MINOS Oscillation Results from The First Year of NuMI Beam Operation

Masaki Ishitsuka, Indiana University
For the MINOS Collaboration

Kyoto University, July 3rd, 2006

Overview of the talk

- Introduction to the MINOS experiment
  - MINOS Physics Goals
  - The NuMI facility and the MINOS detectors
- Beam and detector performance
  - Near detector distributions and comparison with Monte Carlo
  - Beam measurements by the near detector data
- Far detector analysis
  - Near-Far extrapolation of the neutrino flux
  - **Oscillation Analysis with NuMI 1.27x10^{20} pot beam data**

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_{21}^2 : solar+reactor
  - $\boxed{\Delta m_{32}^2}$: Atm-ν+LBL ← **MINOS**
- 3 mixing angles & 1 CPV phase

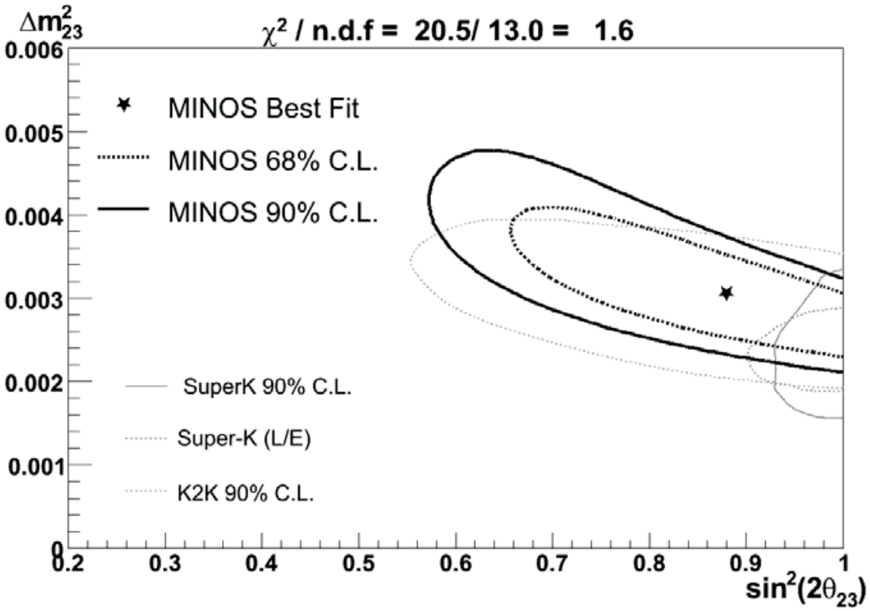
$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

Atm-ν+LBL ← **MINOS**

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

Current knowledge of 2-3 sector of mixing parameters and previous MINOS results

Allowed regions from Super-K, K2K and previous MINOS ($9.3x10^{20}$POT)



Current measurements of Δm^2_{32} and $\sin^2 2\theta_{23}$ from Super-Kamiokande and K2K ($9x10^{19}$ pot)

$\sin^2 2\theta > 0.9$

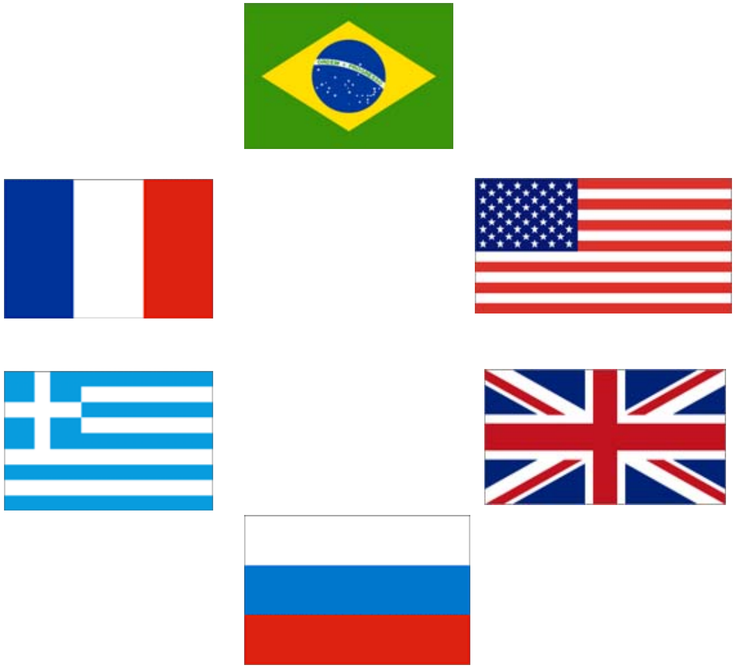
$1.9 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

at 90%CL from SK L/E analysis

The MINOS first result for $9.3x10^{19}$ pot provided a competitive measurement of the mixing parameters.

Oscillation results from $1.27x10^{20}$ pot data is reported in this talk.

The MINOS Collaboration



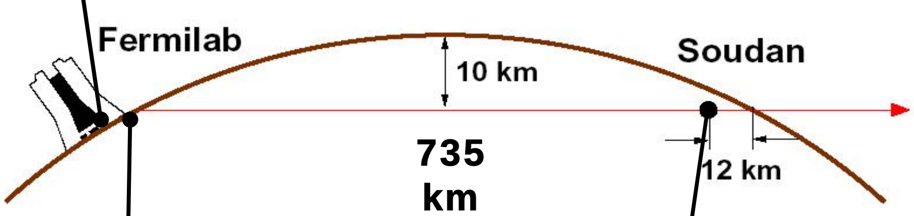
175 scientists
32 institutions
6 countries

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



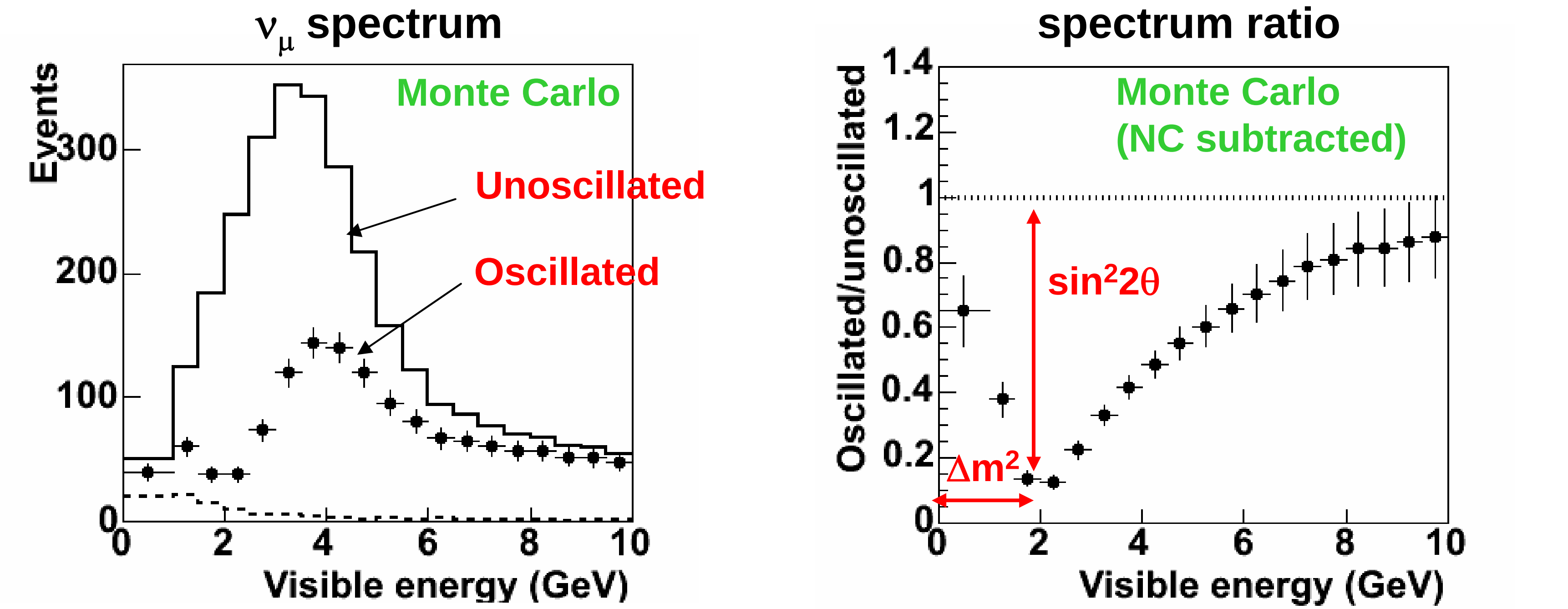
Near detector at Fermilab measure the **un-oscillated** energy spectrum

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:

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

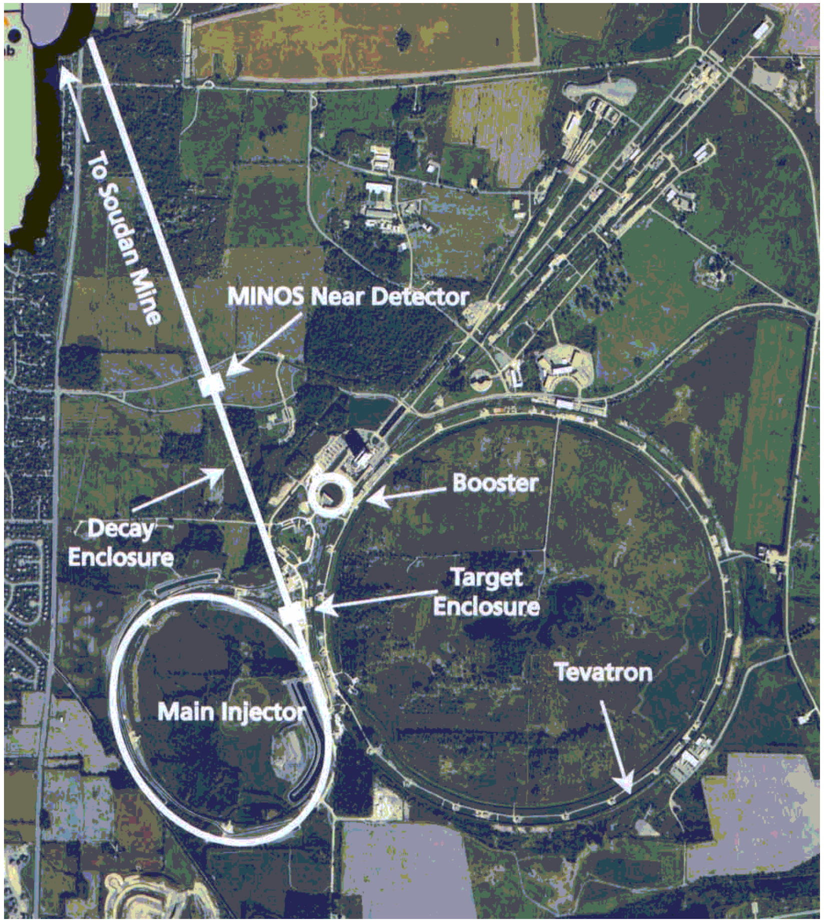


MINOS Physics Goals

- **Demonstrate $\nu_\mu \rightarrow \nu_\tau$ 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: **Phys. Rev. D73 (2006) 072002** [**hep-ex/0512036]**

The NUMI facility



Design parameters:

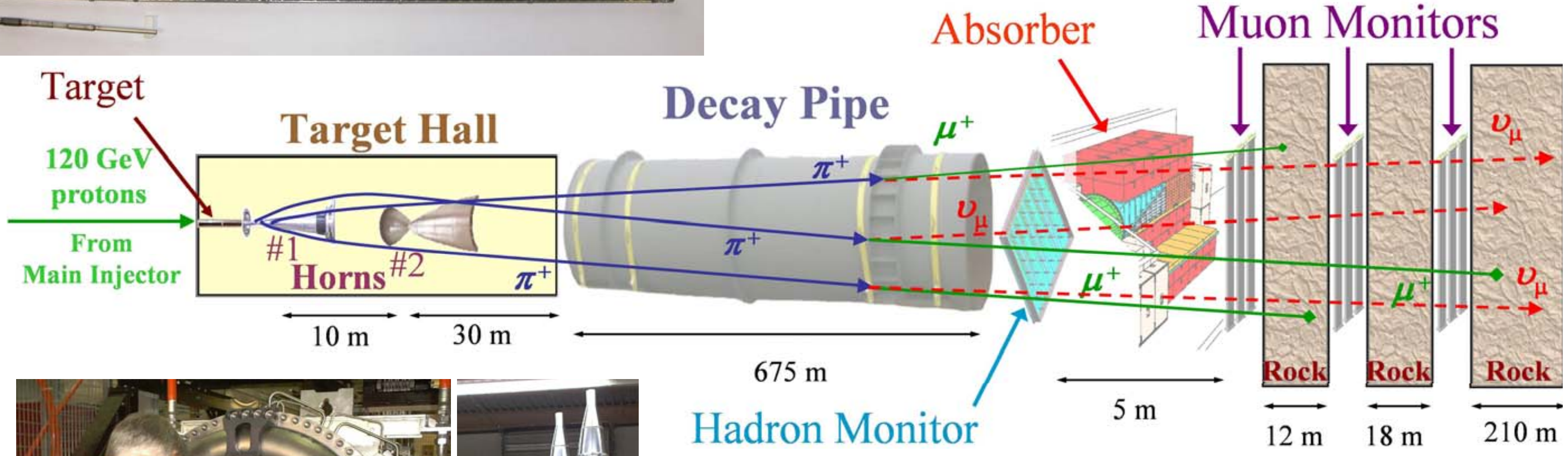
- 120 GeV protons from the Main Injector
- Main Injector can accept up to 6 Booster batches/cycle
- 1.9 second cycle time
- 4×10^{13} protons/pulse
- 0.4 MW
- Single turn extraction (10μs)

Average from 10/5 to 1/6:

- ✓ **2.2 second cycle time**
- ✓ **2.3×10^{13} protons/pulse**
- ✓ **0.17 MW**

Producing the neutrino beam

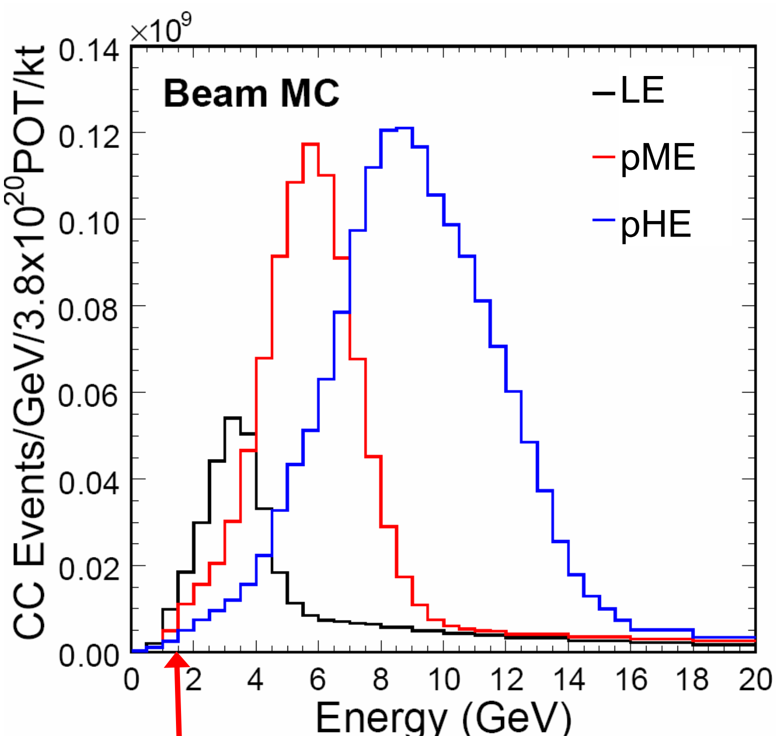
47 segments of graphite of 20 mm length and 6.4×15 mm2 cross section (total length 95.4 cm)



- 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 : **98.7% $\nu_\mu+\bar{\nu}_\mu$ (5.8% $\bar{\nu}_\mu$), 1.3% $\nu_e+\bar{\nu}_e$**
- We have already accumulated data in 5 other beam configurations for systematics studies (~5% of total exposure).



Position of osc. minimum for Δm^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

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

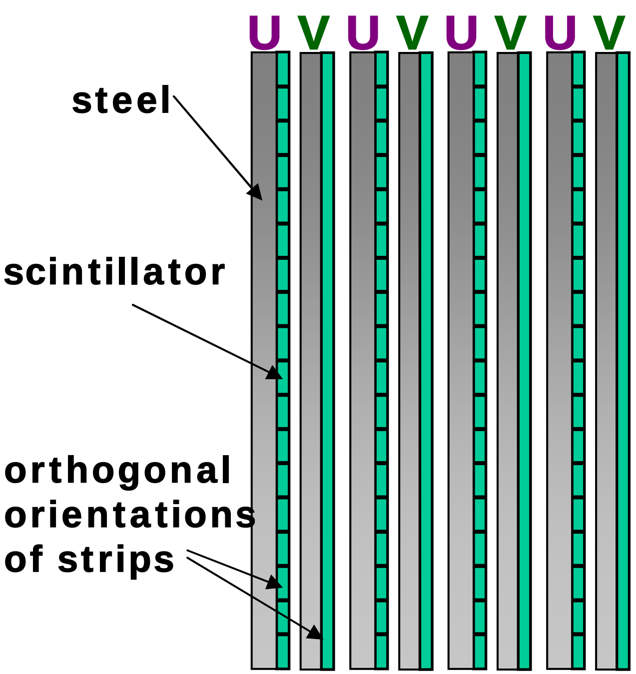
Near and Far Detectors: Identical target components and detection technology

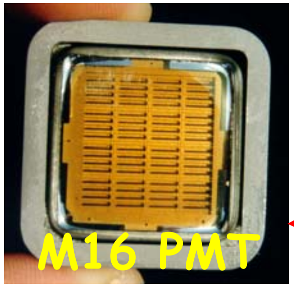
2.54 cm thick magnetized steel plates

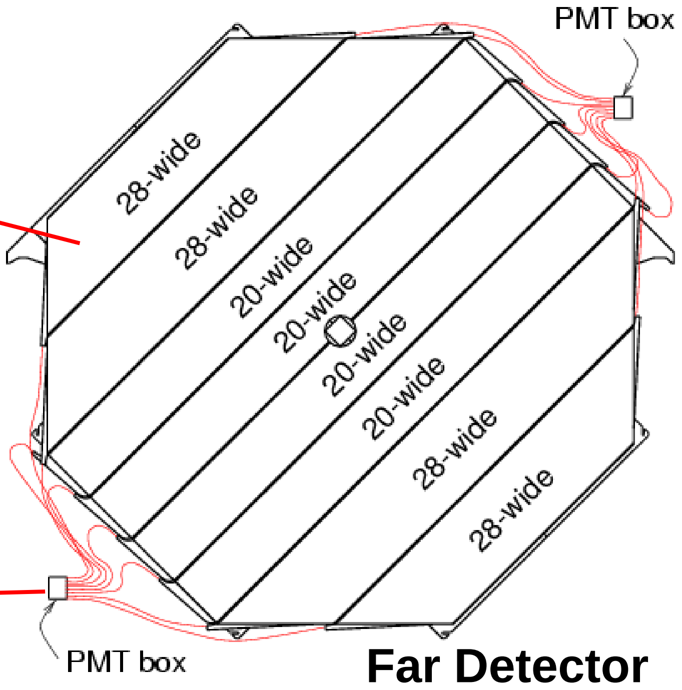
4.1x1cm co-extruded scintillator strips (MINOS-developed technology)

orthogonal orientation on alternate planes – U,V

optical fibre readout to multi-anode PMTs

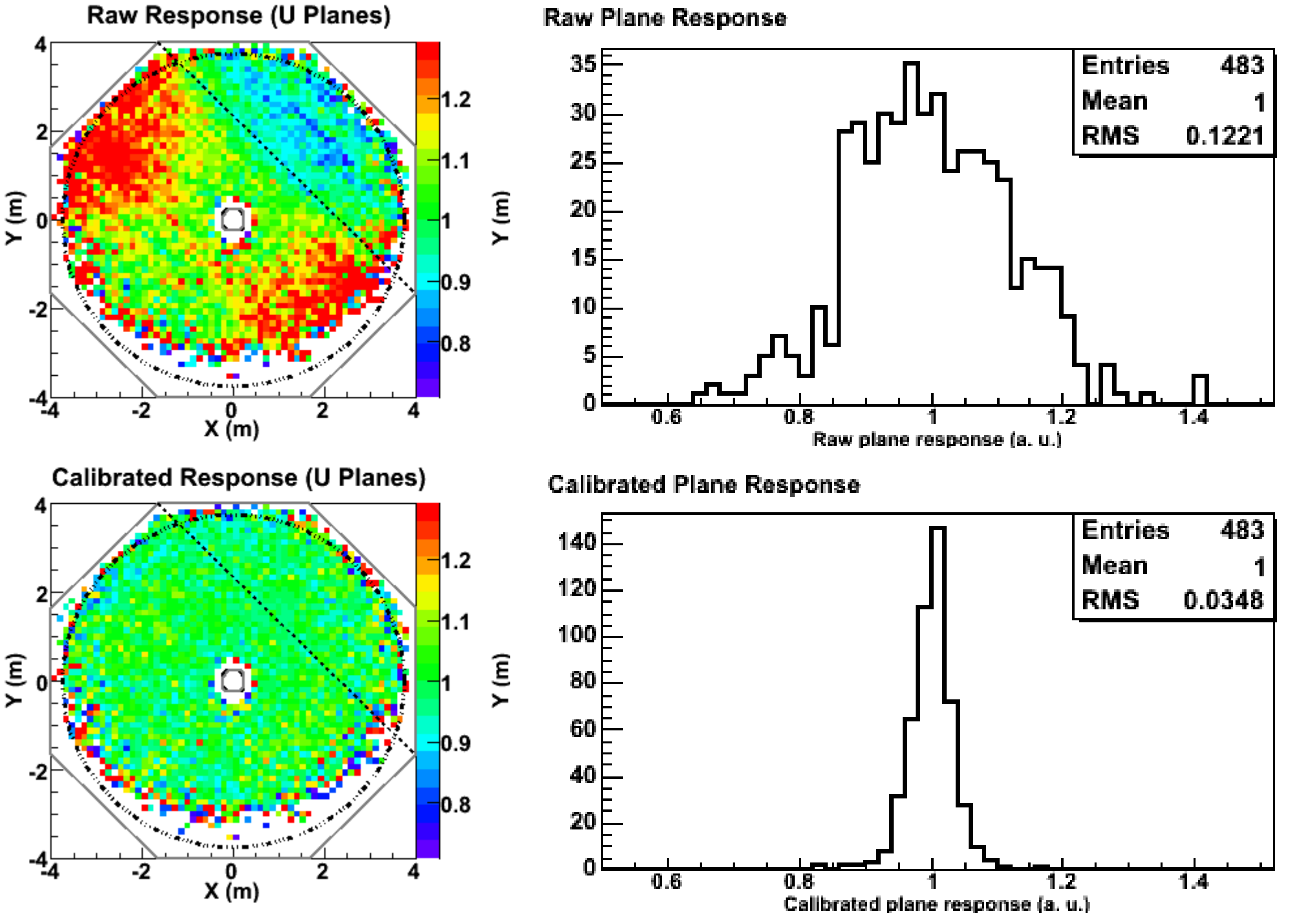




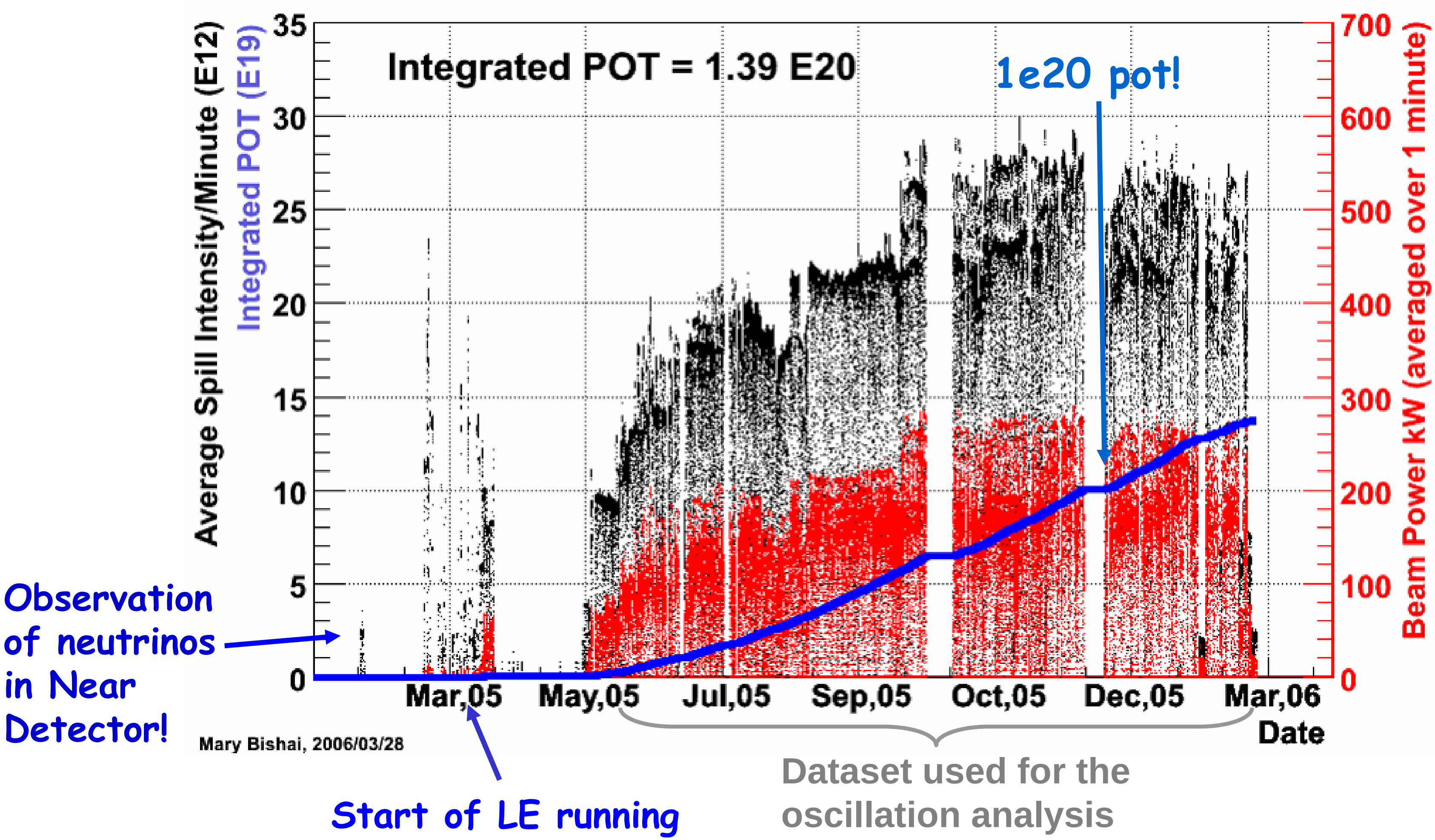


MINOS Calibration system

- 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:
  - 5.7% absolute error
  - 2% relative

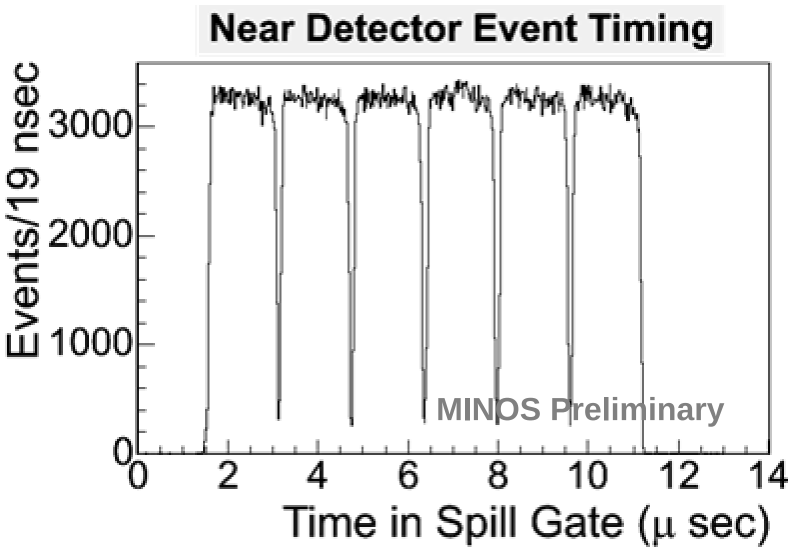


First year of NuMI beam operation



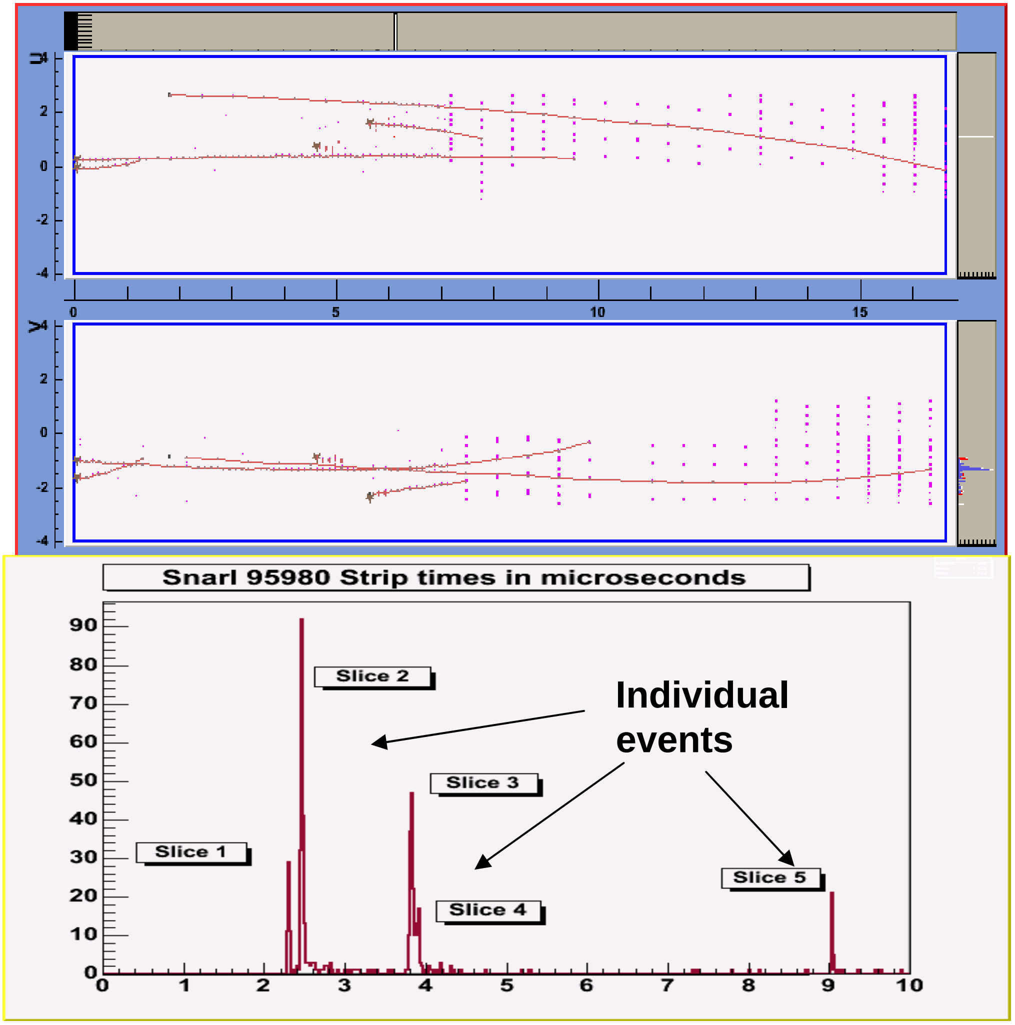
Near detector events

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



Batch structure clearly seen!

One near detector spill



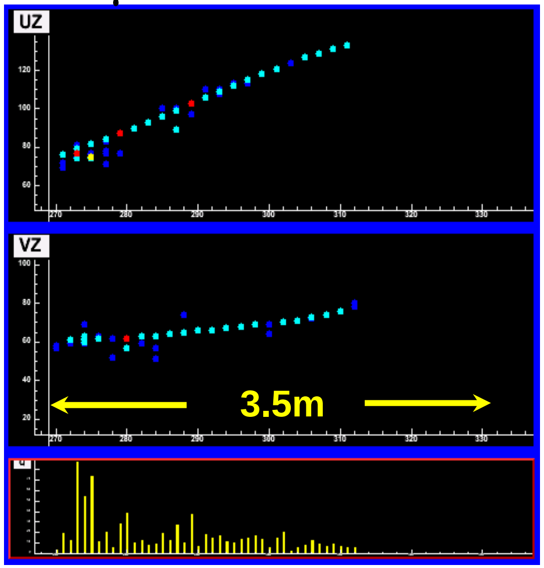
Time (us)

Event topologies

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

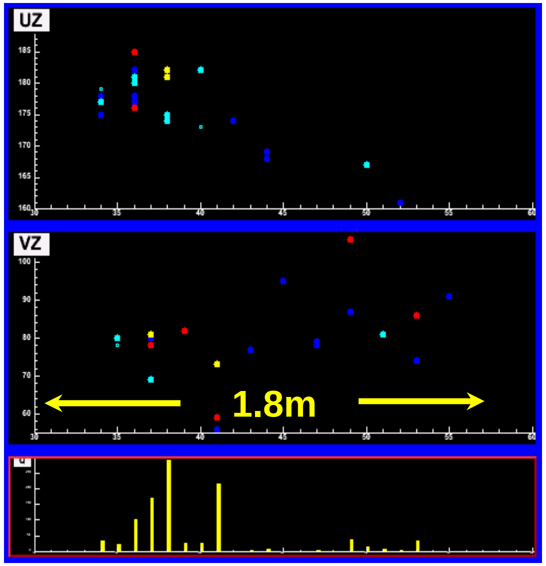
Monte Carlo

ν_μ CC Event



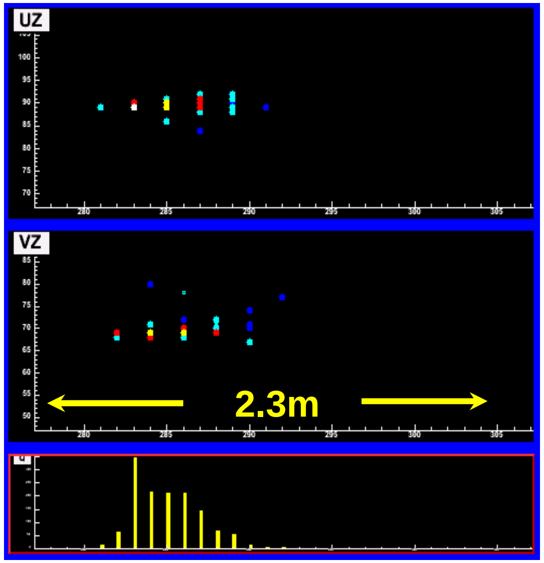
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

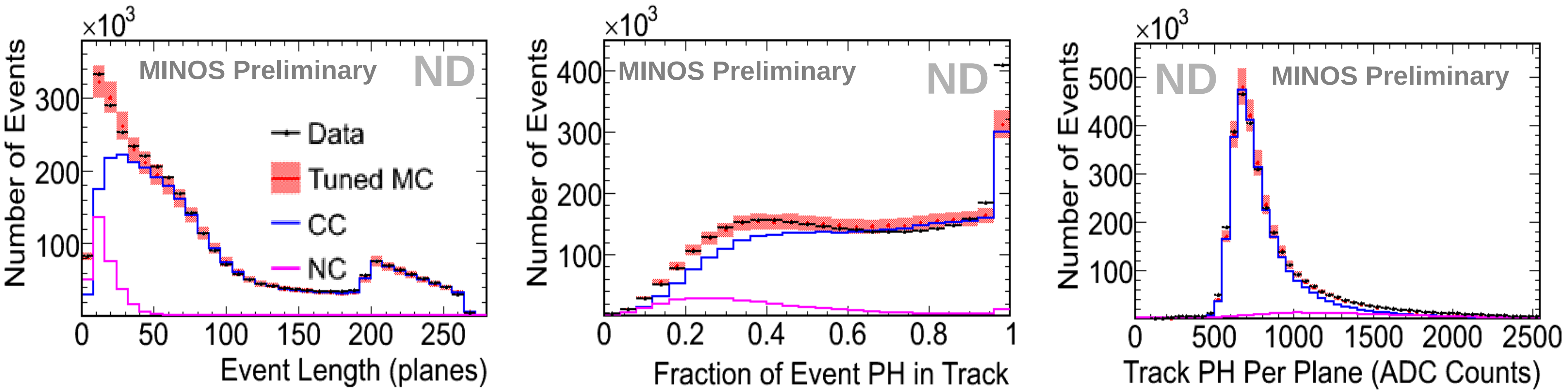
$$E_\nu = E_{shower} + P_\mu$$

55%/√E

6% range, 10% curvature

Selecting CC events

CC events are selected using a likelihood-based procedure



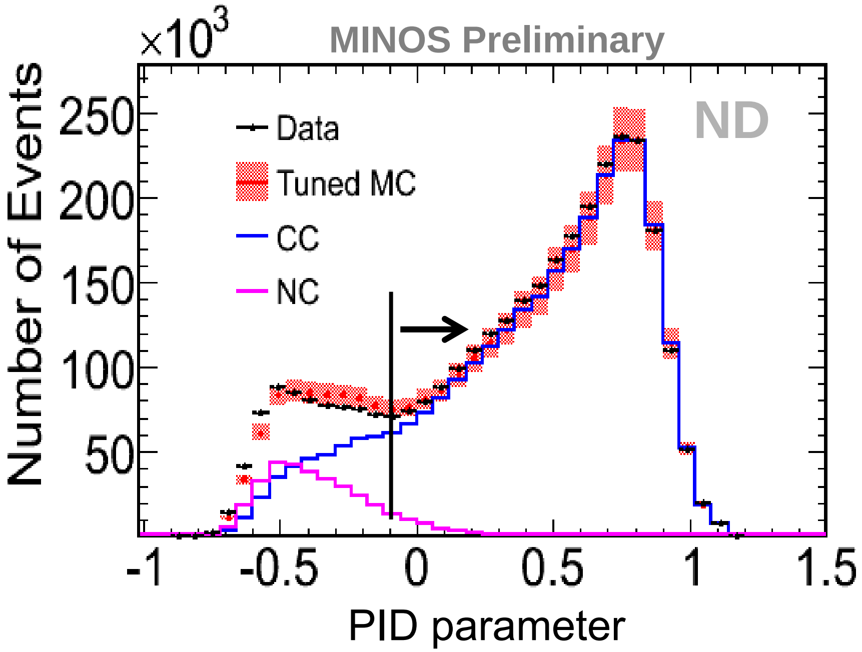
- **Event length in planes** (*related to muon momentum*)
- **Fraction of event pulse height in the reconstructed track** (*related to the inelasticity of CC events*)
- **Average track pulse height per plane** (*related to dE/dX of the reconstructed track*)

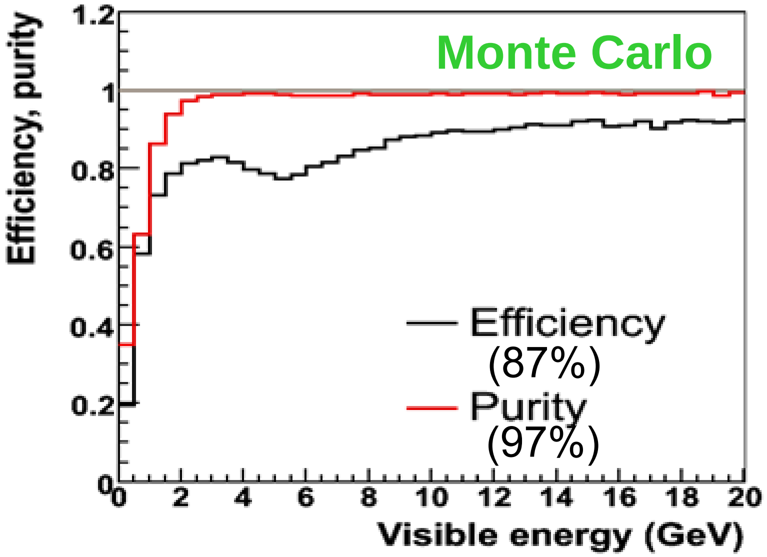
CC selection efficiencies

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

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

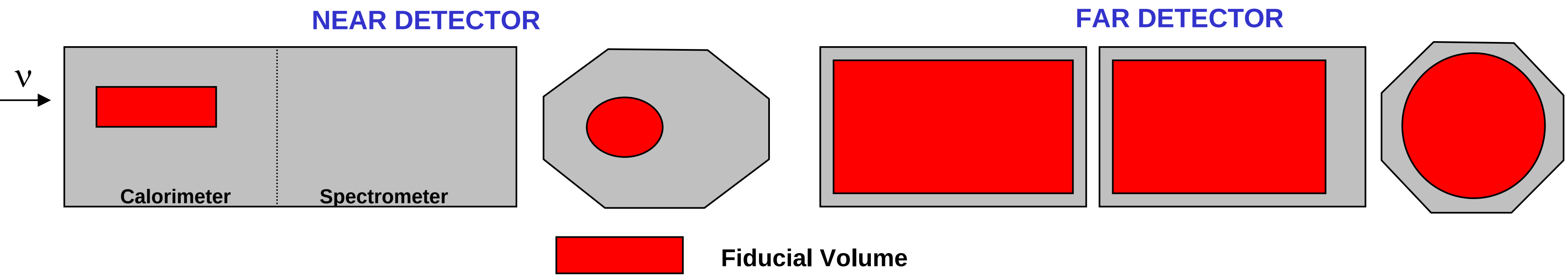
- CC-like events are defined by the cut PID>-0.2 in the FD (>-0.1 in the ND)
  - NC contamination is limited to the lowest visible energy bins (below 1.5 GeV)
  - Selection efficiency is quite flat as a function of visible energy





Event selection cuts – Near and Far

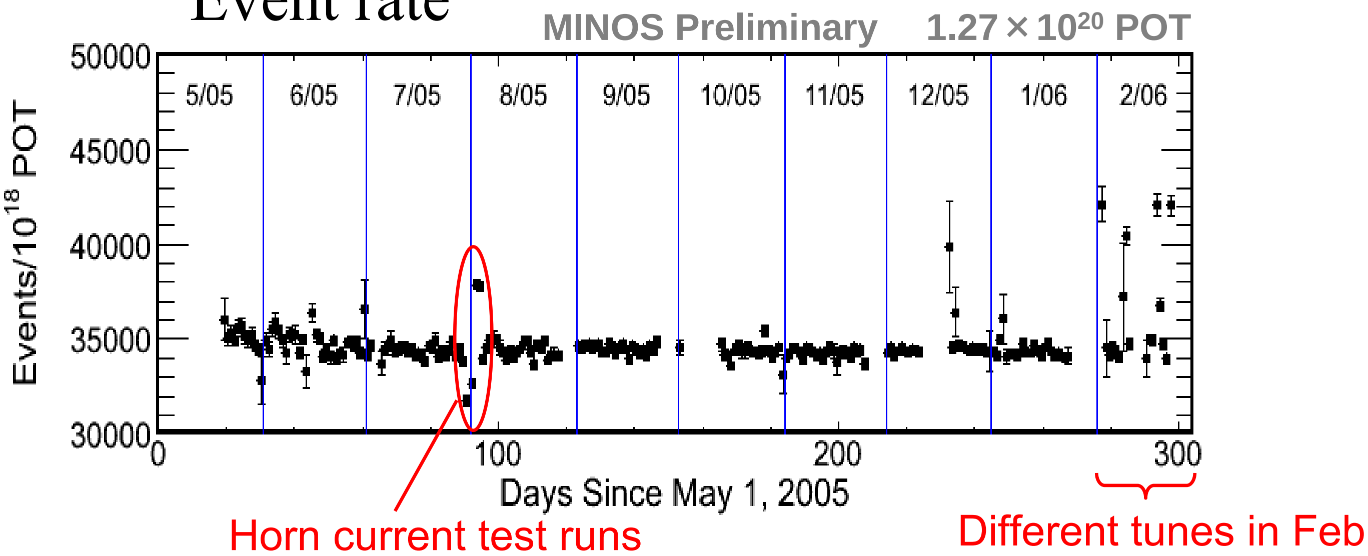
1. Event must contain at least one good reconstructed track
2. The reconstructed track vertex should be within the fiducial volume of the detector:
   - ND: 1m < z < 5m (z measured from the front face of the detector), R< 1m from beam centre.
   - FD: z>50cm from front face, z>2m from rear face, R< 3.7m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



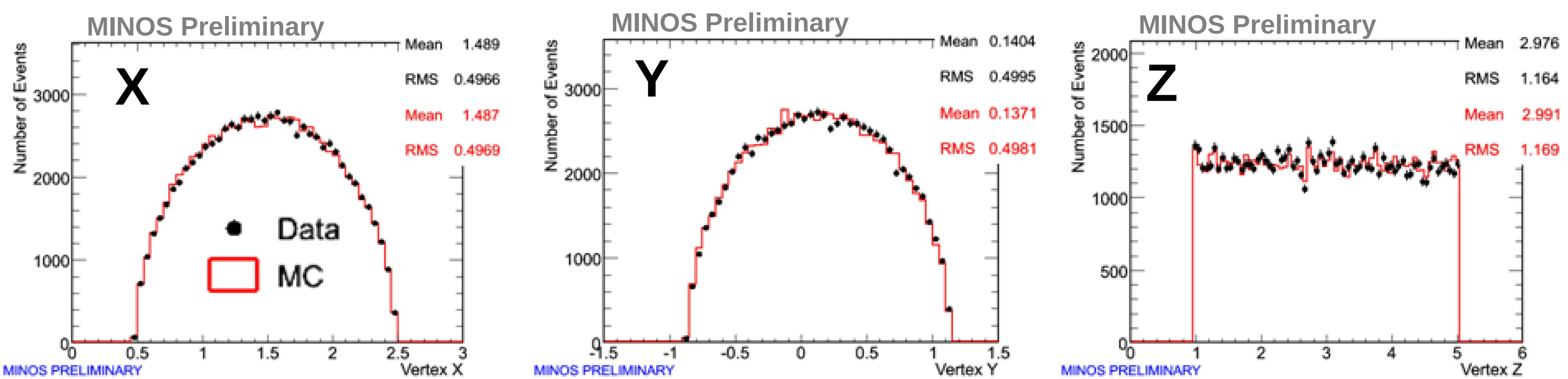
3. The fitted track should have negative charge (selects ν_μ)
4. Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.

Near detector data distributions

Event rate



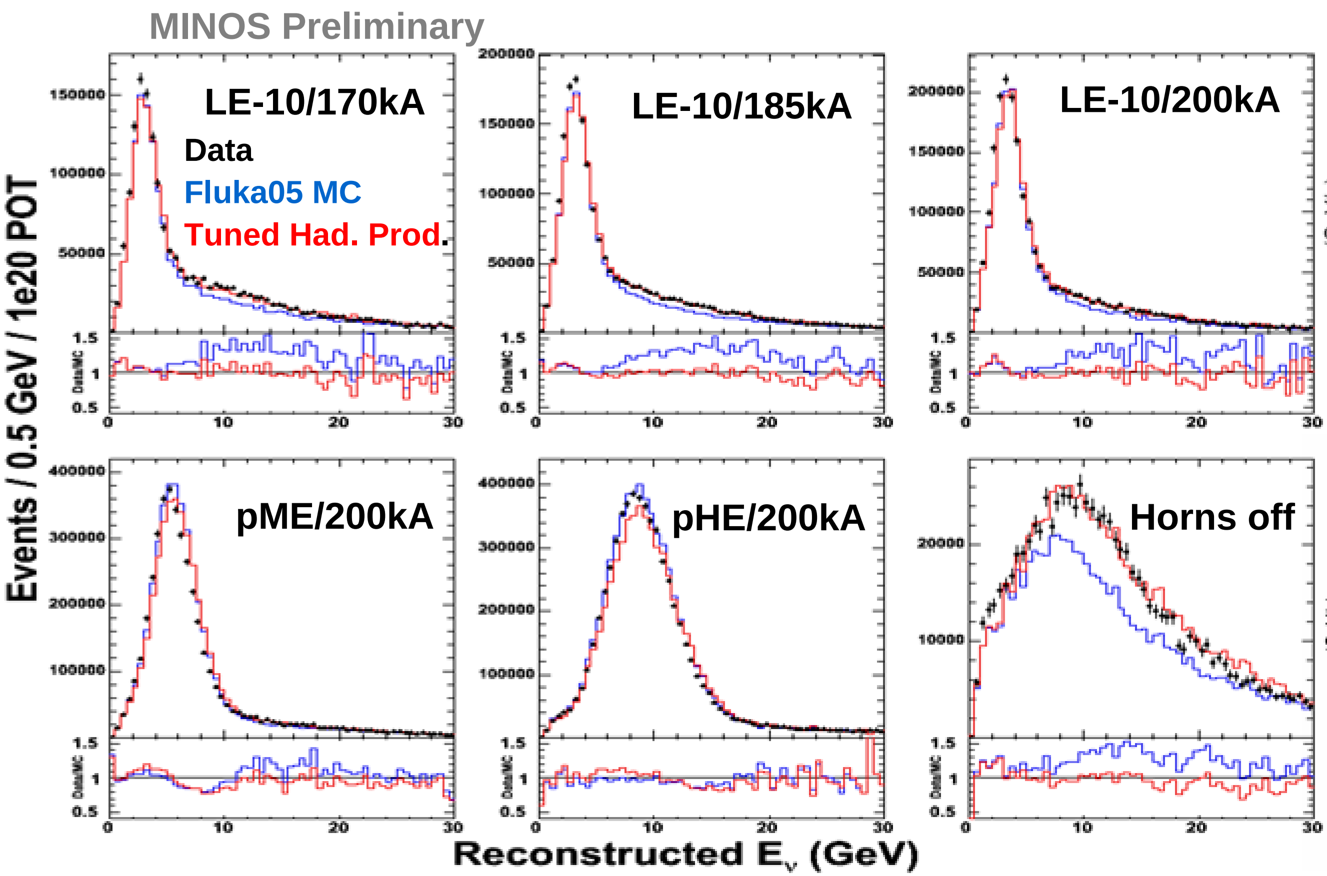
Event vertices in the ND



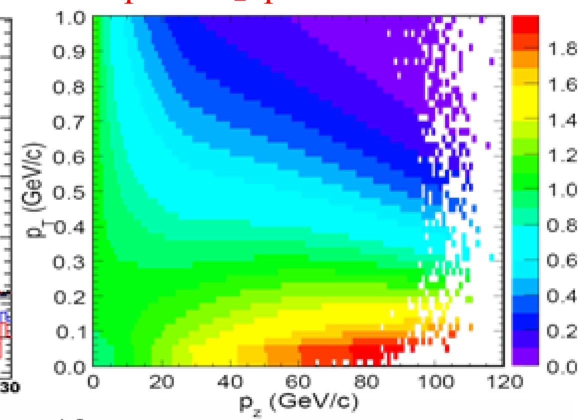
Energy spectra in the ND and hadron production tuning

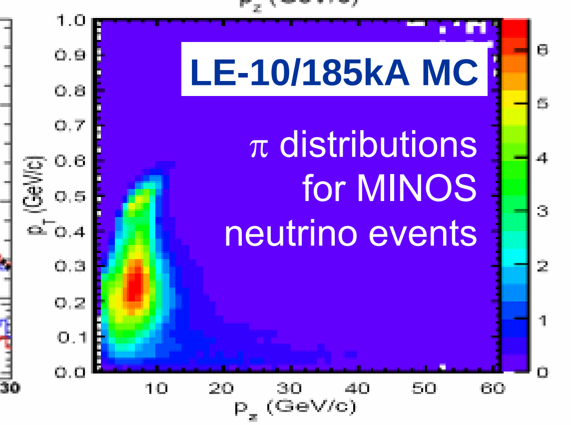
Agreement between data and Fluka05 Beam MC is within the systematic errors

→ Further improvement by hadron production tuning as a funtion of x_F and p_T



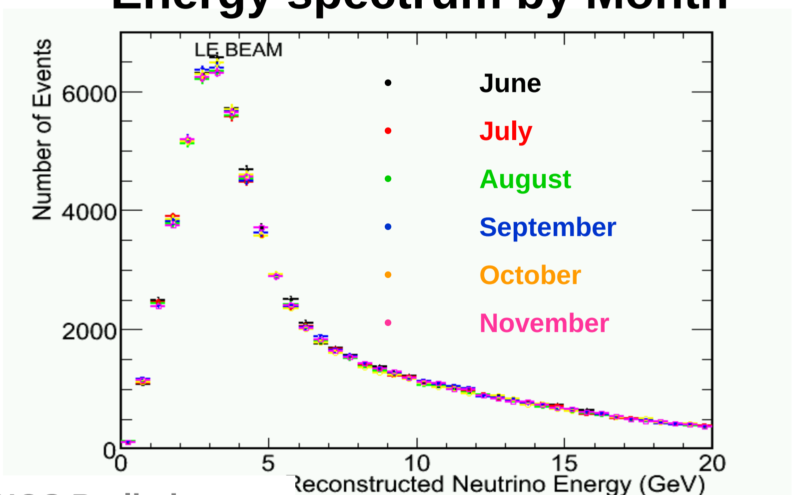
Weights applied as a function of hadronic x_F and p_T.





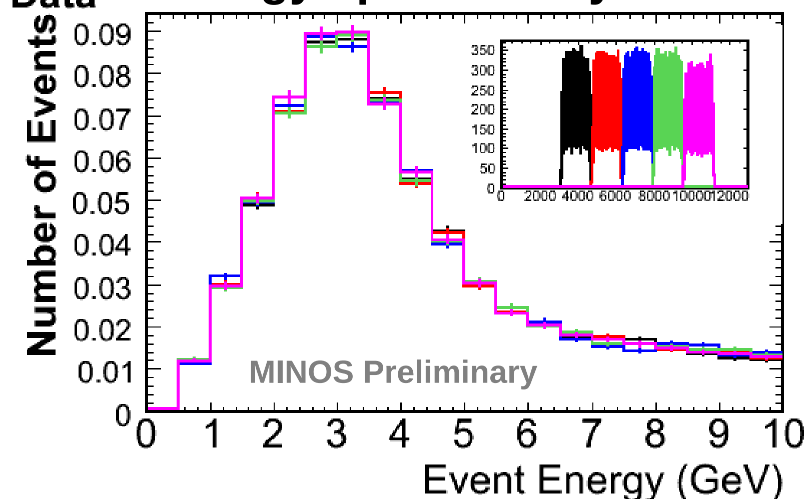
Stability of the energy spectrum & reconstruction

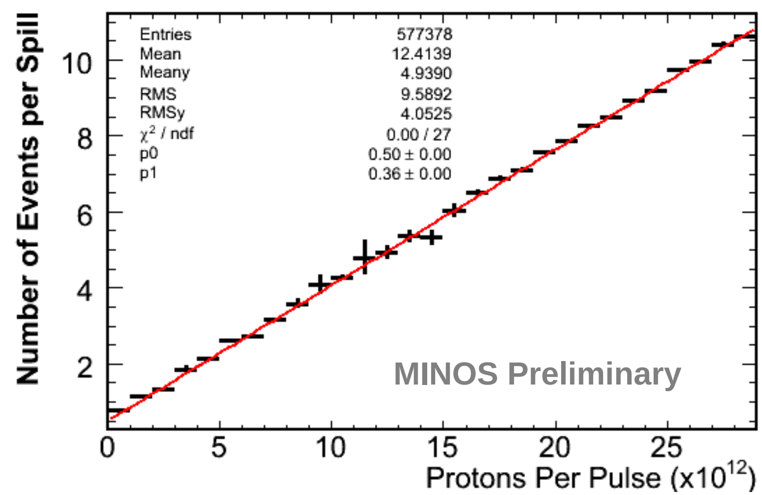
Energy spectrum by Month



MINOS Preliminary

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

Performing a blind analysis

Far detector blinding

- Unknown fraction of FD events were hidden
  - Blinded as a function of event length and energy
- The “Open” FD data used to check data quality

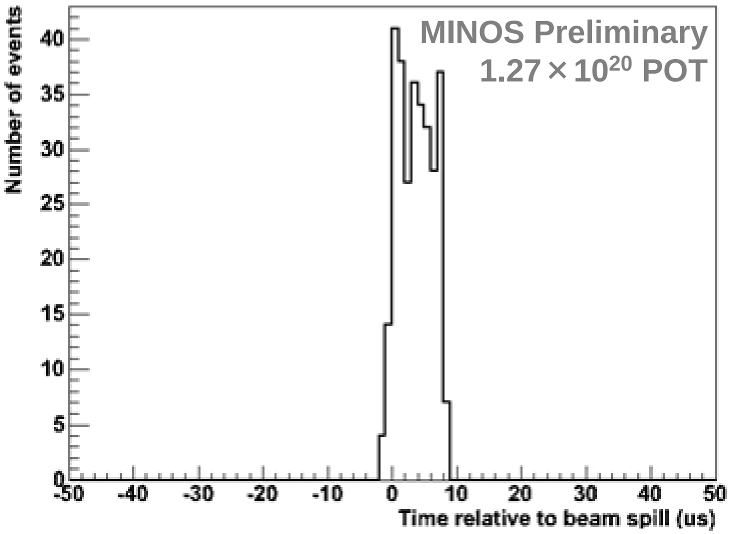
Near detector data was open

- Used to study beam properties, cross sections, and detector systematics

Analysis procedures were defined prior to 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



Time of neutrino interactions from beam spill (μs)

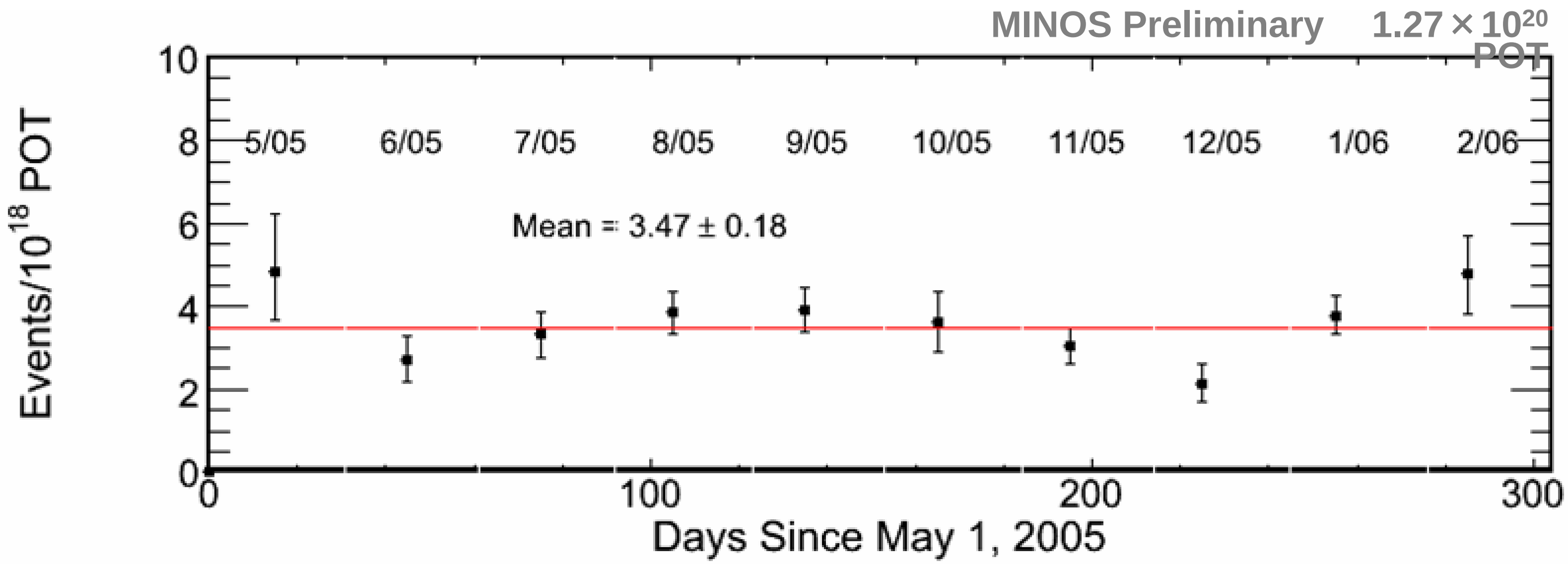
- Neutrino events have distinctive topology and are easily separated from cosmic muons
  - Backgrounds were estimated by fake triggers:

0 events in 2.6 million fake trrigers survived cuts → upper limit of 0.5 background events

Far detector beam data analysis

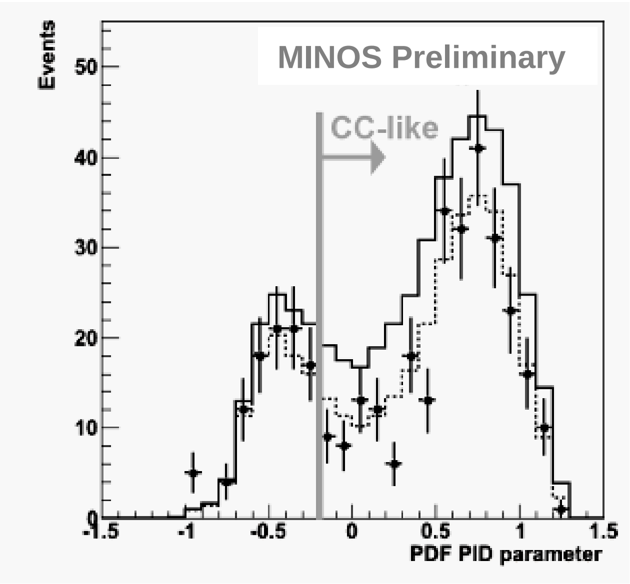
Oscillation analysis was performed using data taken in the LE configuration from May 20th 2005 – March 3rd 2006

- **Total integrated POT: 1.27×10^{20}**

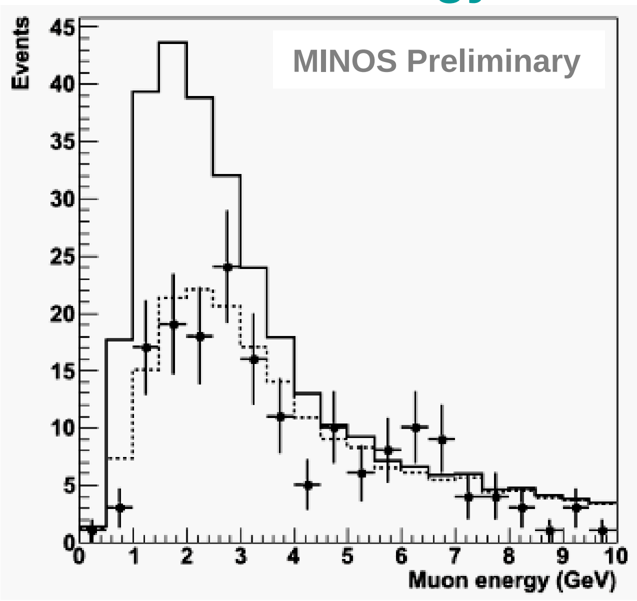


Far detector distributions

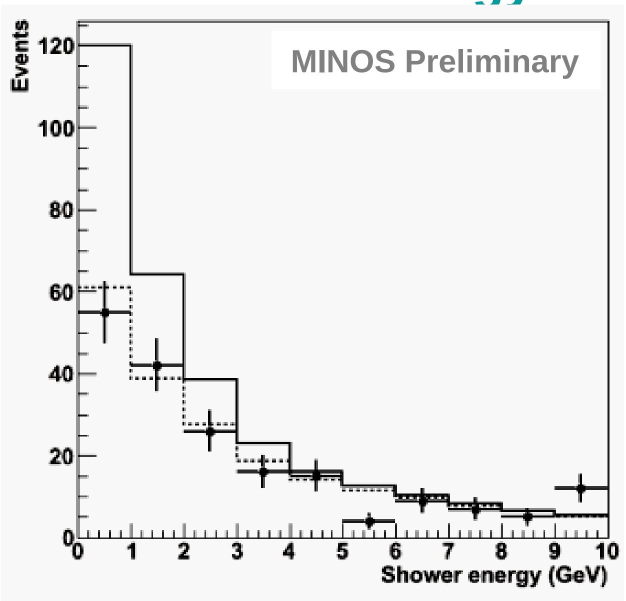
PID parameter



Muon energy



Shower Energy



Data

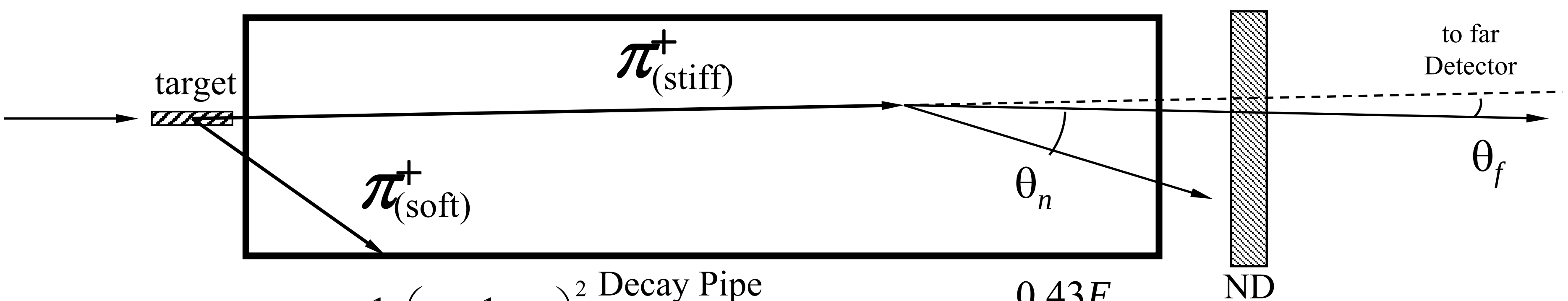
Predicted no oscillations

Best-fit

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.



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

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

Procedure of predicting the FD spectrum

A)

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

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

B)

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

BEAM MATRIX

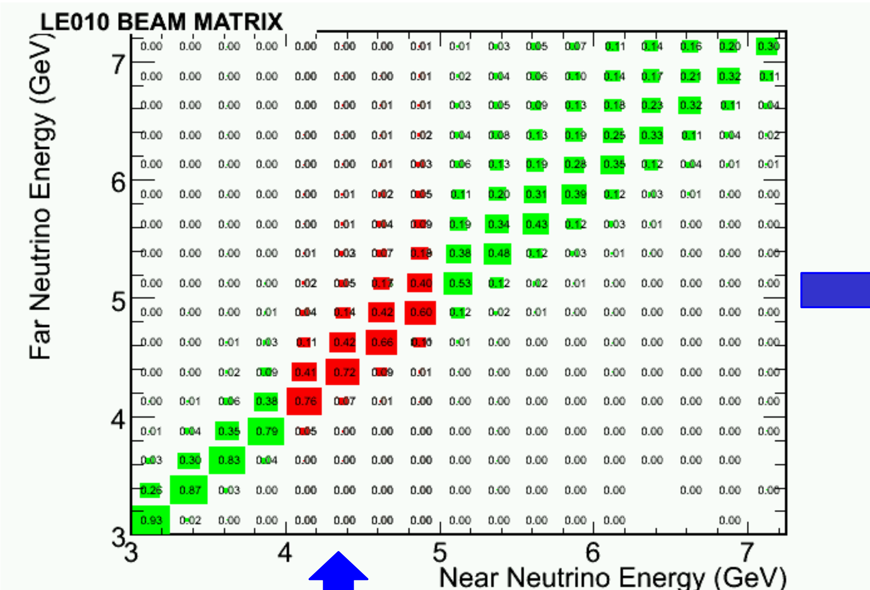
C)

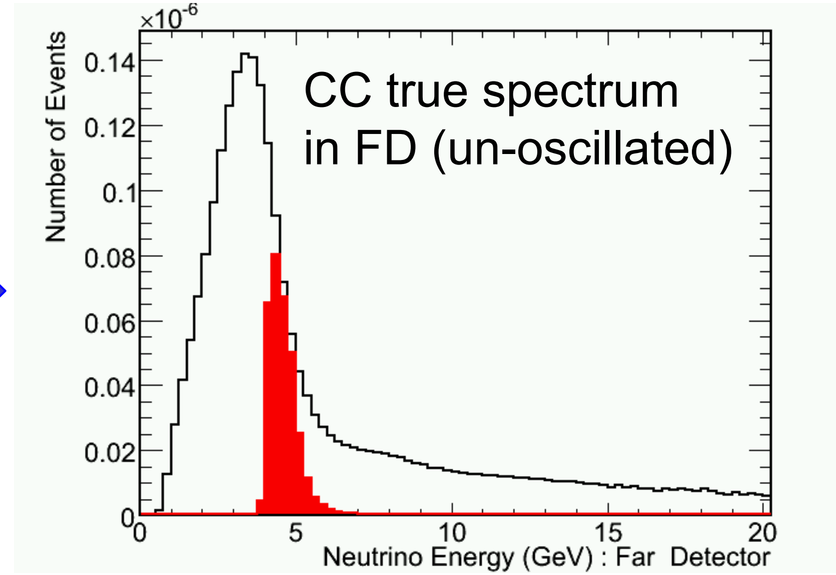
$$E^{\textit{True}}_{\textit{Far}\ \text{CC}} \Rightarrow E^{\text{Reconstructed}}_{\textit{Far}\ \text{CC-like}}$$

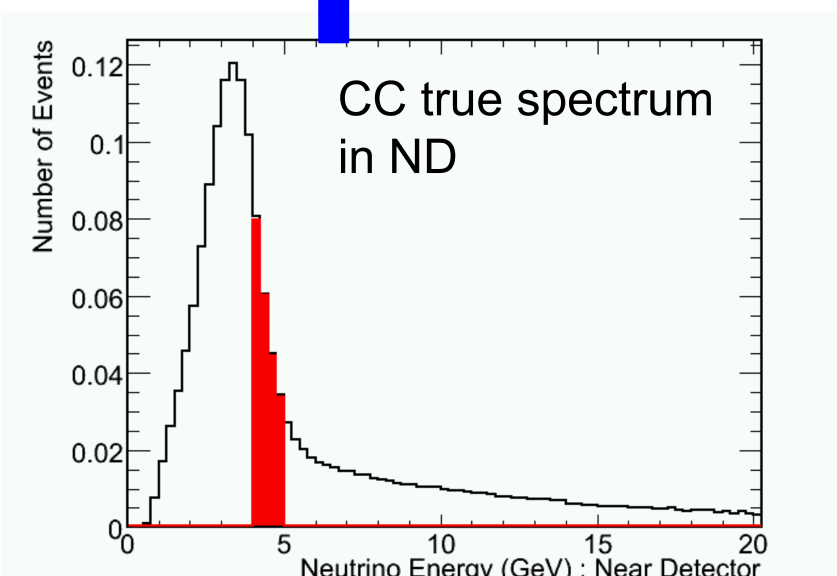
i) Oscillation, True => Reconstructed, Correction for efficiency to obtain CC oscillated spectrum

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

Different methods for predicting the FD spectrum

Three alternative ND to FD extrapolation methods:

ND fit :

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

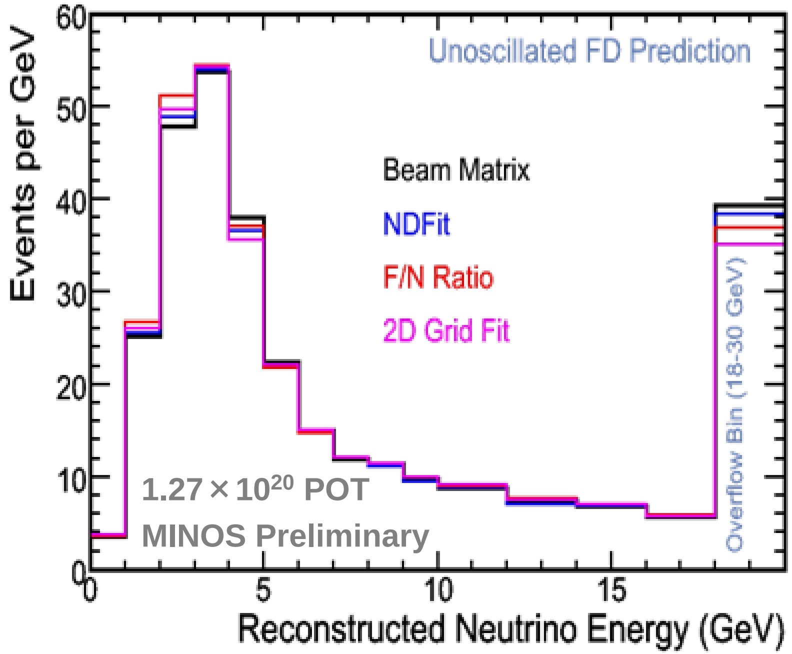
2D Grid fit :

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

F/N ratio :

Extrapolation using the Far/Near spectrum ratio from MC

Predicted FD unoscillated spectra



The methods are robust to different categories of systematics

Numbers of observed and expected events

1.27×10^{20} POT MINOS Preliminary Numbers

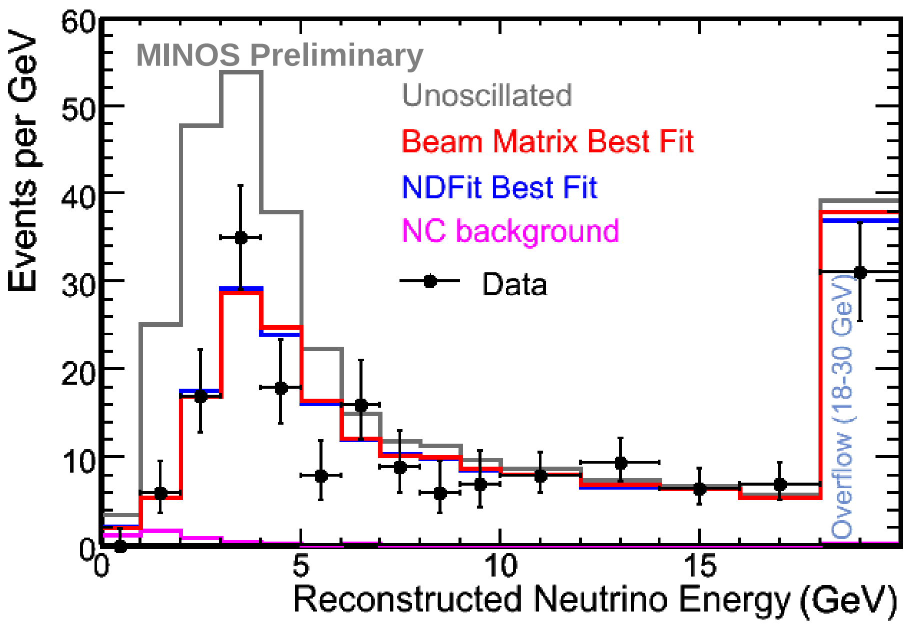
Data sample	Observed	Expected (matrix, no osc.)	Ratio (matrix, no-osc.)	Expected (ND fit, no osc.)
ν_μ (<30 GeV)	215	336±21	0.64±0.08	333
ν_μ (<10 GeV)	122	239±17	0.51±0.08	238
ν_μ (<5 GeV)	67	168±12	0.45±0.09	169

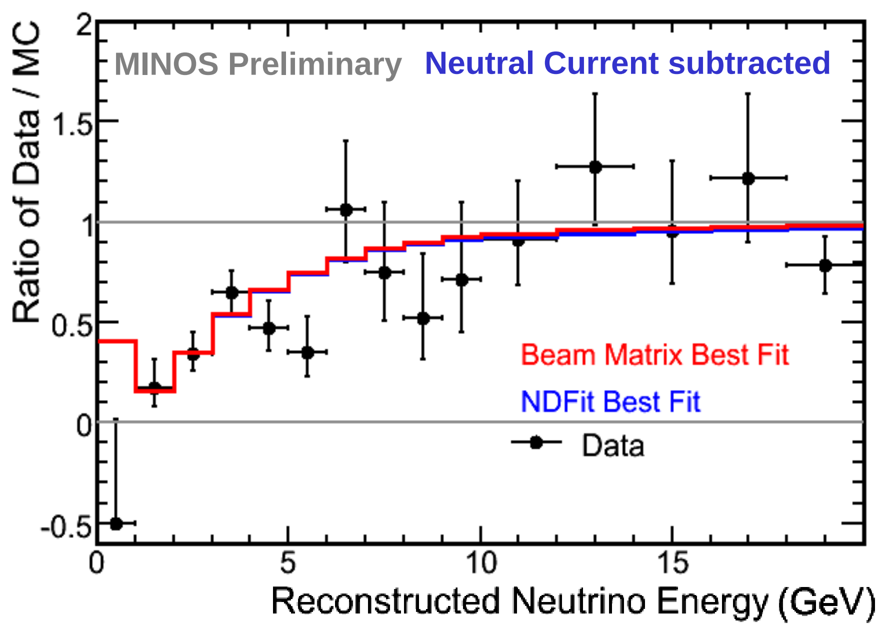
- **Energy dependent deficit is observed**
- **Significance of the deficit below 10 GeV is 5.9 σ (stat+syst)**

MINOS observed spectrum and the best-fit for 1.27x10^{20}POT

$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i) + \frac{(1-N)^2}{0.04^2}$$

o_i : observed # events
e_i : expected # events
N : absolute normalization



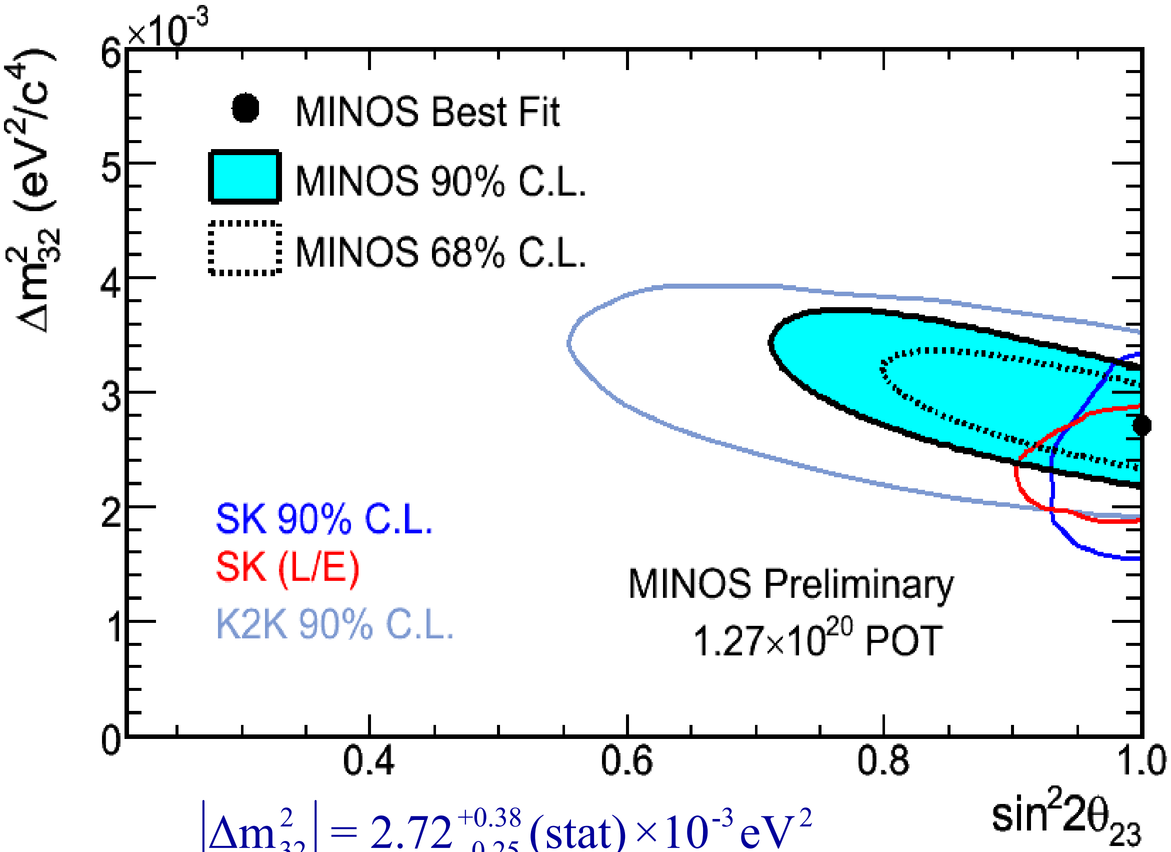


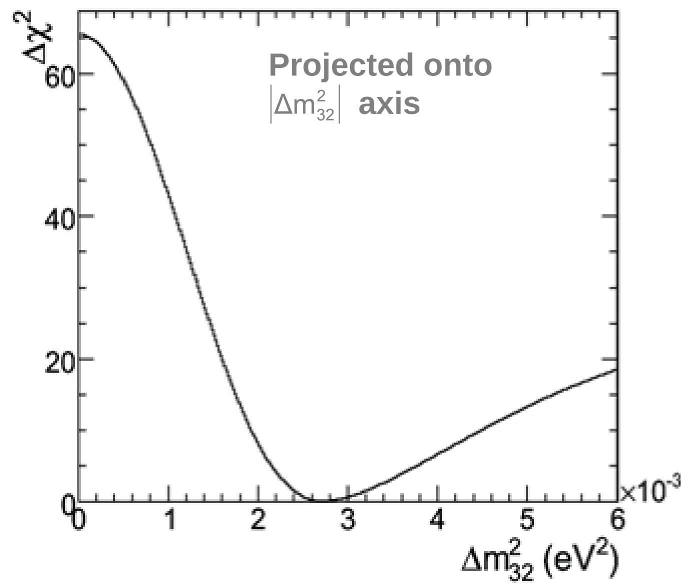
$$\left|\Delta m^2_{32}\right| = 2.72^{+0.38}_{-0.25}(\text{stat}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat})$$

$$\text{Normalization} = 0.98$$

Allowed regions





$$\left|\Delta m^2_{32}\right| = 2.72^{+0.38}_{-0.25}\,(\mathrm{stat}) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{\,-0.13}\,(\mathrm{stat})$$

Constrained to $\sin^2 2\theta_{23} \leq 1$

Statistical errors

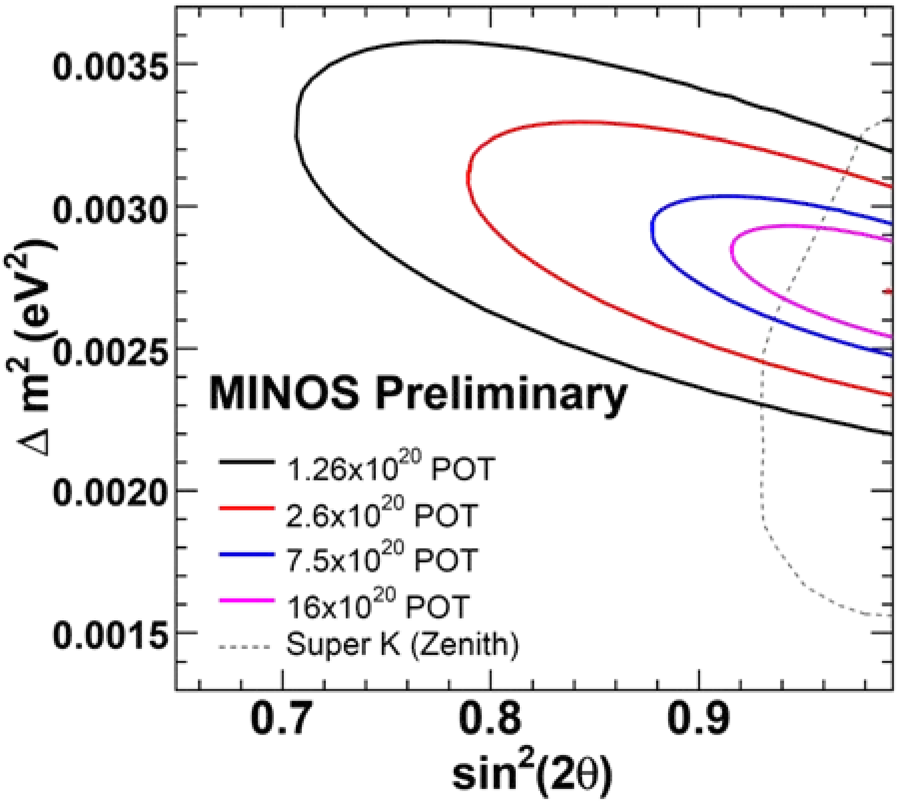
Systematic errors

MINOS Preliminary Numbers

Uncertainty	Δm^2 ($\times 10^{-3}$ eV^2)	$\sin^2 2\theta$
Near/Far normalisation +/- 4%	0.003	0.000
Muon energy scale +/- 2%	0.035	0.003
Relative Shower energy scale +/- 2%	0.010	0.003
NC contamination +/- 50%	0.088	0.038
CC cross-section uncertainties	0.016	0.004
Intranuclear re-scattering / absolute energy scale (+/- 6%)	0.083	0.018
Reconstruction	0.013	0.005
Beam uncertainty	0.025	0.005
Fit bias	0.010	0.010
Total (sum in quadrature)	**0.131**	**0.044**
Statistical sensitivity	**0.36**	**0.12**

Projected sensitivity of MINOS

ν_μ disappearance



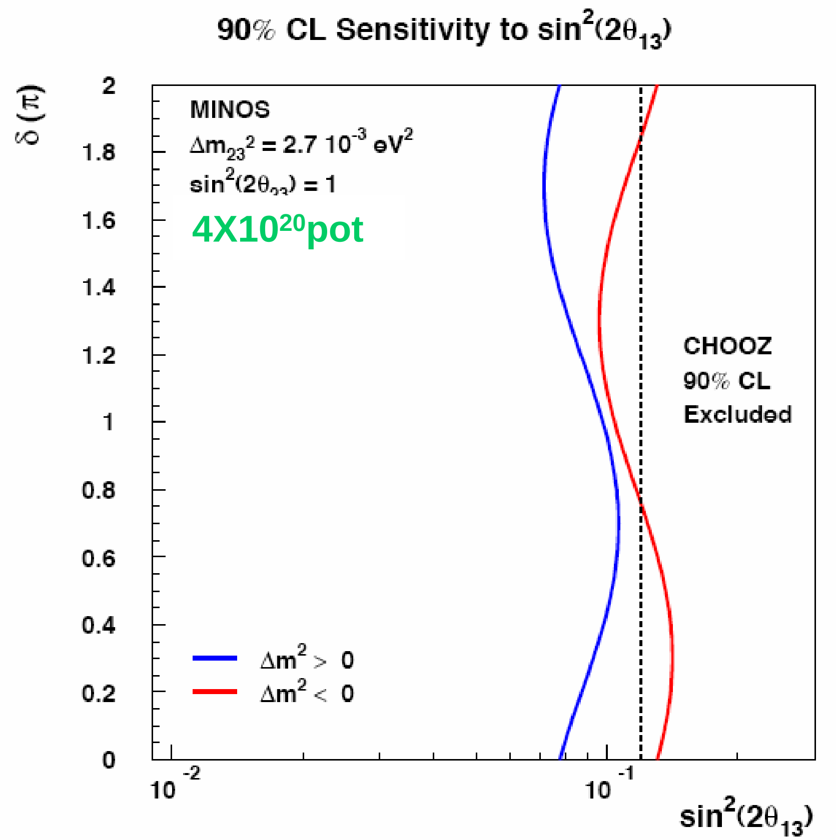
Input parameters: $|\Delta m^2_{32}| = 2.72\text{x}10^{-3}\text{eV}^2$

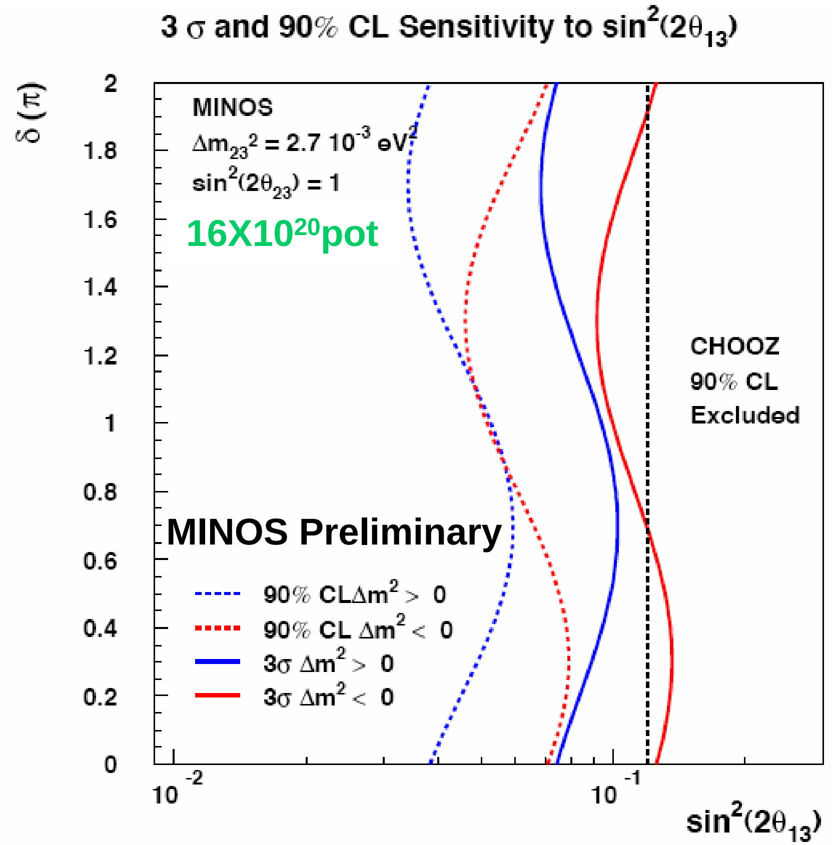
$\sin^2 2\theta_{23} = 1.00$

90%CL, statistical error only

Projected sensitivity of MINOS

Search for sub-dominant $\nu_\mu \to \nu_e$





- MINOS sensitivity as a function of CP violating phase and mass hierarchy
- Reasonable chance of making the first measurement of non-zero θ_{13}!

Summary and conclusions

- Preliminary MINOS oscillation results from the first year of NuMI beam operation was presented.
- Our exposure to data is 1.27×10^{20} pot.
- Deficit of ν_μ events below 10GeV disfavors no oscillation at 5.9 σ (rate only) .
- FD spectrum distortion is consistent with ν_μ disappearance with the following parameters:

$$\left|\Delta m^2_{32}\right| = 2.72^{+0.38}_{-0.25}(\text{stat}) \pm 0.13(\text{syst}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat}) \pm 0.04(\text{syst})$$

- MINOS is taking data from the 2nd year of NuMI beam operation.
- Significant improvement in precision of oscillation parameters should be made with a larger dataset.