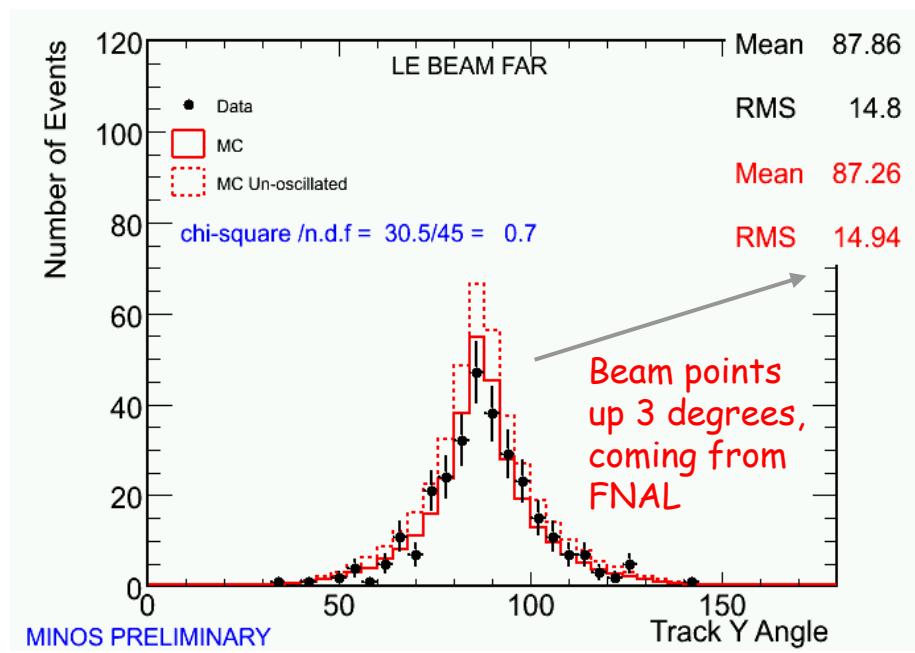
- Directly use Near Detector data to perform extrapolation between Near and Far.
  - Use Monte Carlo to provide necessary corrections due to energy smearing and acceptance, i.e to transform from reconstructed to true.
- Use our knowledge of pion decay kinematics and the geometry of our beamline to predict the true FD energy spectrum from the true ND spectrum.
  - This **Beam Matrix** encapsulates the knowledge of pion 2-body decay kinematics & geometry.



Far Detector Data

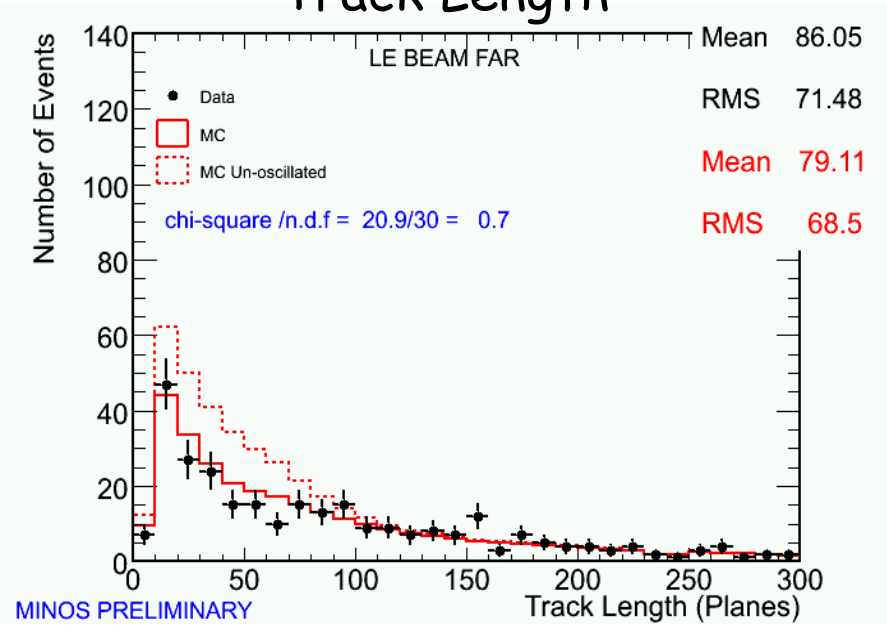
- Far Detector Data
  - The blinding procedure hides an unknown fraction of FarDet events based on their length and total energy deposition.
  - performed extensive data quality checks on the open fraction
  - Unblinding criteria were:
    - no problems with the Far Detector beam dataset (missing events, reconstruction problems, etc.)
    - Oscillation analysis (cuts and fitting procedures) pre-defined and validated on MC; no re-tuning of cuts allowed after unblinding



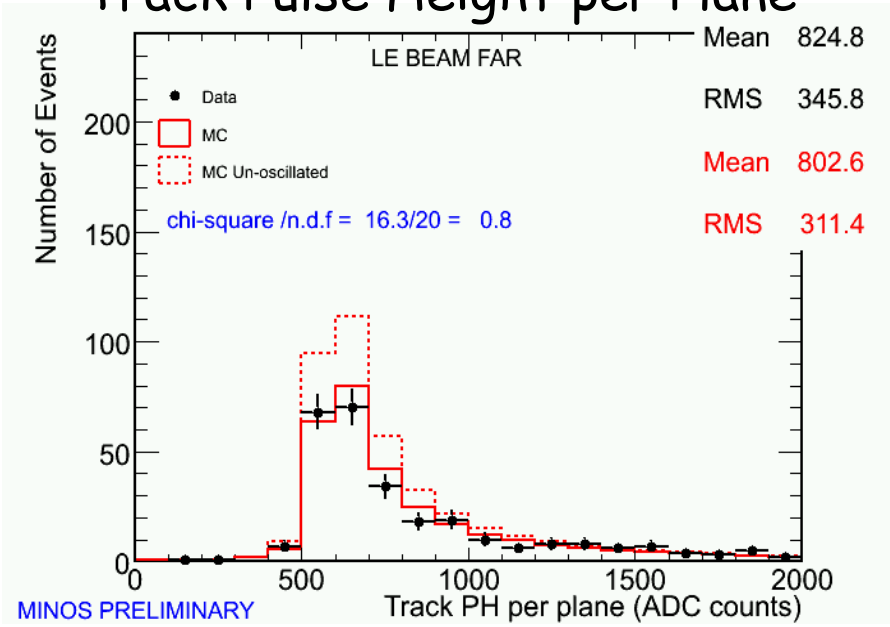


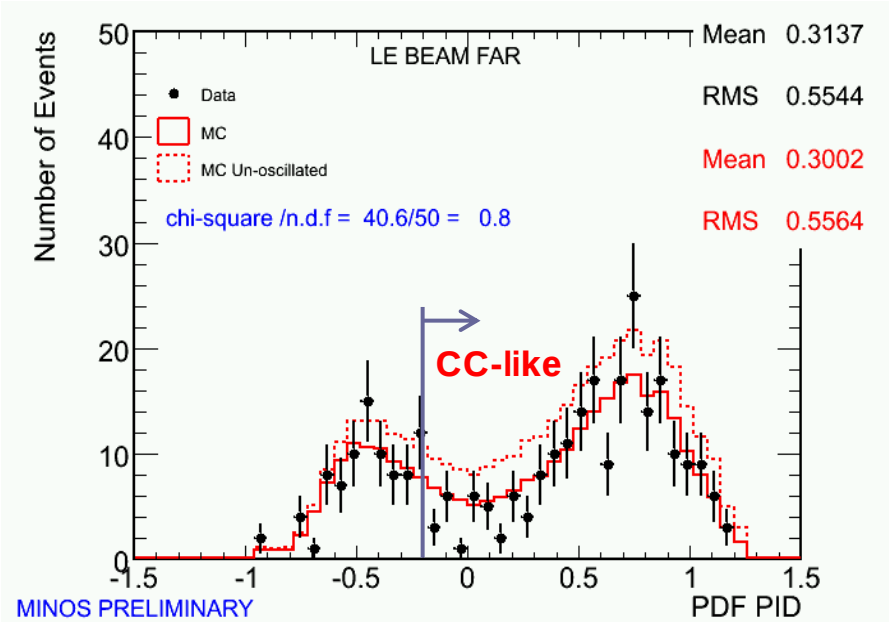
Far Detector – track quantities & PID

Track Length



Track Pulse Height per Plane





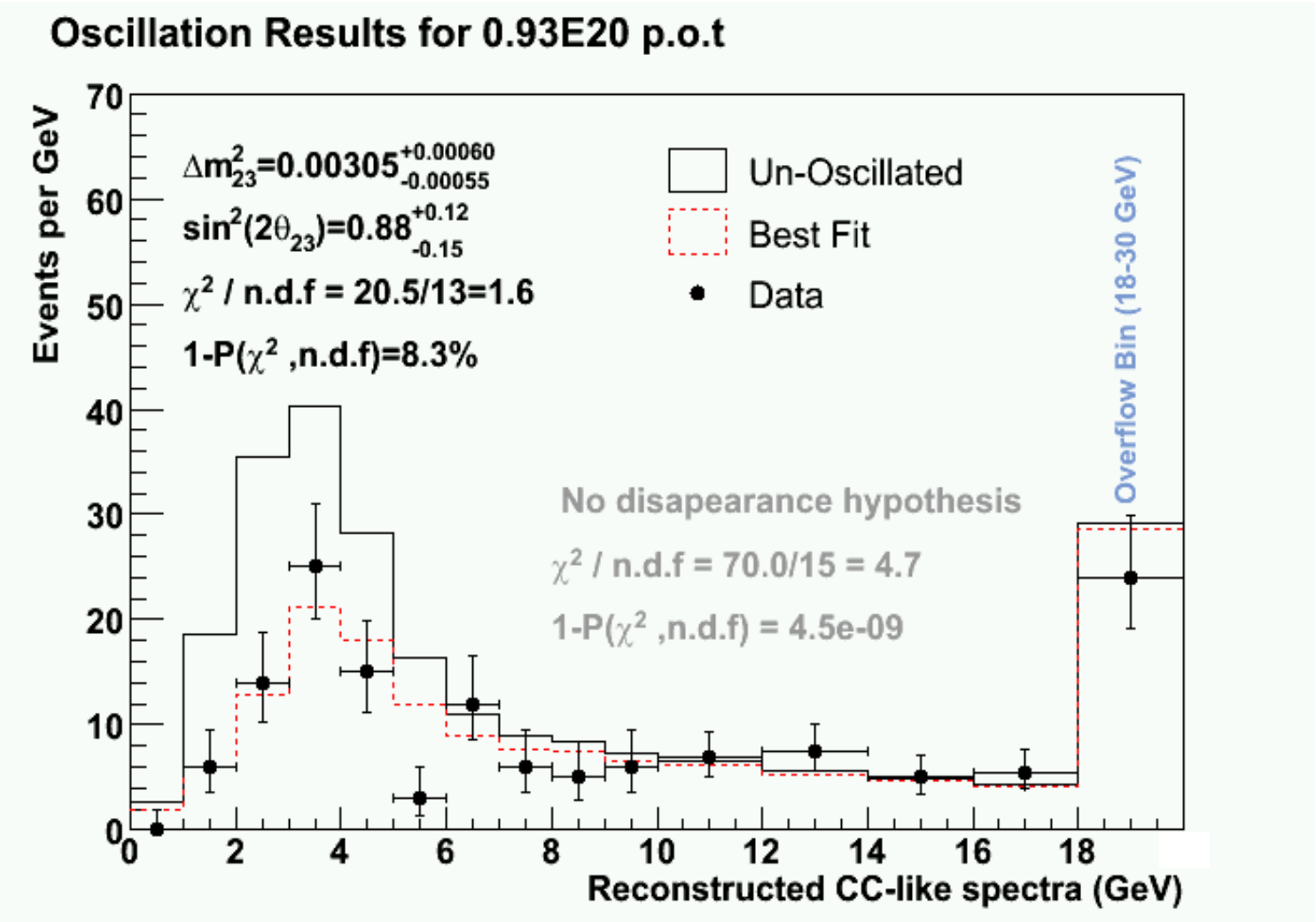
Particle Identification Parameter

Numbers of Observed & Expected Events

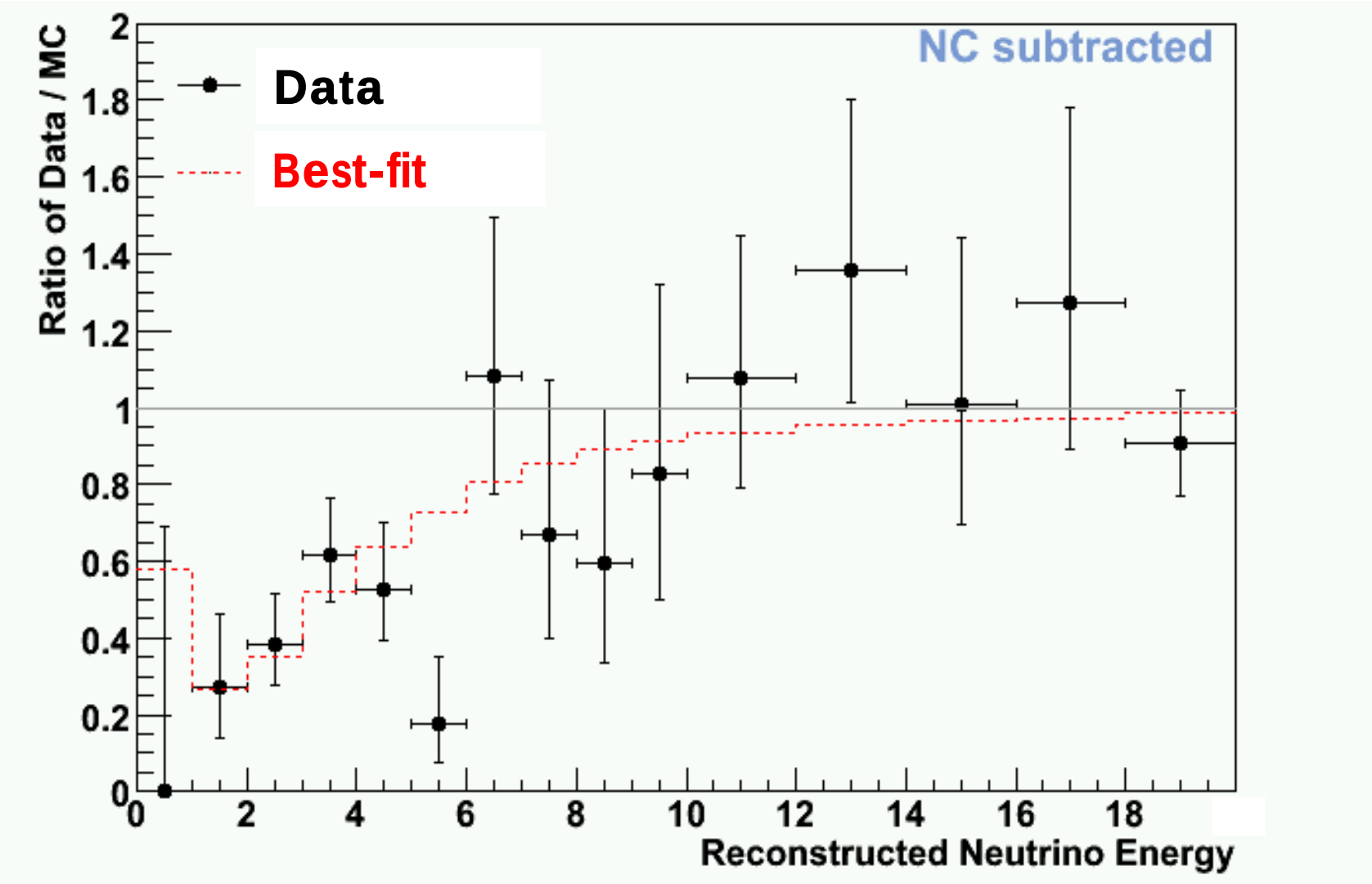
Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\nu_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

We observe a 33% deficit of events between 0 and 30 GeV with respect to the no oscillations expectation.

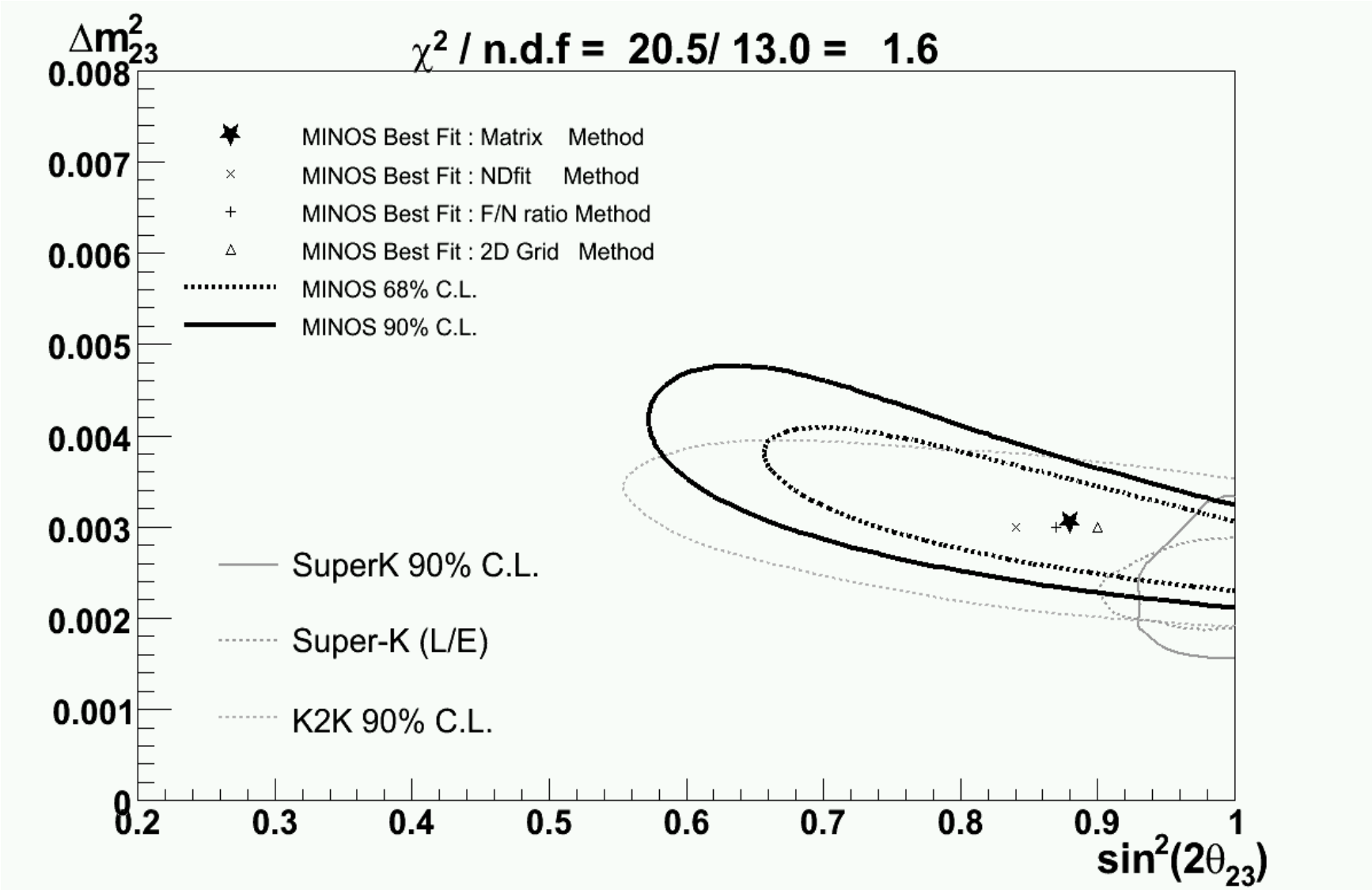
Best Fit Spectrum



Ratio of Data / MC



Allowed Regions



Systematic errors Preliminary

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)	$\sin^2 2\theta$ shift
Normalization +/- 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**