MINOS Results and Future Prospects

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(on behalf of the MINOS Collaboration)

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Frontiers in Particle Physics and Cosmology (KEKTC6)

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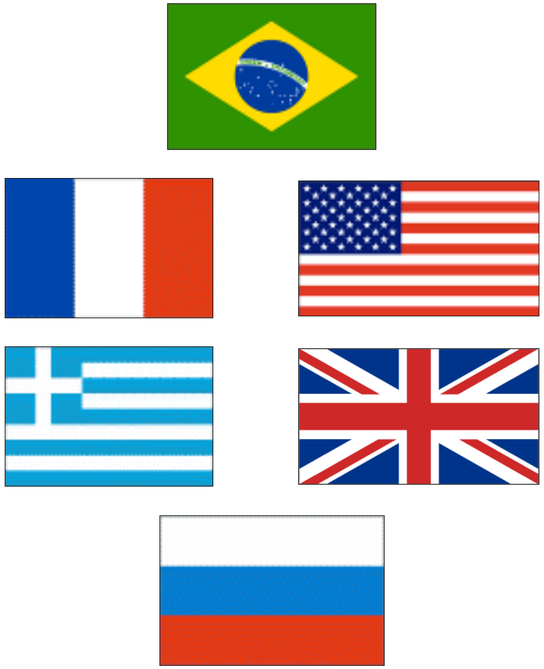
Celebrating 50 years of world class science

Introduction

- Experimental setup
- Physics goals
- Neutrino beam
- Near and Far detectors
- Muon neutrino disappearance analysis
  - Results
  - Future sensitivity
- Neutrino Time-Of-Flight analysis
- Sensitivity to sub-dominant neutrino oscillations – θ_{13}

The MINOS Collaboration

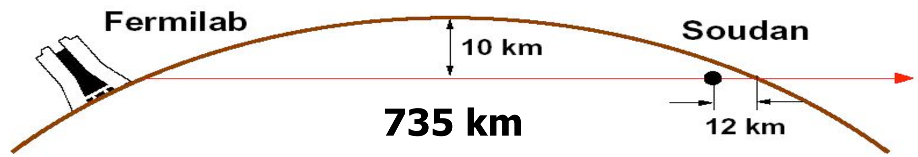


32 institutions
175 scientists

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

MINOS Overview

- Main Injector Neutrino Oscillation Search
- Neutrinos at the Main Injector (NuMI) beam at Fermilab
- Two detectors:
- Near detector at Fermilab
  - measure beam composition
  - energy spectrum
- Far detector in Minnesota
  - search for evidence of oscillations



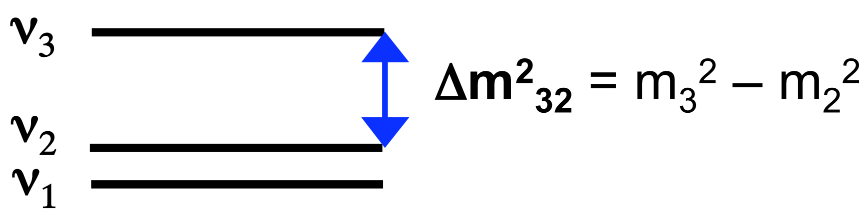
MINOS Physics Goals

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for/constrain exotic phenomena
- Compare ν, $\bar{\nu}$ oscillations
- Atmospheric neutrino oscillations
  - **Phys. Rev. D73, 072002 (2006)**

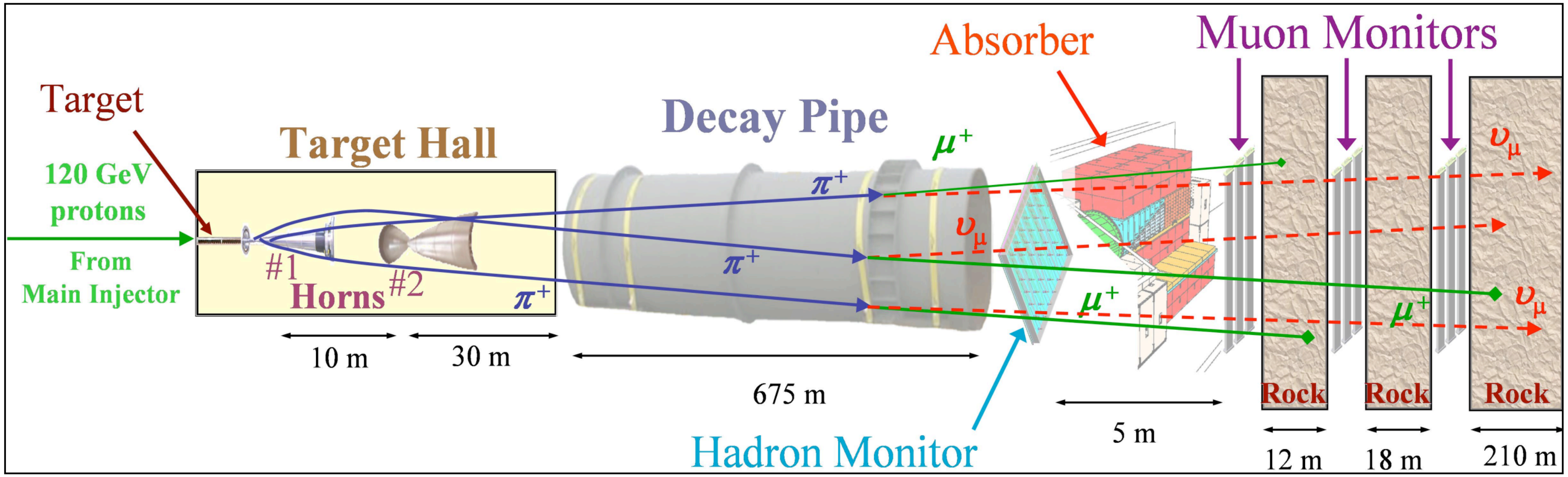
ν_e appearance

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

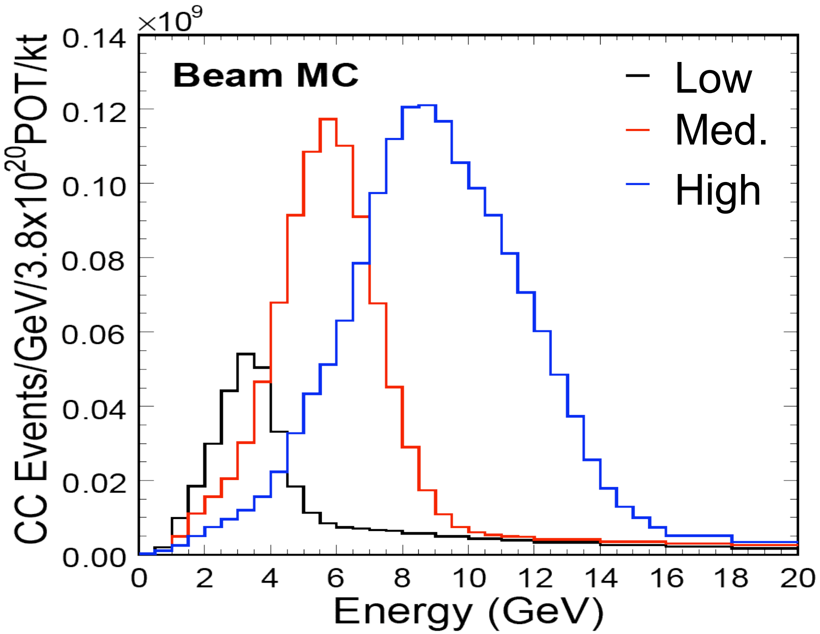
ν_μ disappearance

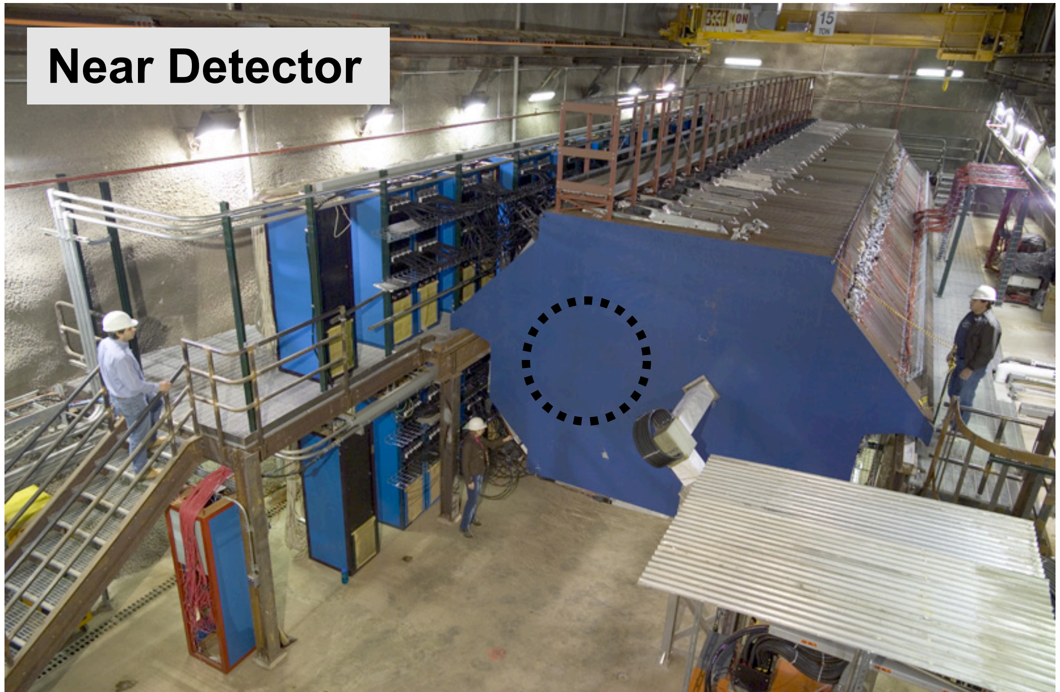


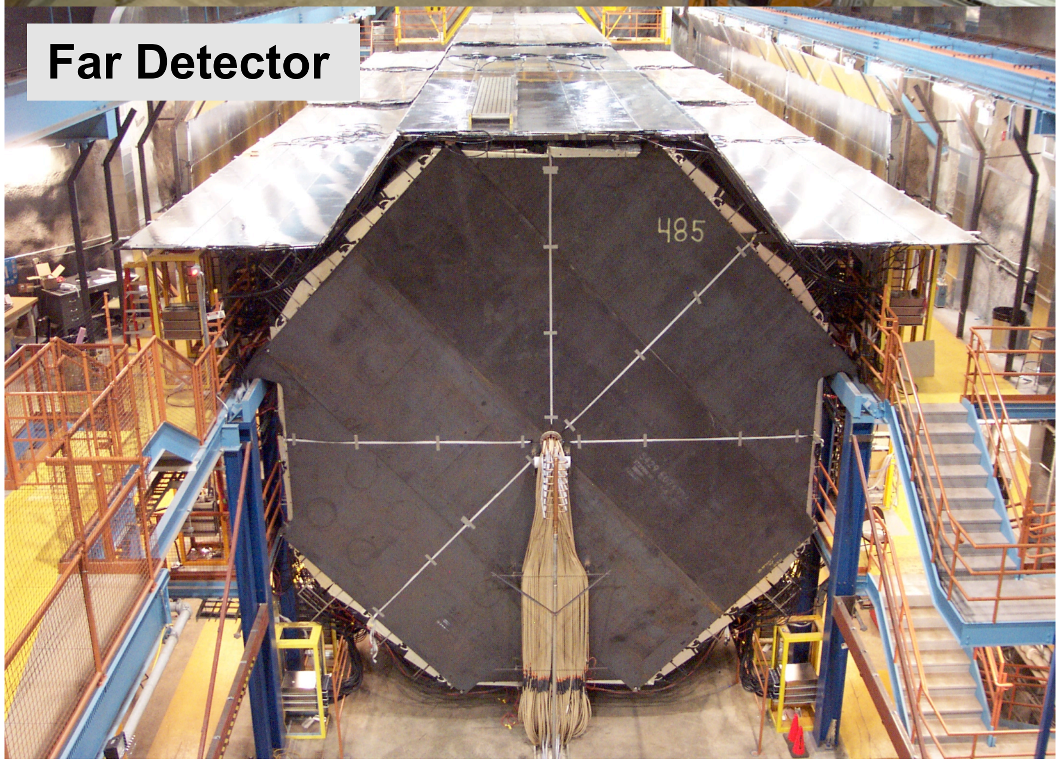
Neutrino Beam (NuMI)



- Protons strike target
- 2 magnetic horns focus secondary π/K
- decay of π/K produces neutrinos
- variable beam energy
- short pulse: ~10 μs





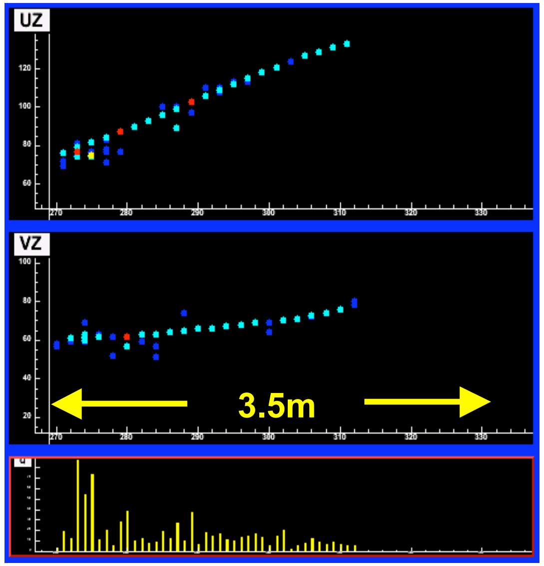


MINOS Detectors

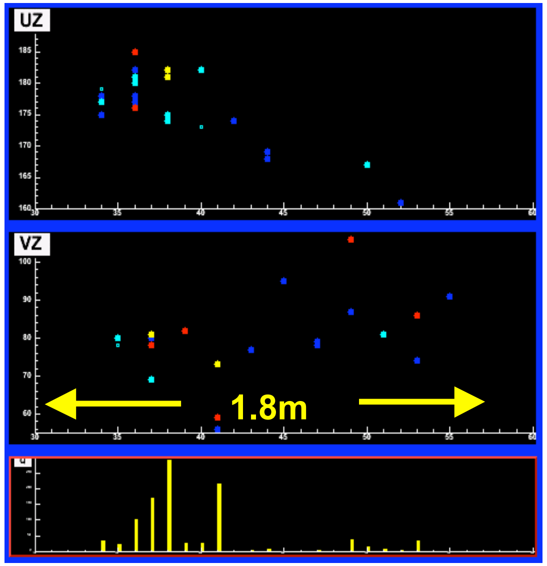
- Massive
  - 1 kt Near detector
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
  - scintillator strips
    - 1 cm thick
    - 4 cm wide
  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

MINOS Event Topologies

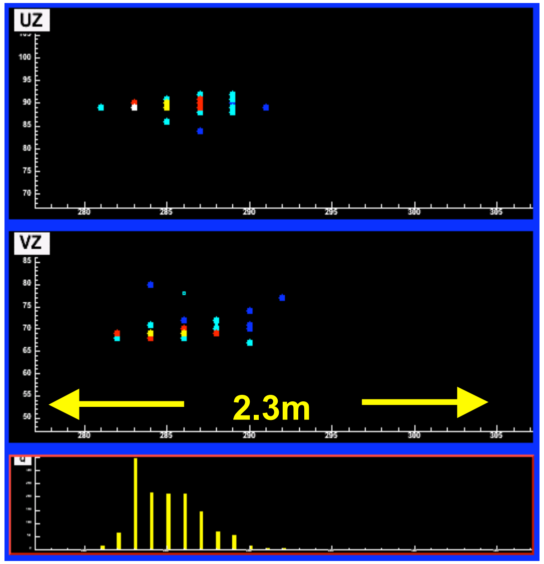
ν_μ CC Event



NC Event



ν_e CC Event



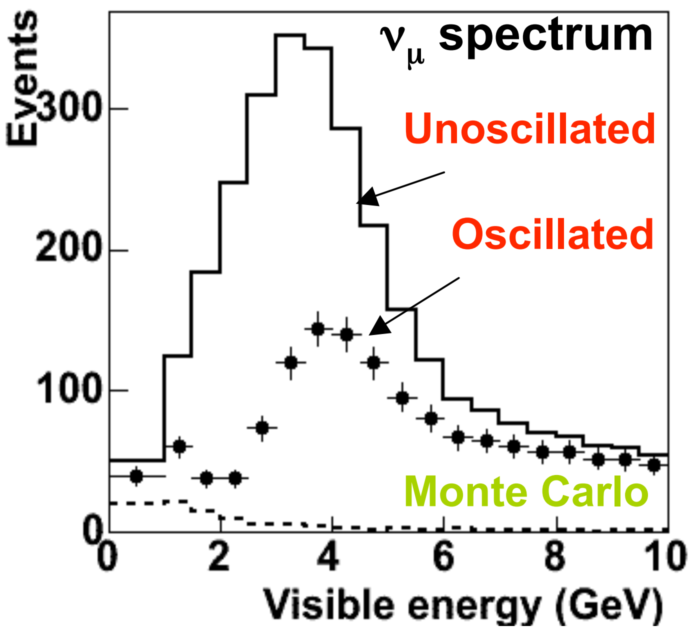
- **long μ track+ hadronic activity at vertex**
- **short event, often diffuse**
- **short, with typical EM shower profile**

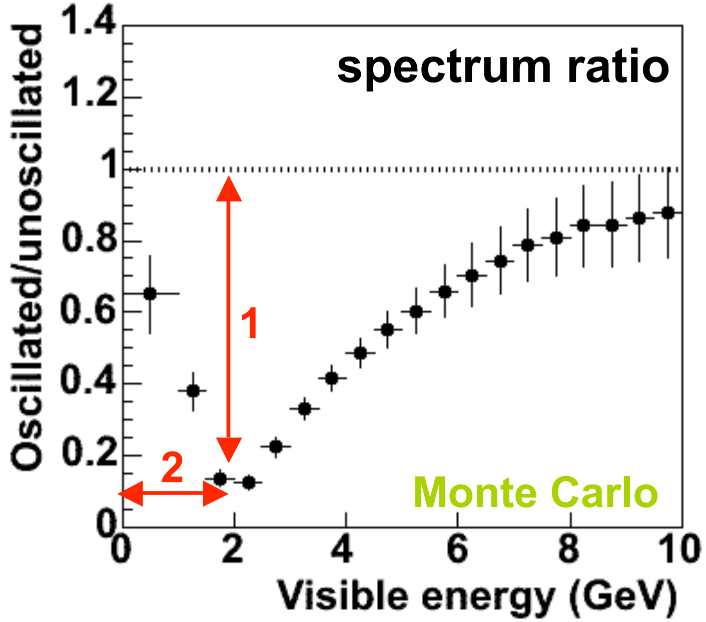
Monte Carlo

Muon Neutrino Disappearance Analysis

Experimental Approach

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate
  - Compare to measured spectrum at Far detector



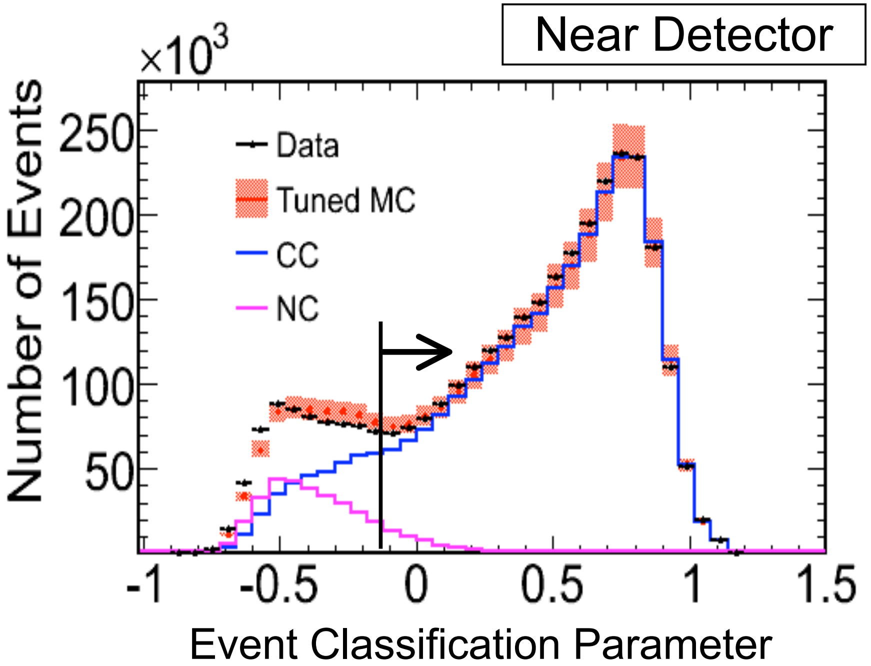


$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta}\,\sin^2(1.267\boxed{\Delta m^2}L/E)$$

1 2

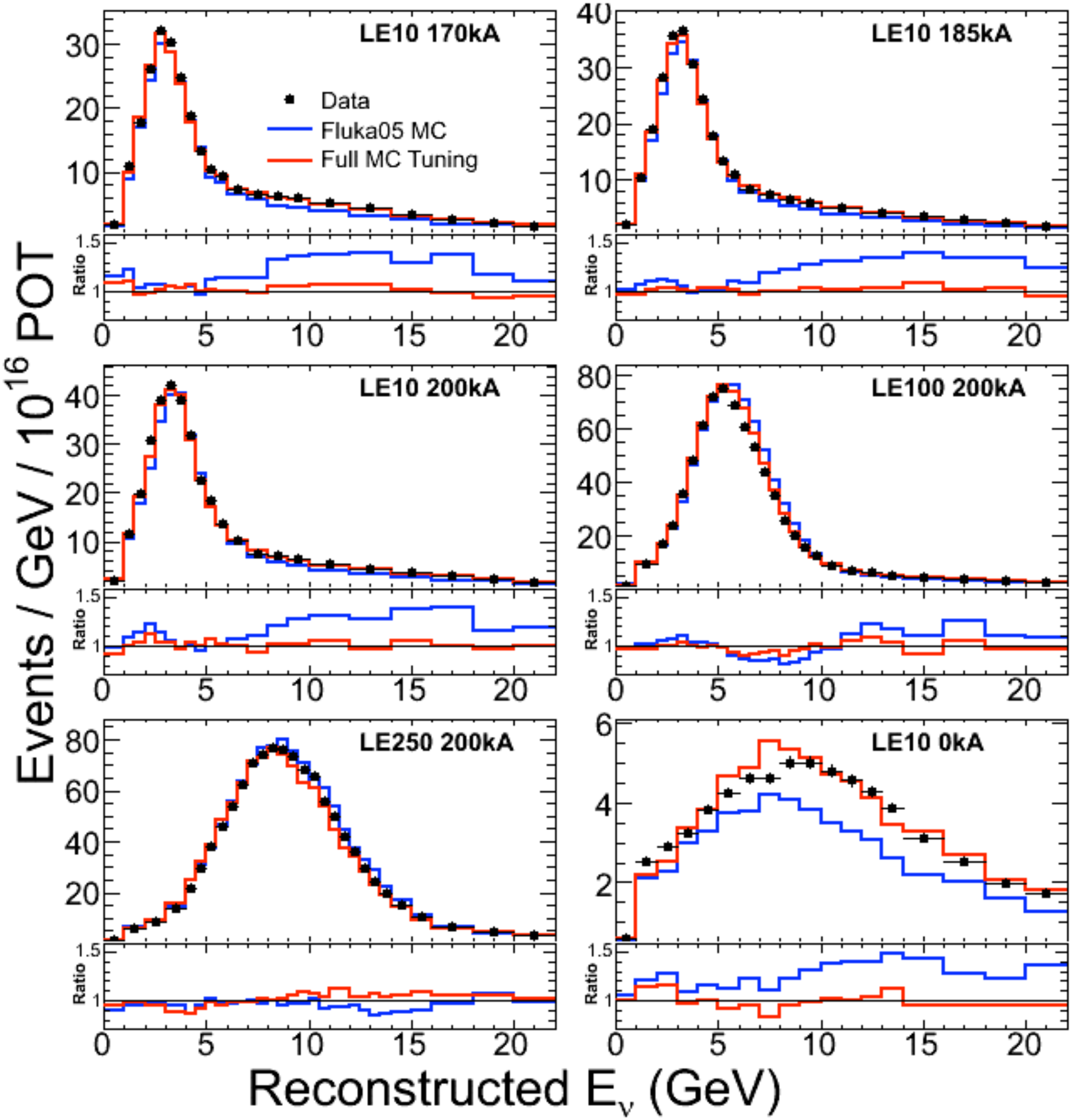
Event Classification

- Separate 2 event types:
  - **Charged Current ν_μ** (oscillations cause deficit)
  - **Neutral Current** (all active neutrinos = no change)
- Event classification parameter
  - likelihood-based
  - 3 Probability Density Functions
    - Track length
    - Pulse height fraction in track
    - Pulse height per plane



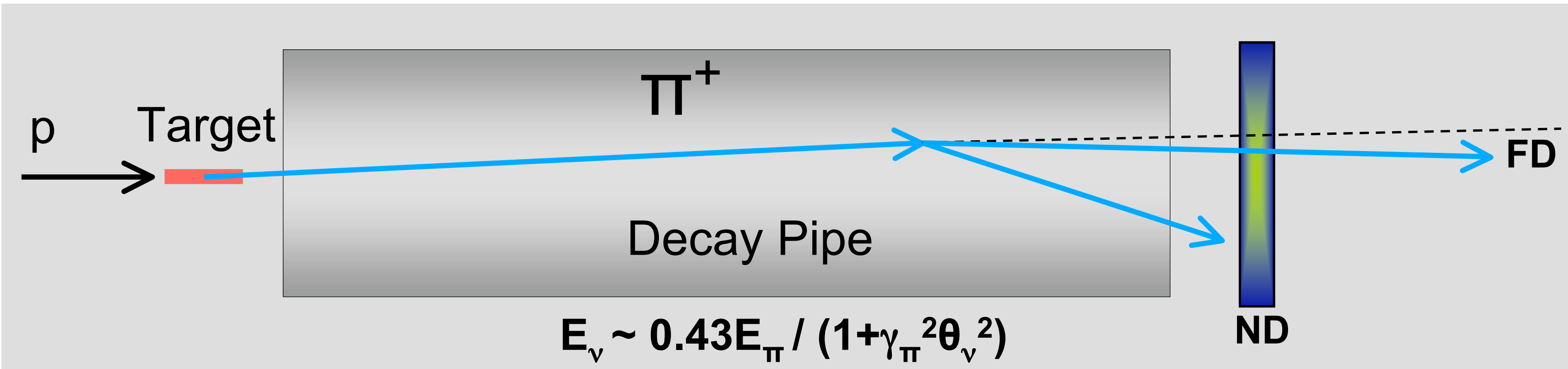
Tuning the beam MC

- 6 beam configurations
- Use Near detector data
- Fit to a model of hadron production
- Reweight MC



Near to Far Extrapolation

- Far detector spectrum != Near detector
  - Project different solid angles
  - π/K decay kinematics
    - average neutrino energy varies with angle



- Extrapolate Near detector spectrum
  - using knowledge of beam line geometry and π/K decay kinematics

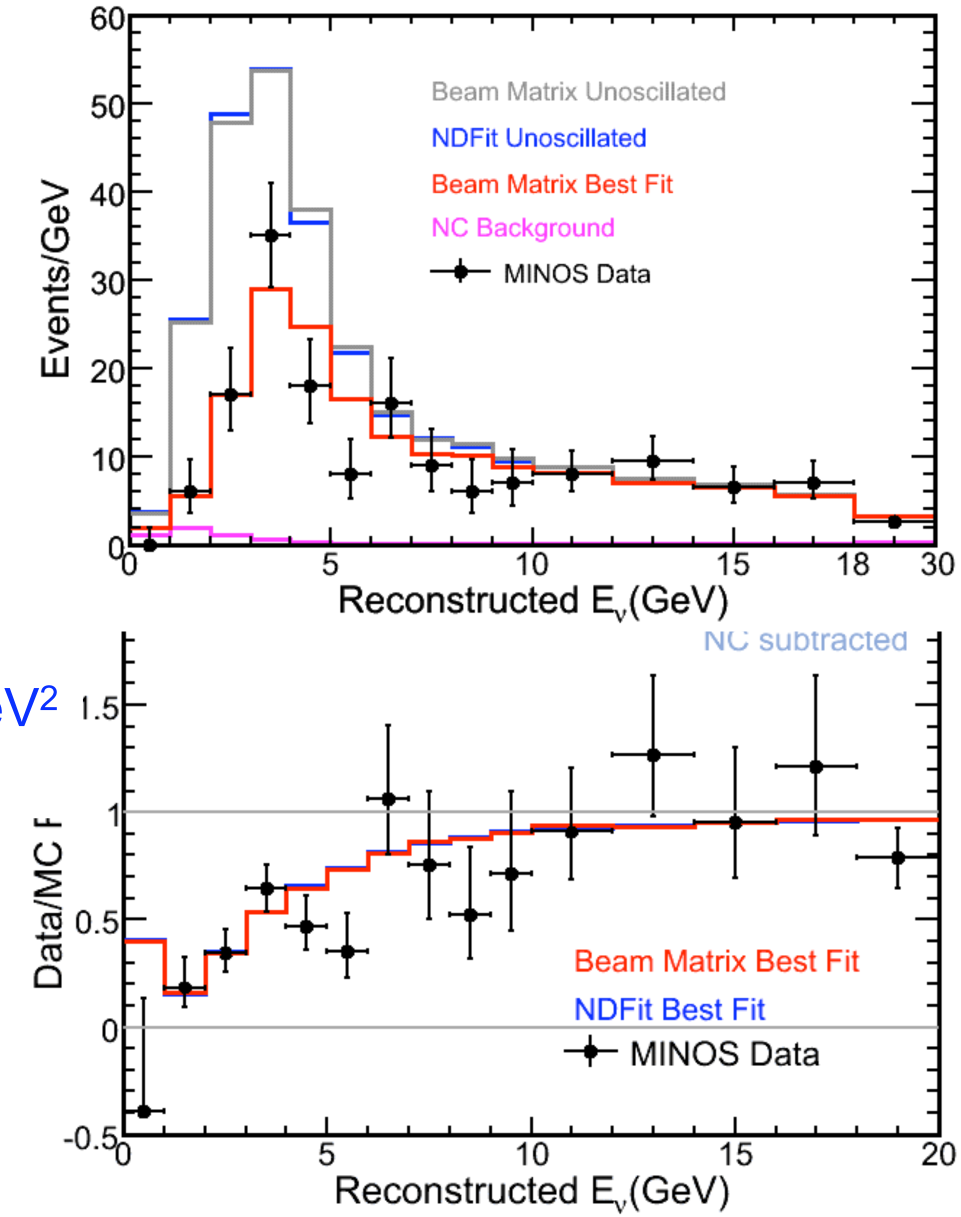
MINOS Best-fit Spectrum

- Data from first year: 1.27×10^{20} POT
- Exclude no oscillations at 6.2σ (rate only, <10 GeV)
- Best fit oscillation parameters:

$|\Delta m^2_{32}| = 2.74\ ^{+0.44}_{-0.26}$ (stat + syst) x 10^{-3} eV^2
$\sin^2 2\theta_{23} = 1.00\ _{-0.13}$ (stat + syst)

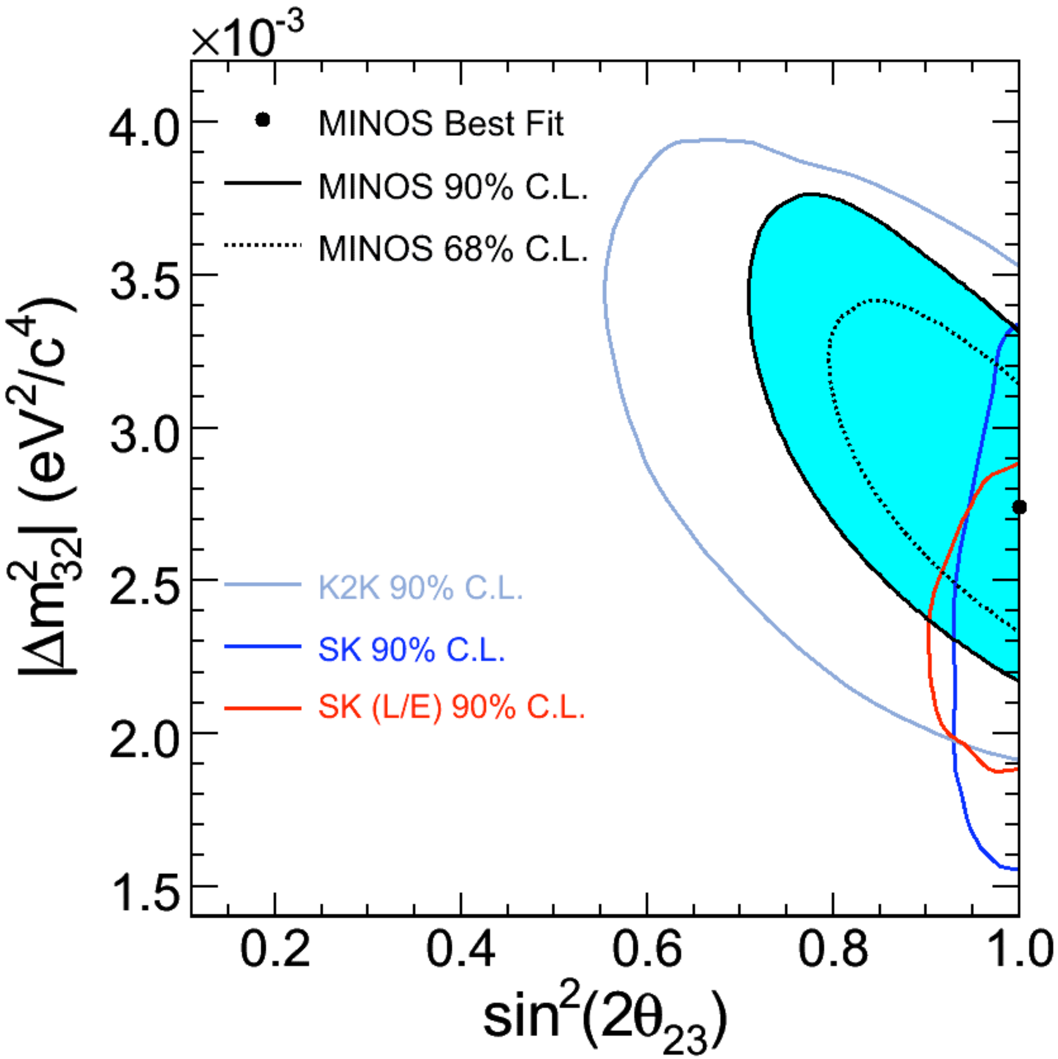
- Constraining the fit to $\sin^2(2\theta_{23}) = 1$ yields:

$|\Delta m^2_{32}| = 2.74 \pm 0.28 \times 10^{-3}$ eV^2



Allowed Region

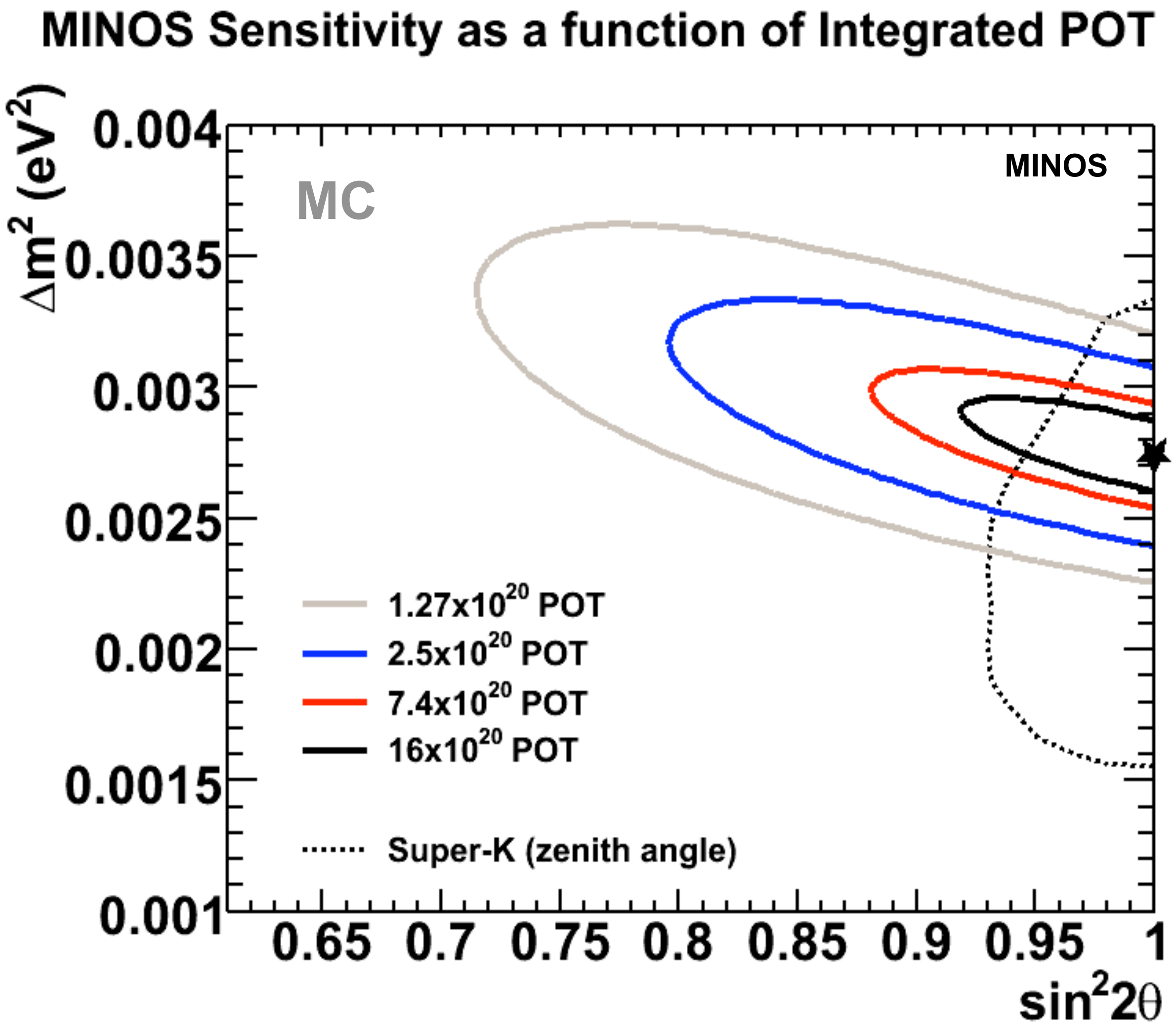
- Consistent with previous experiments
- Already competitive in measurement of $|\Delta m^2_{32}|$



- Phys.Rev.Lett.97:191801,2006
- PRD to be published

MINOS Predicted Sensitivity

- Sensitivity for different POT
- Evaluated at current best fit point
- Contours are 90% C.L. statistical errors only



Quiz Question

on Jeopardy
(US Quiz Show)

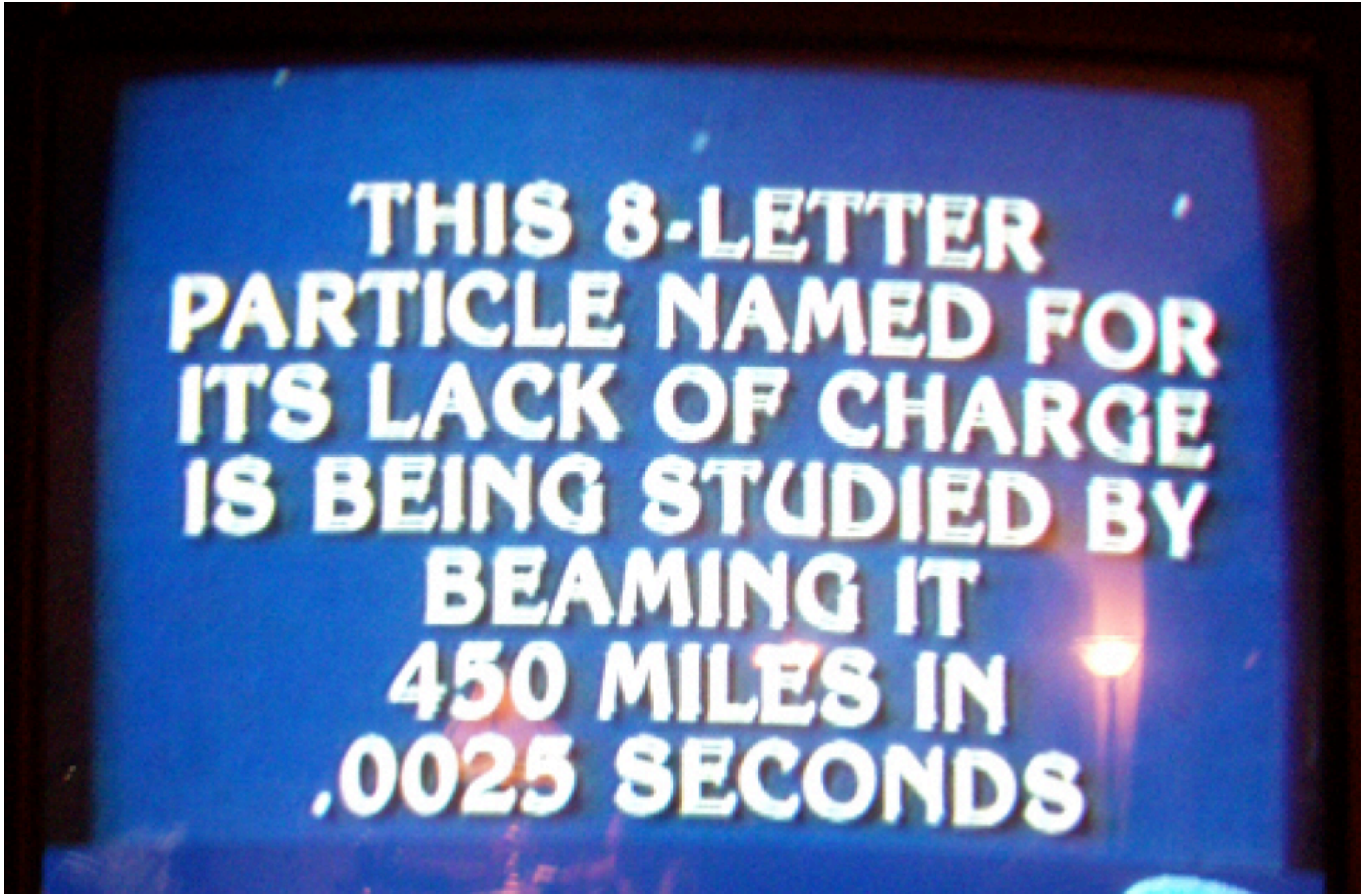
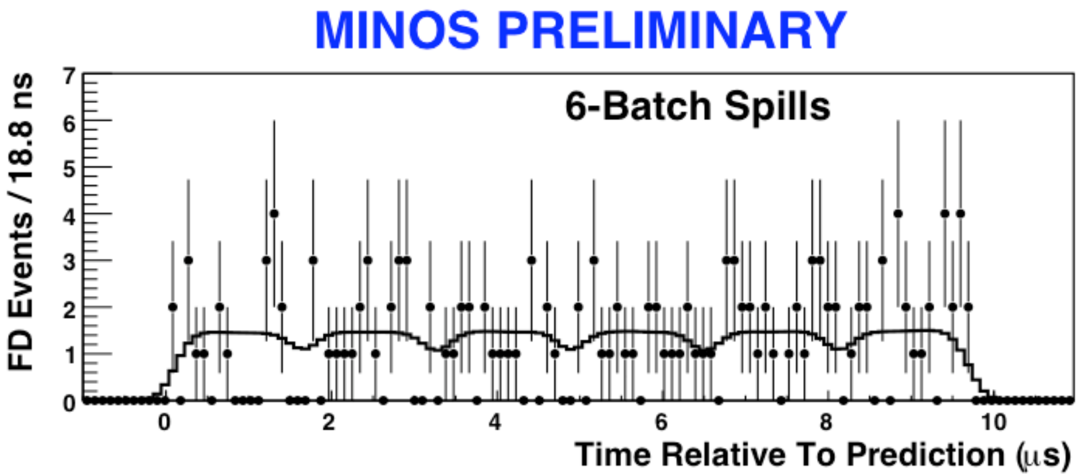


Photo by Jeff Nelson

Neutrino Time-Of-Flight (NEW!)

- GPS synchronises two detectors
- Know distance between detectors precisely:
  - 734,298.6 +/- 0.7 m
  - ~2.5 ms at c
- Measure distribution of event times in two detectors
- Loglikelihood fit to time distribution allowing δ_t to vary



Far detector events = points
Near detector prediction= solid line

Time-Of-Flight Result (NEW!)

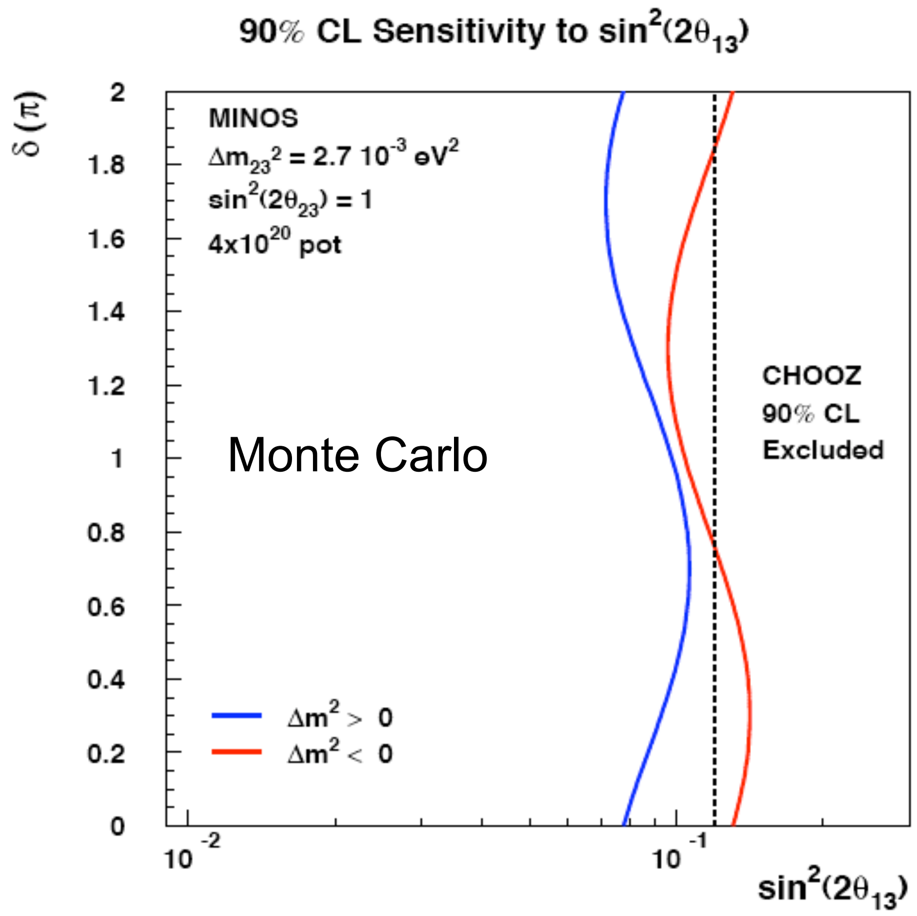
- MINOS T.O.F.:
  - 2449223 +/- 84 (stat.) +/- 164 (syst.) ns @ 99% C.L.
- Nominal T.O.F.:
  - 2449356 ns (@ c)
- In terms of velocity:
  - $(v-c)/c = (5.4 \pm 7.5) \times 10^{-5}$ (99% C.L.)
- Previous experiment had baseline of ~500 m with timing precision of ~ns, gave result of:
  - $|v-c|/c < 4 \times 10^{-5}$ (95% C.L.)

Search for sub-dominant neutrino oscillations

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

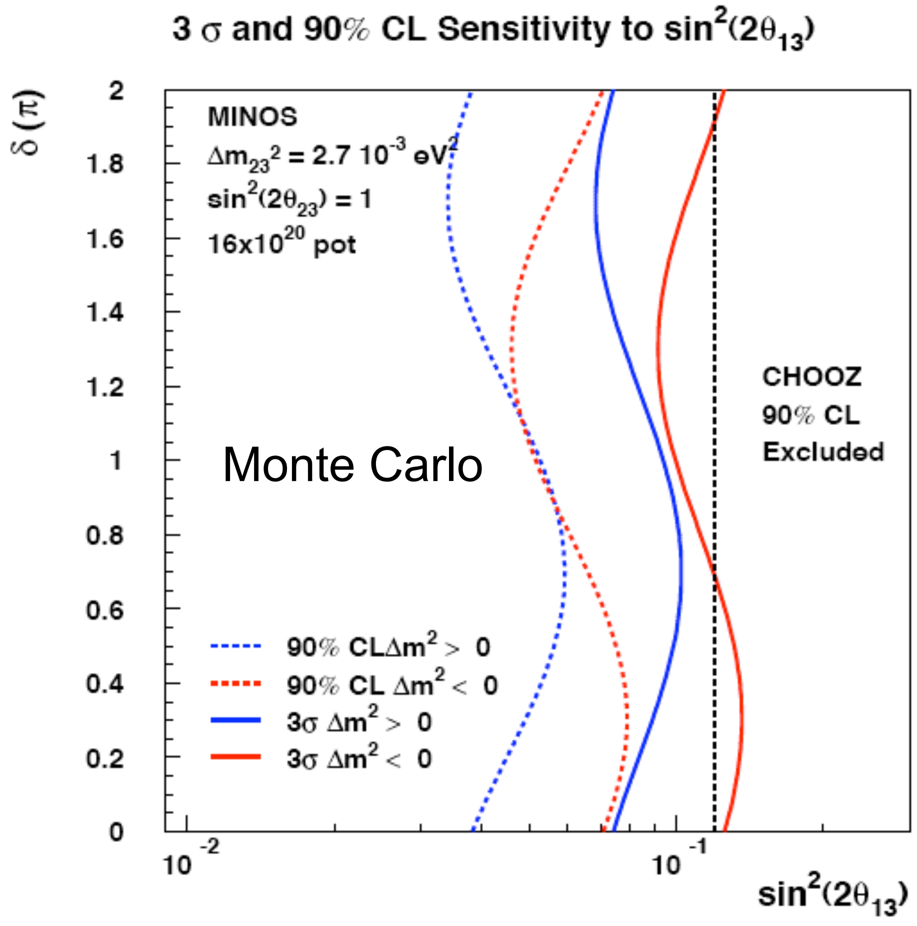
- Sub-dominant neutrino oscillations
  - Look for ν_e appearance
  - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
    - plus CPv and matter effects
- Look for events with compact shower and typical EM profile
  - MINOS optimised for ν_μ
  - ν_e signal selection is harder
    - Steel thickness 2.54cm = $1.44X_0$
    - Strip width 4.1cm ~ Molière radius (3.7cm)
  - Primary background from NC events, also
    - beam ν_e, high-y ν_μ CC, oscillated ν_τ in FD
- However, first indication of non-zero θ_{13} possible

Sensitivity to θ_{13} ($4x10^{20}$ POT)



- Can improve on current best limit from CHOOZ
  - Matter effects can change ν_e yield by ±20%
  - Reach depends strongly on POT
  - With $16x10^{20}$ POT can make significant improvements to world's best limit and increase chance of discovery!

Sensitivity to θ_{13} ($16x10^{20}$ POT)



Dashed lines = 90% C.L.

Solid lines = 3σ

Analysis underway...

Conclusions

- MINOS: long-baseline neutrino oscillation experiment
  - NuMI neutrino beam at Fermilab
  - Two massive detectors
- Analysis of 1st year of beam data (1.27×10^{20} POT):
  - Exclude no oscillations at 6.2σ (rate only, <10 GeV)
  - Results:

$$|\Delta m^2_{32}| = 2.74\,^{+0.44}_{-0.26}\ \text{(stat + syst)} \times 10^{-3}\ \text{eV}^2$$

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

- Constraining the fit to $\sin^2(2\theta_{23}) = 1$ yields:

$$|\Delta m^2_{32}| = 2.74 \pm 0.28 \times 10^{-3}\ \text{eV}^2$$

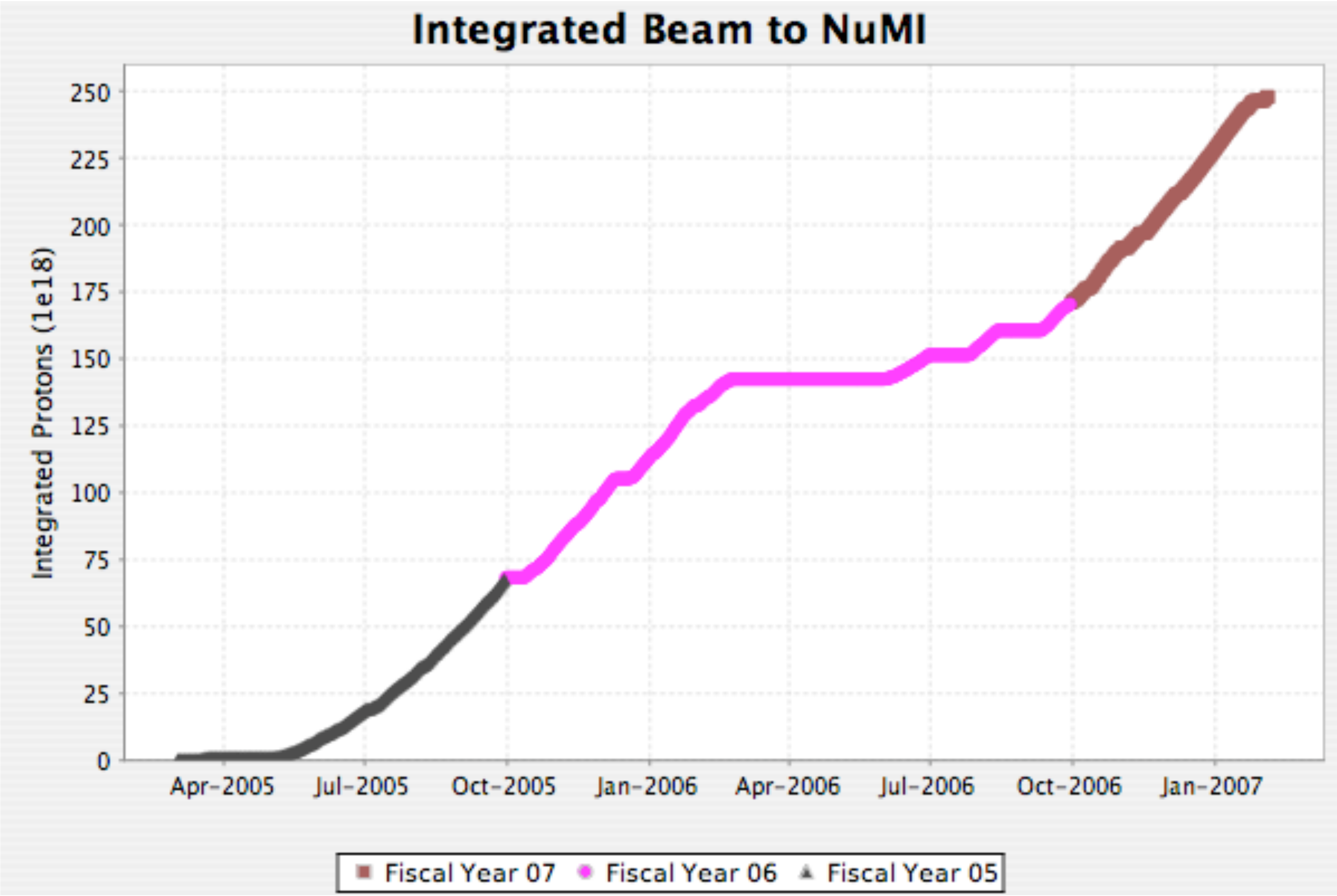
- Time-of-flight measurement:

$$(v-c)/c = (5.4 +/- 7.5) \times 10^{-5}\ @\ 99\%\ \text{C.L.}$$

- Sensitivity to θ_{13} – improve on Chooz
- Updated Δm^2 measurement this summer...

... and MUCH MORE TO COME

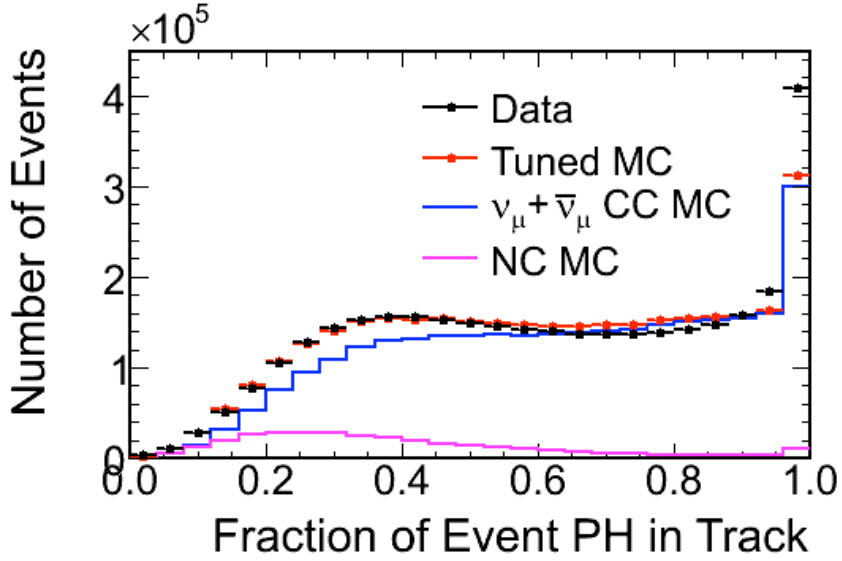
Backup slides

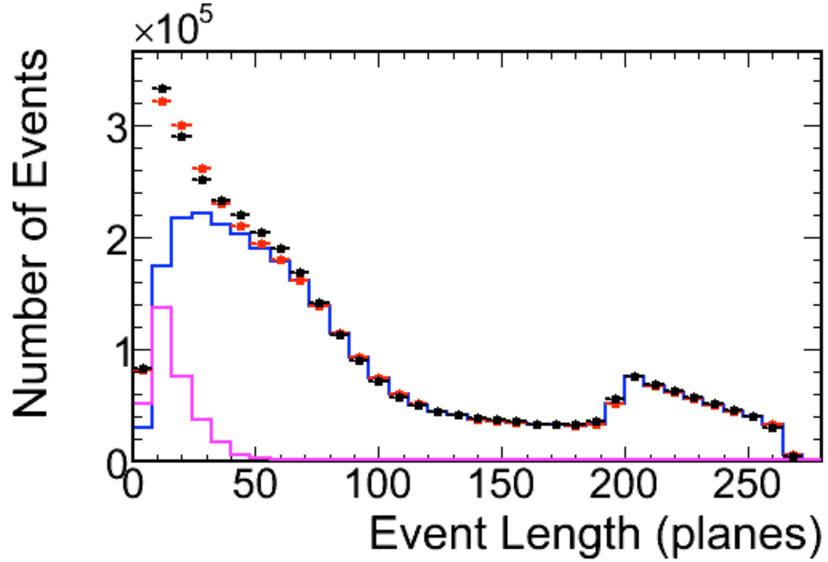


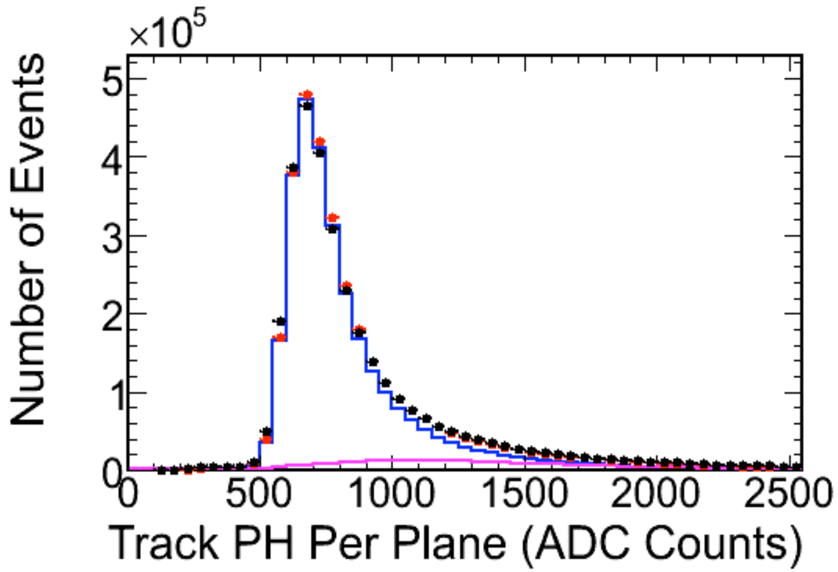
Integrated Beam to NuMI
Integrated Protons (1e18)
250
225
200
175
150
125
100
75
50
25
0
Apr-2005
Jul-2005
Oct-2005
Jan-2006
Apr-2006
Jul-2006
Oct-2006
Jan-2007
Fiscal Year 07
Fiscal Year 06
Fiscal Year 05

MINOS ν_μ-CC Event Selection

- Fiducial Cuts (near and far)
- Select μ- tracks (ν_μ)
- CC/NC classification cuts



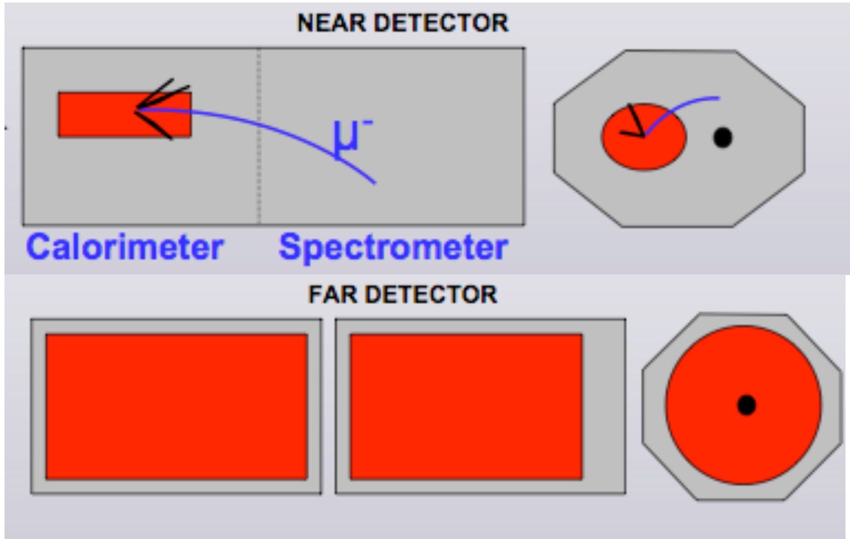


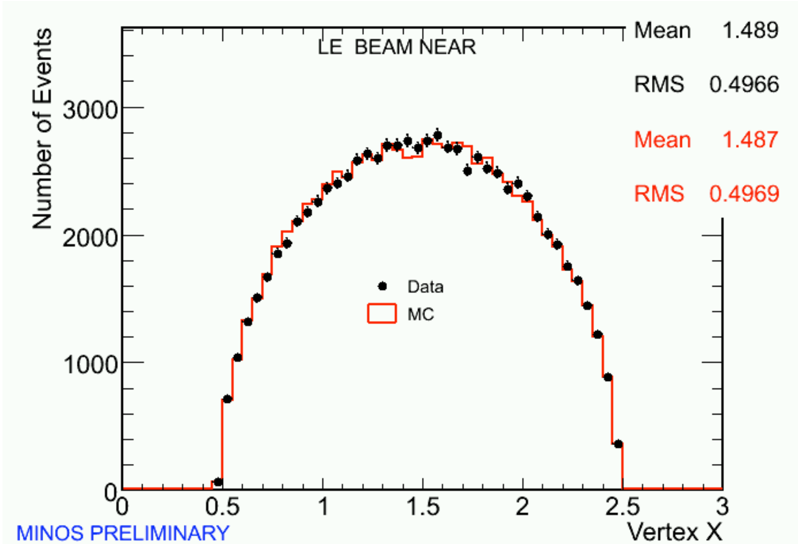


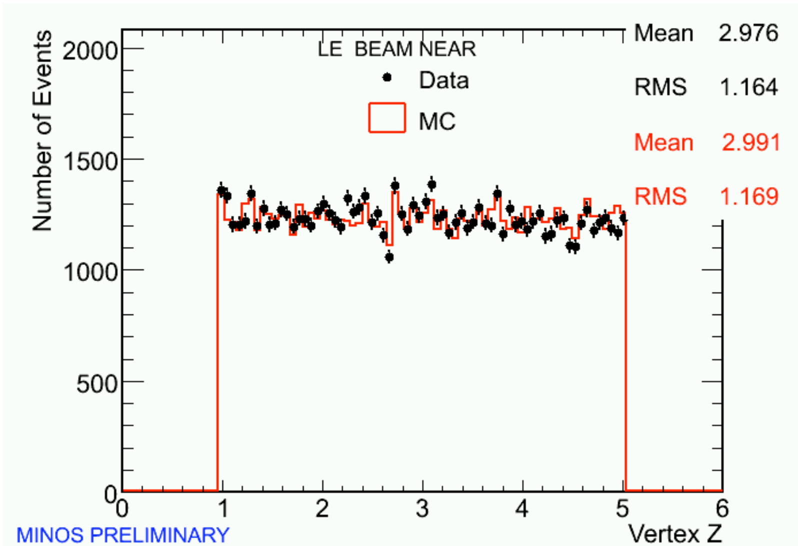
- Far detector specific cuts to remove cosmic ray and light injection contamination
- Far detector data was blinded, all cuts developed & tuned with MC

MINOS ν_μ-CC Event Selection

- Event contains at least one reconstructed track
- Reconstructed vertex is within fiducial volume
- Near: 1 < z < 5 m, r < 1 m from beam center
- Far: 0.5 < z < 14.3 m or 16.2 < z < 28.0 m, r < 3.7 m

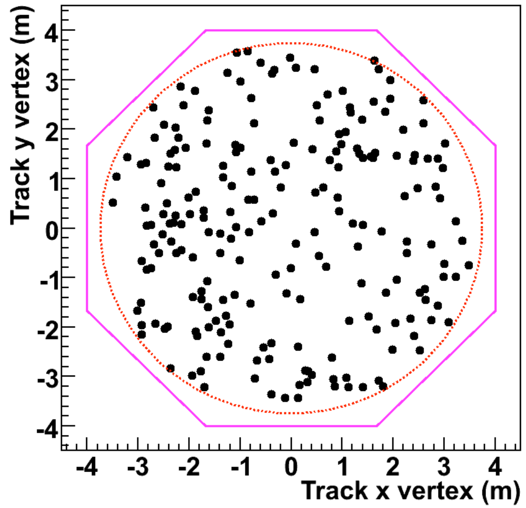


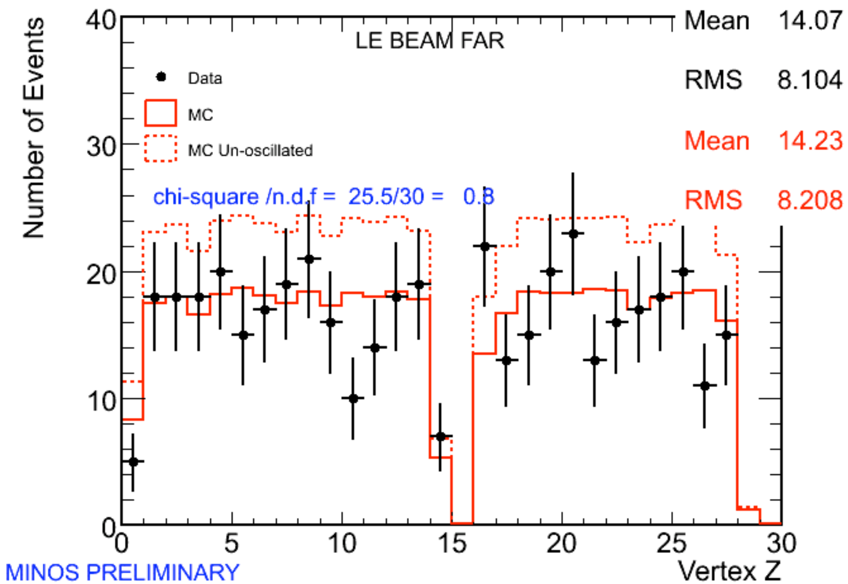


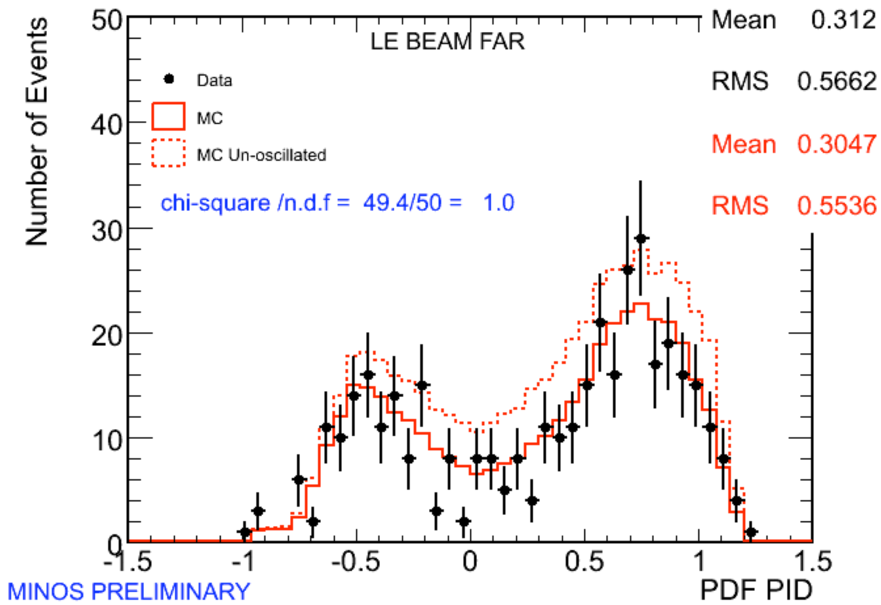


Far Detector Beam Data Selection

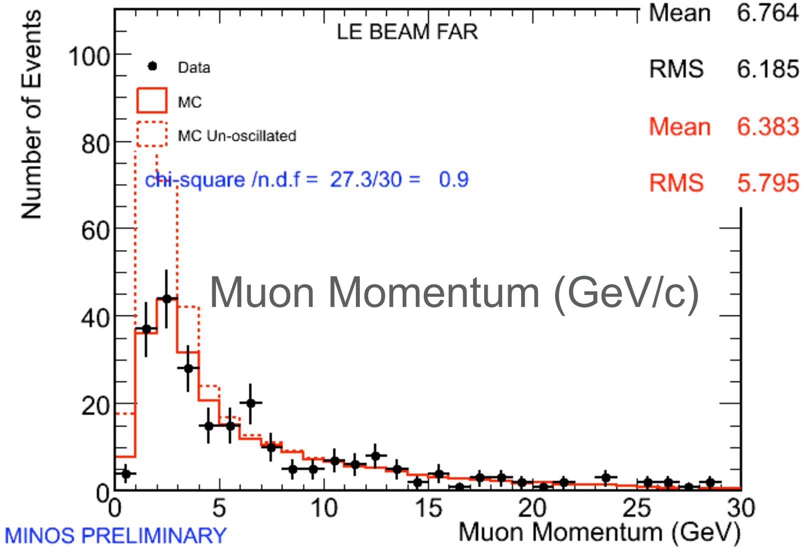
- FD data selected based on position, direction and timing information
- Cosine of angle between track direction and beam direction > 0.6
- Events have -20 < t < 30 μs (GPS)
- Cosmic ray background estimated using sidebands, <0.5 events
- 215 ν_μ CC events

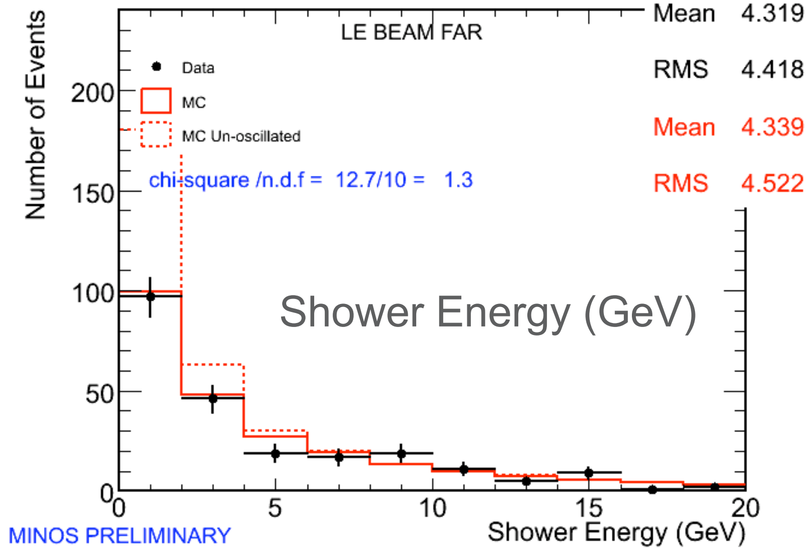


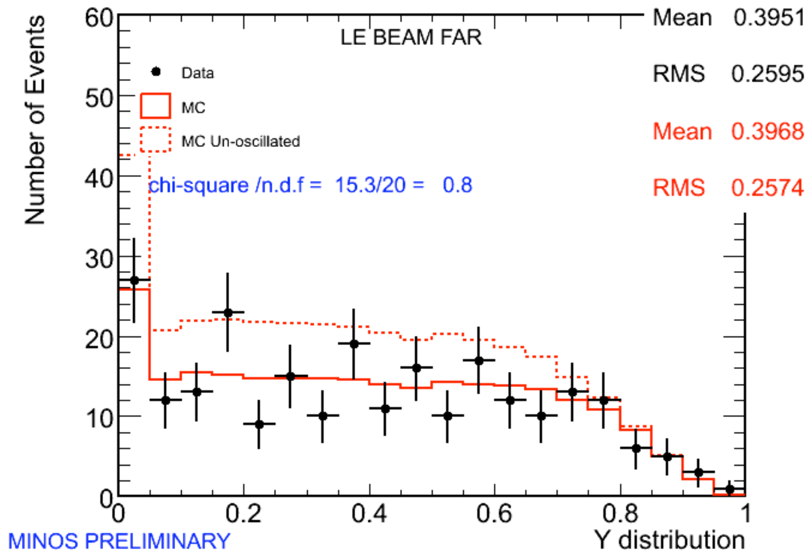




Physics Distributions





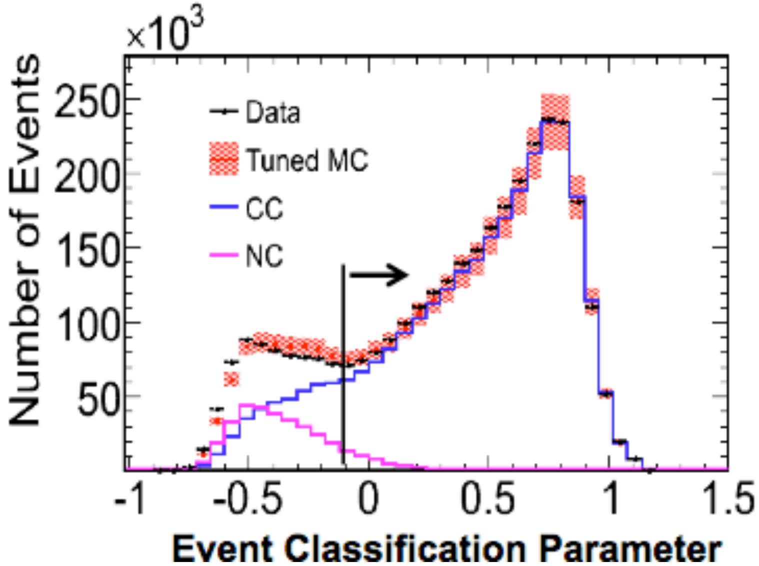


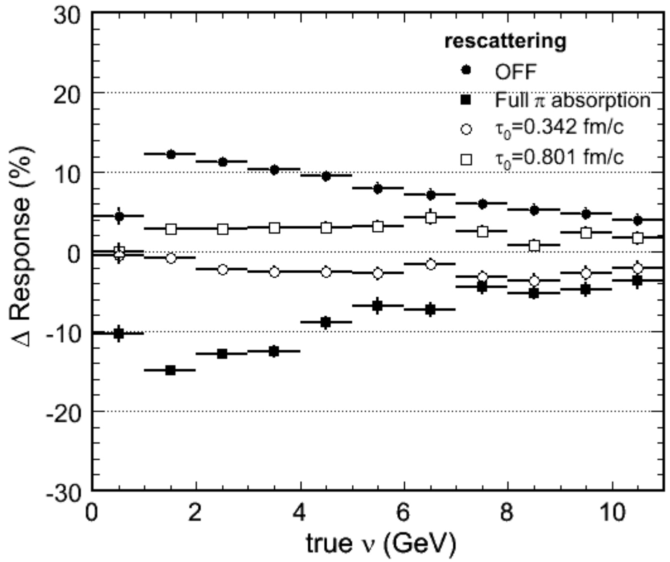
$y = E_{shw}/(E_{shw}+P_{\mu})$

Jeff Hartnell, KEKTC6

Systematic Uncertainties

- Neutral Currents
  - Look at PID in near detector vs energy
  - Large uncertainty in low energy NC cross sections
  - δ(NC contamination): 50%
- Intranuclear Rescattering
  - Models for pion energy loss in nucleus vary
  - Hadron formation zone affects visible energy in ν CC event
  - δ(Hadron Energy Scale)=11%





M.Kordosky, NuINT05

Summary of Systematic Uncertainties

Preliminary Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2 2\theta$
Near/Far normalization ±4%	0.050	0.005
Absolute hadronic energy scale ±11%	0.060	0.048
NC contamination ±50%	0.090	0.050
All other systematic uncertainties	0.044	0.011
Total systematic (summed in quadrature)	0.13	0.07
Statistical error (data)	0.36	0.12

- Size of uncertainties are obtained by doing MC studies
- Make a set of fake data but shifted by the values in the table, fit fake data
- Table shows shift in the oscillation parameters
- 3 largest uncertainties included in oscillation fit as nuisance parameters

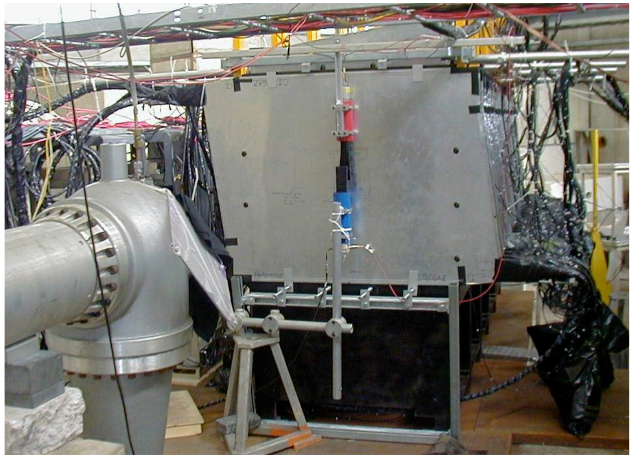
Observed vs. Expected

Data Sample	FD Data	Expected (Matrix Method; Unoscillated)	Data/MC (Matrix Method)
ν_μ (<30 GeV)	215	336.0±14.4	0.64±0.05
ν_μ (<10 GeV)	122	238.7±10.7	0.51±0.05
ν_μ (<5 GeV)	76	168.4±8.8	0.45±0.06

- Below 10 GeV a 49% deficit is observed
- Significance is 6.2σ (stat+syst)

MINOS Calibration System

- **Calibration of ND, FD Response:**
- LED-based Light Injection system
  - Track PMT gains
- Cosmic Ray Muons
  - Remove variations along and between strips
  - Stopping muons for detector-detector calibration
- Overall energy scale:
  - Test-beam with mini-MINOS detector
  - Measured e/μ/π/p response



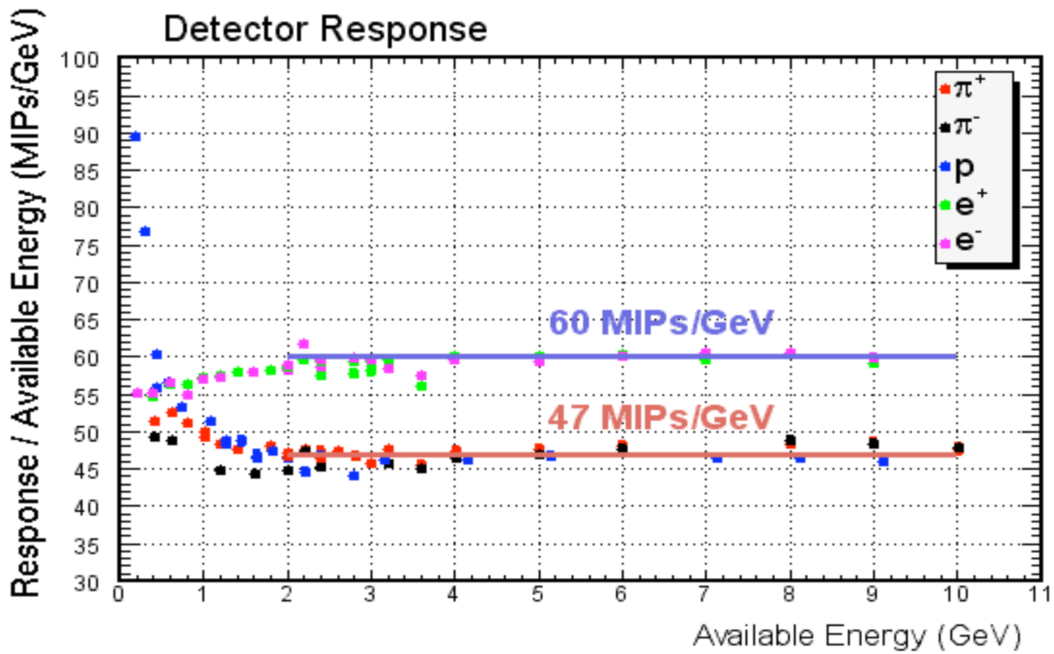
Energy resolution: (E in GeV)

Hadrons:

56% / √E ⊕ 2%

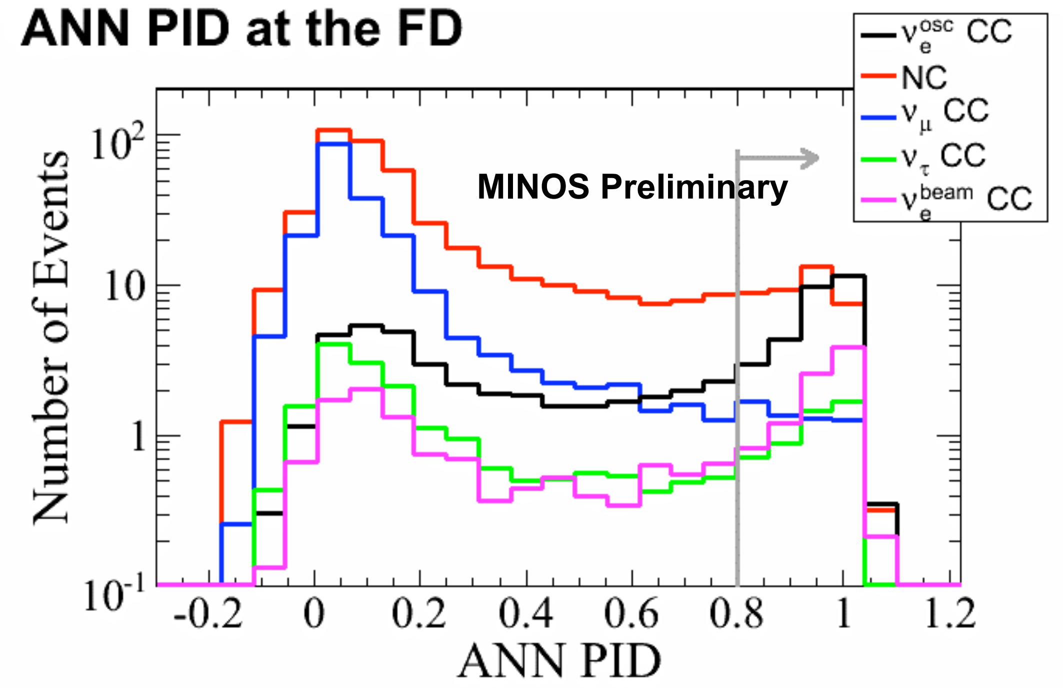
Electrons:

21% / √ E ⊕ 4% / E



Backup: MINOS
ν_e Signal / Background

- Goal: must distinguish between EM and hadronic shower energy
- Several discriminating techniques have been tried to enhance signal/background separation
  - Cuts, Multivariate Discriminant Analysis, ANN, Image recognition



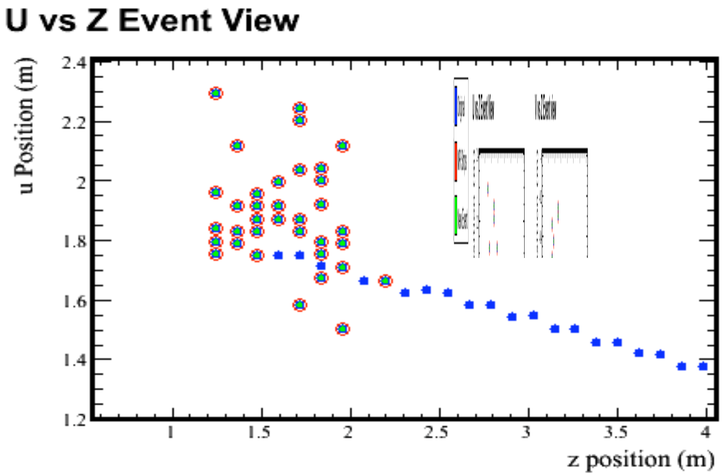
ν_μ CC	NC	ν_e^{beam}	ν_τ CC	Total	ν_e^{osc}
5.6	39.0	8.7	4.7	58.0	29.1

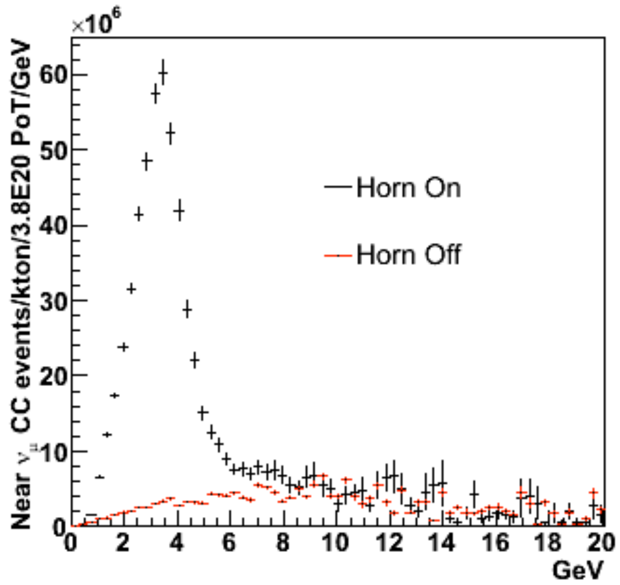
Neural Net example

- Oscillation parameters:
  $\sin^2(2\theta_{13}) = 0.1$
  $|\Delta m_{32}|^2 = 2.7\times10^{-3}eV^2$
  $\sin^2(2\theta_{23}) = 1$
- POT = $16\text{x}10^{20}$
- Oscillated ν_e are shown in black
- Cutting at 0.8:
  - ν_e purity ~ 30%
  - Signal/$\sqrt{}$Background = 3.8

Backup: Study MINOS ν_e Background with Data

- Several techniques developed to measure backgrounds in ND:
- Muon removal from CC events to estimate NC contribution
  - Assumes similar hadron multiplicities/shower topologies
  - Requires some corrections from MC
- Using horn off data to resolve NC, ν_μ CC background components
  - During horn off running, pions are no longer focused and energy spectrum peak disappears
  - Running event selection on horn-off data enhances NC component of background





MINOS PRELIMINARY
Summary of systematic uncertainties on relative time.

	Description	Uncertainty (99% C.L)
A	Distance between detectors	6 ns
B	ND Antenna fibre length	67 ns
C	ND electronics latencies	77 ns
D	FD Antenna fibre length	101 ns
E	FD electronics latencies	9 ns
F	GPS and transceivers	74 ns
G	Detector readout differences	24 ns
	Total	164 ns

Systematic uncertainties on time measurement between Near and Far Detectors (Sys. uncertainty on t_2-t_1)