MINOS Results and Future Prospects

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(on behalf of the MINOS Collaboration)

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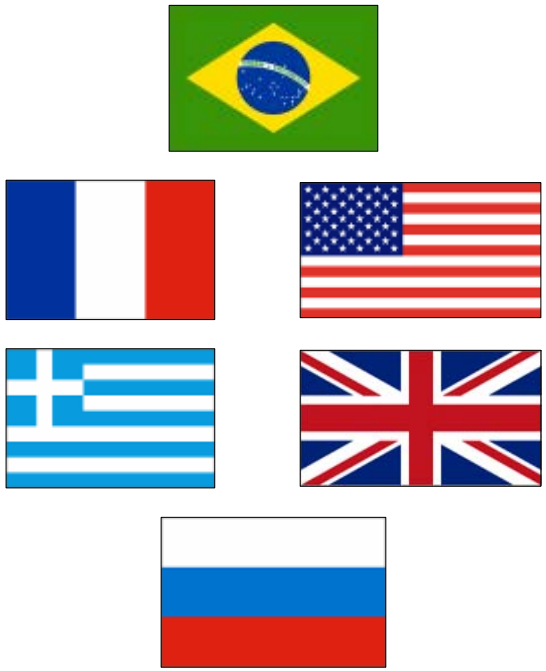
Introduction

- 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

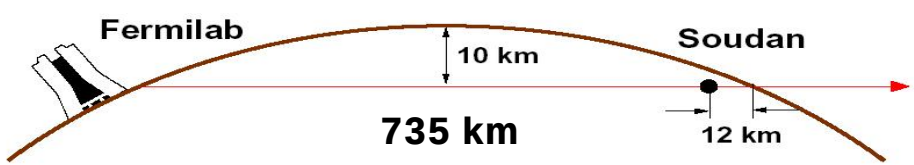


32 institutions
175 scientists

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



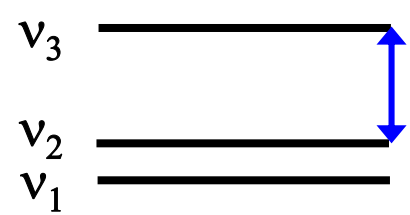
MINOS Physics Goals

- 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

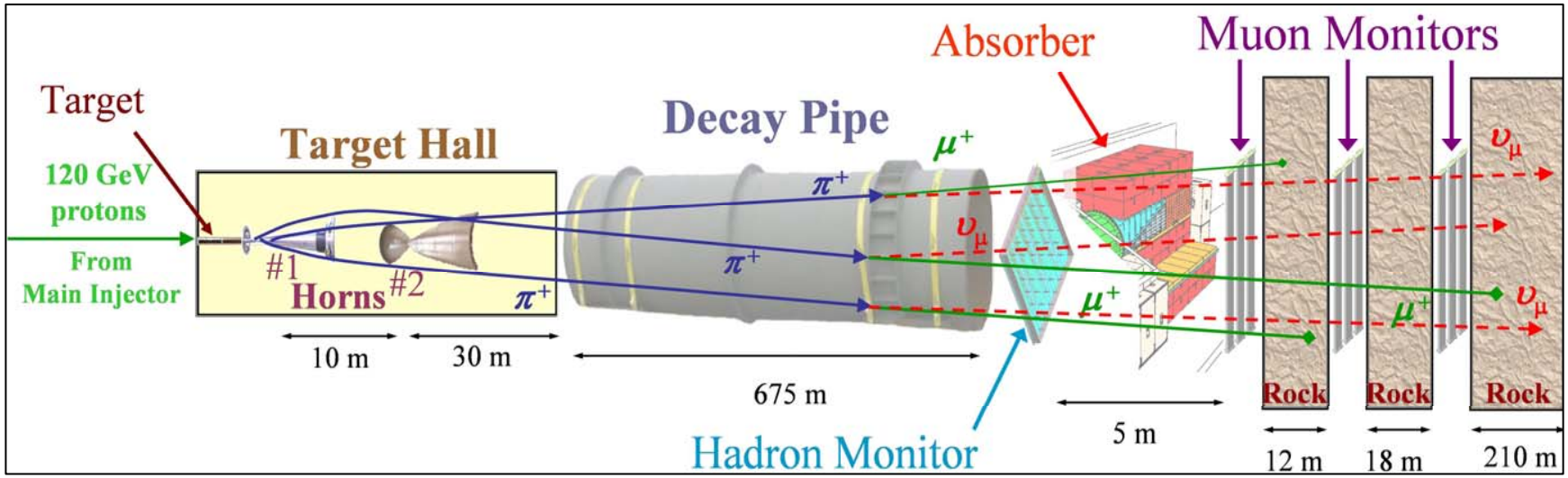
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & \boxed{U_{\mu 3}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ν_μ disappearance

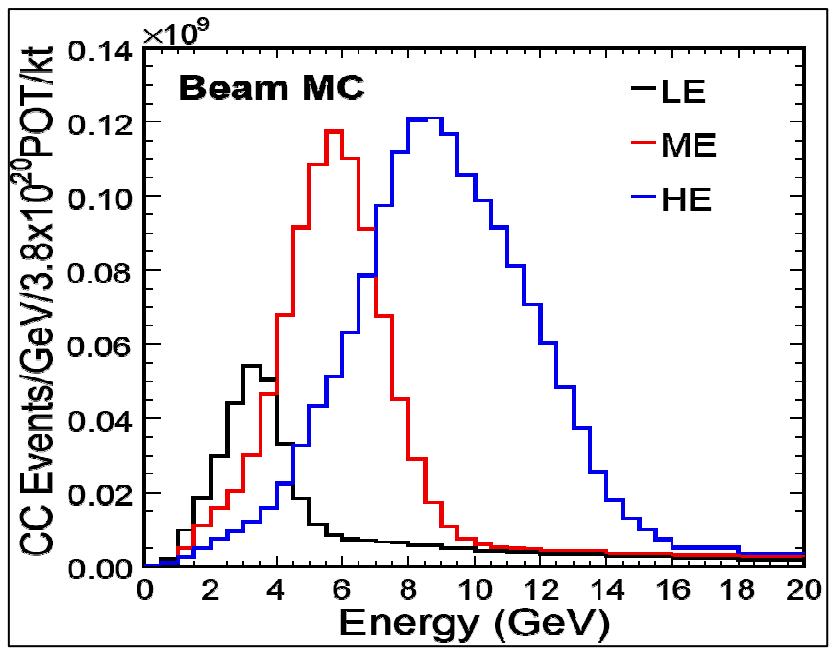


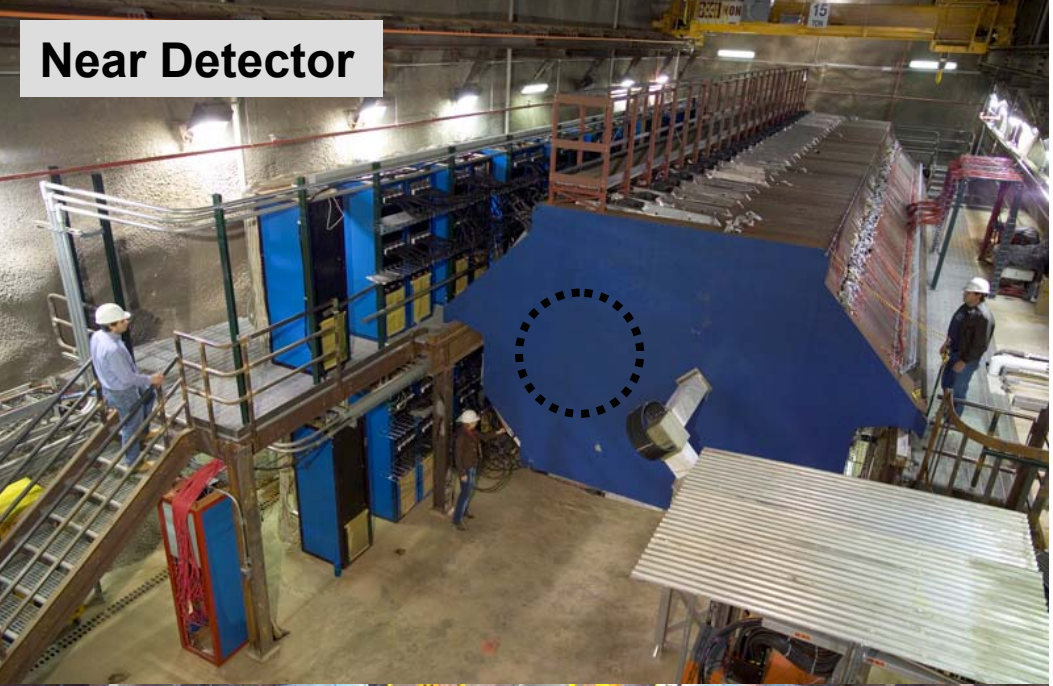
$\Delta \mathbf{m^2_{32}} = m_3^2 - m_2^2$

Neutrino Beam (NuMI)



- Protons strike target
- 2 magnetic horns focus secondary π/K
- decay of π/K produces neutrinos
- variable beam energy



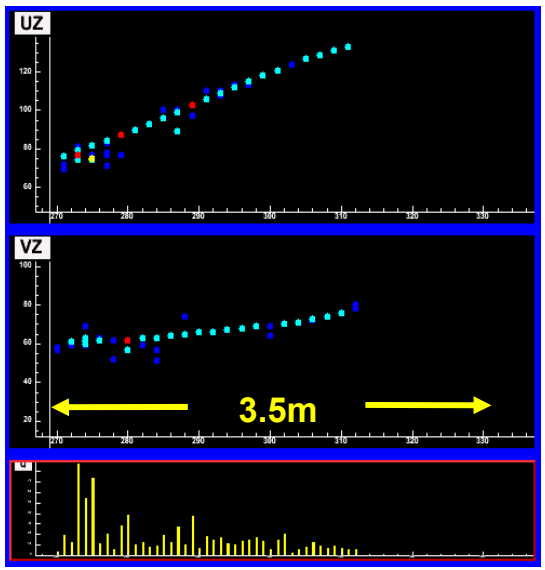


MINOS Detectors

- 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)

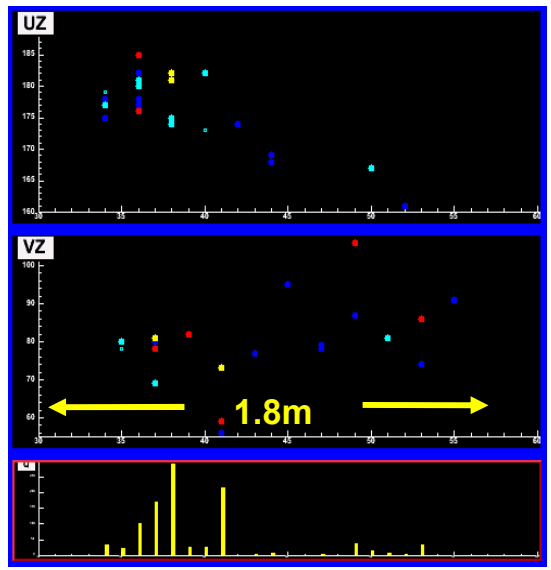
MINOS Event Topologies

ν_μ CC Event



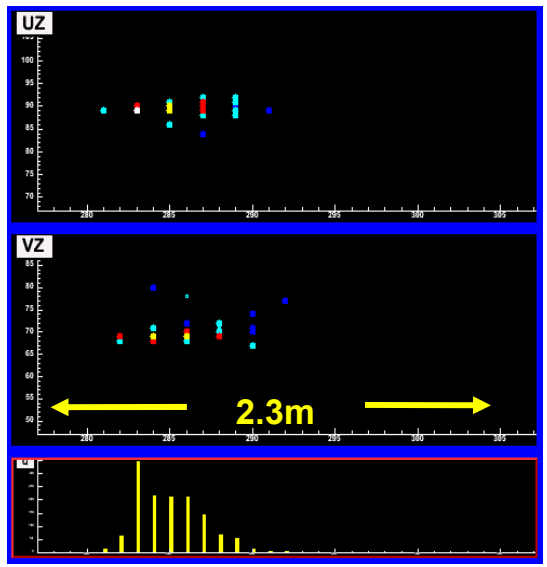
- long μ track+ hadronic activity at vertex

NC Event



- short event, often diffuse

ν_e CC Event



- short, with typical EM shower profile

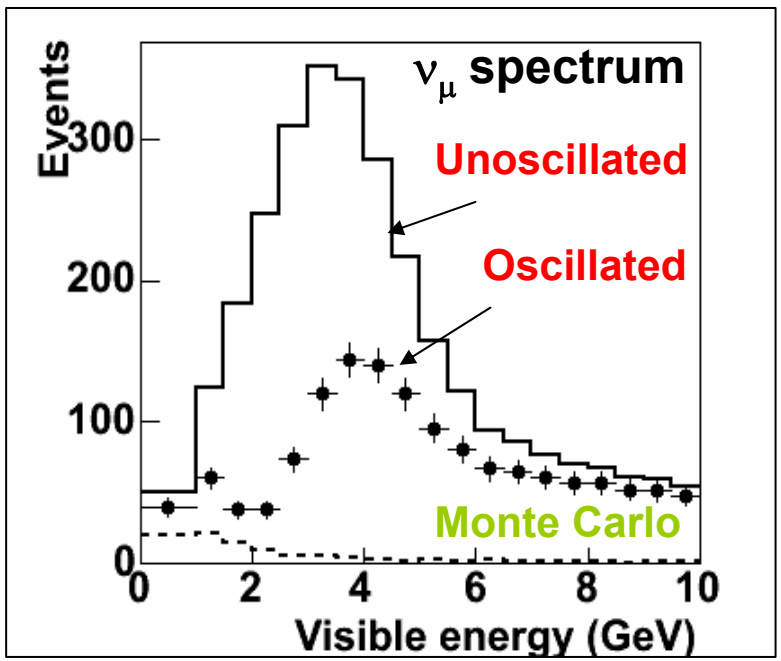
Monte Carlo

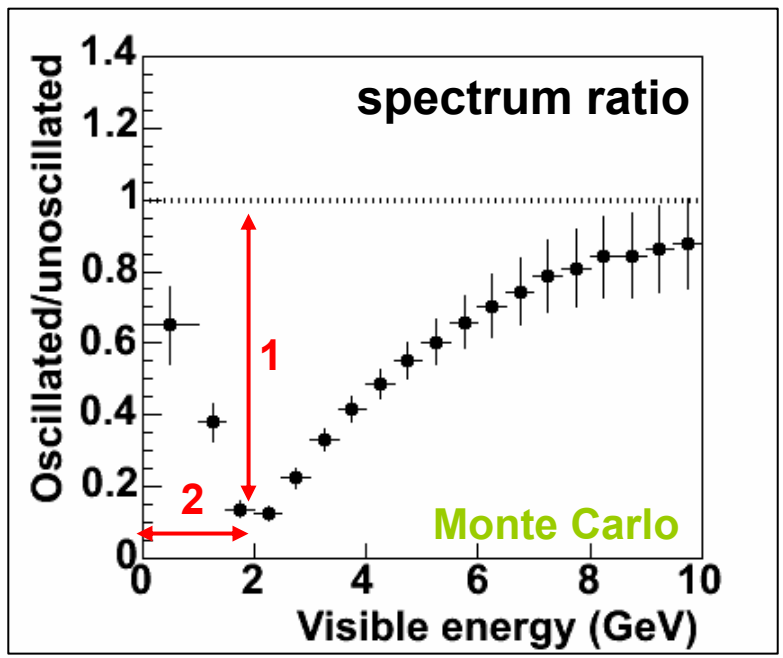
Muon Neutrino Disappearance Analysis

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

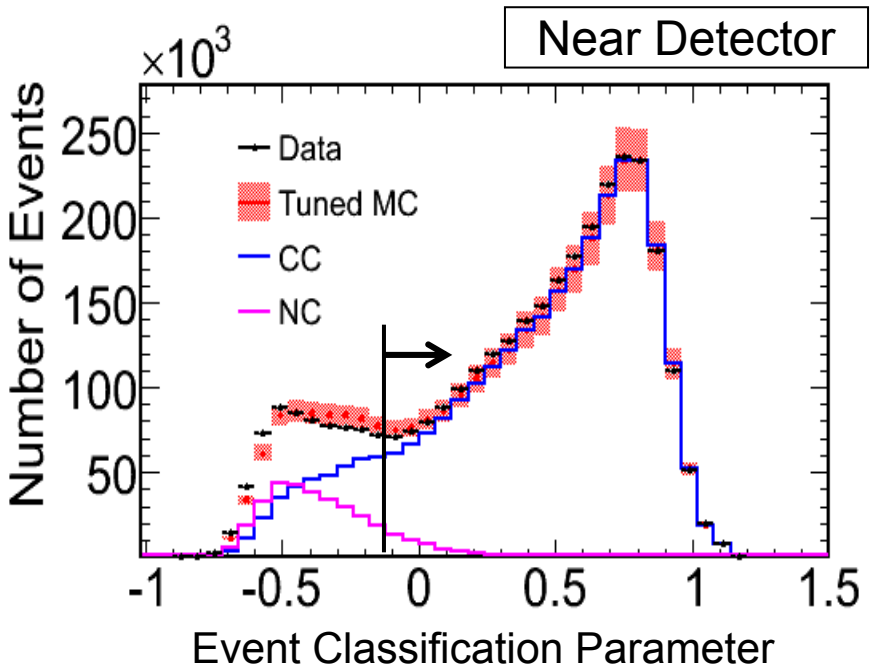
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L/E)$$





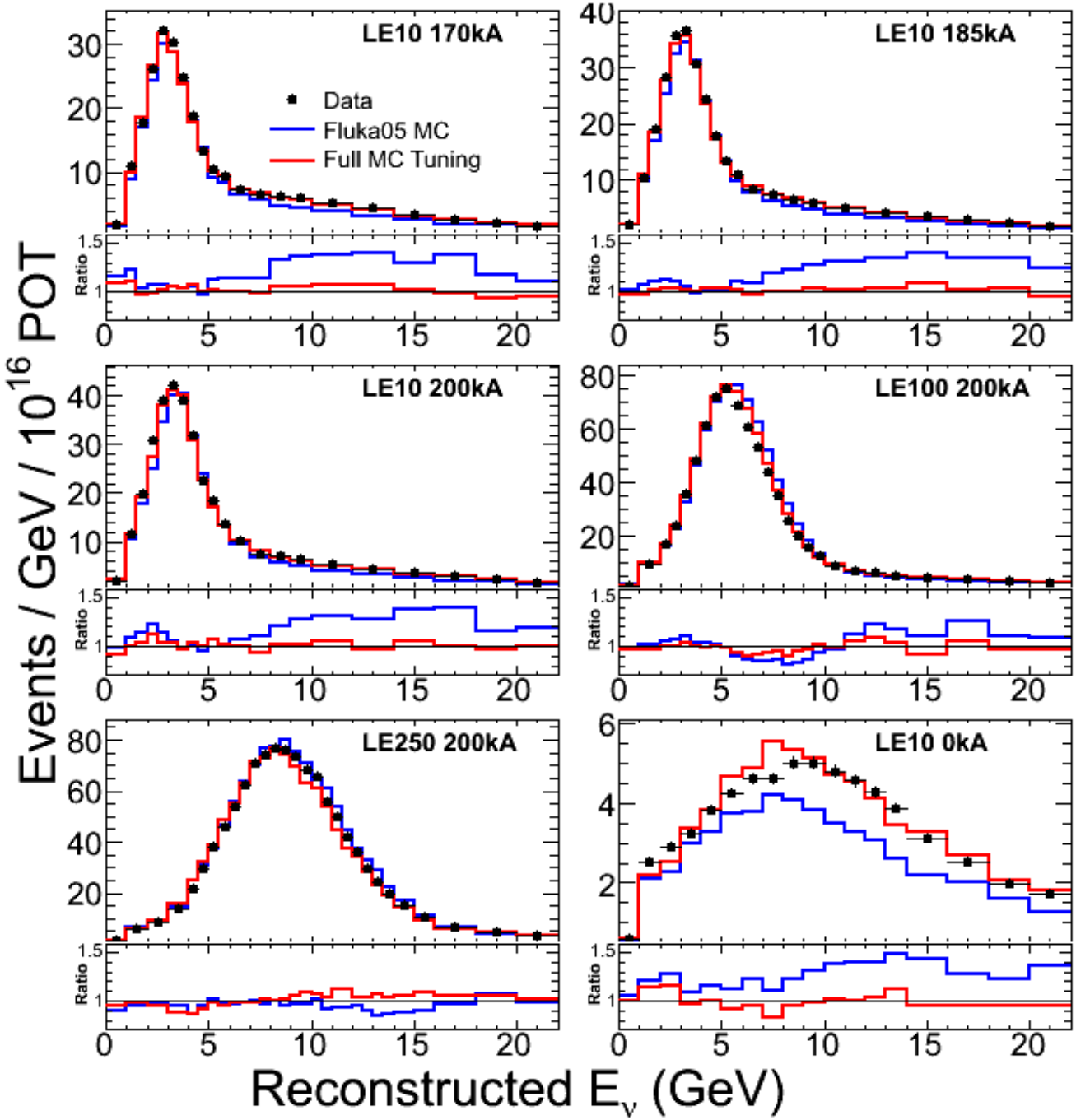
Event Classification

- 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



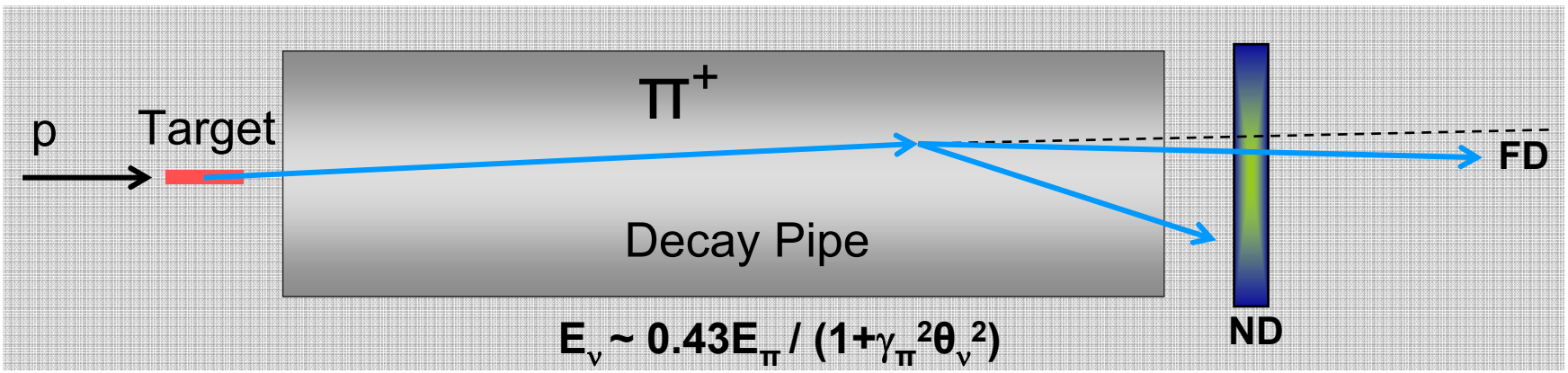
Tuning the beam MC

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



Predicting Far Energy Spectrum

- 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

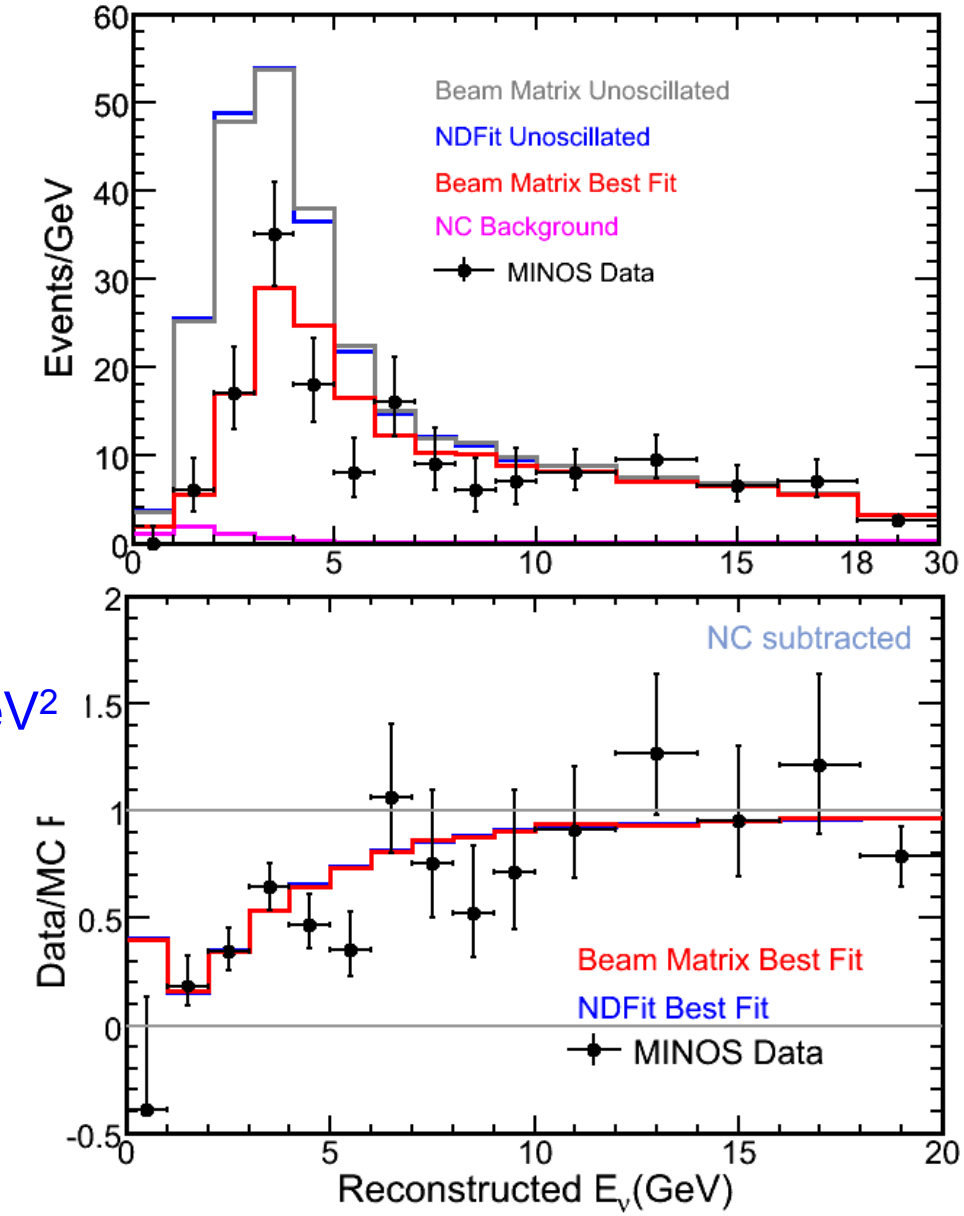
MINOS Best-fit Spectrum

- Data from first year: 1.27×10^{20} POT
- Exclude no oscillations at 6.2σ (rate only)
- 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)

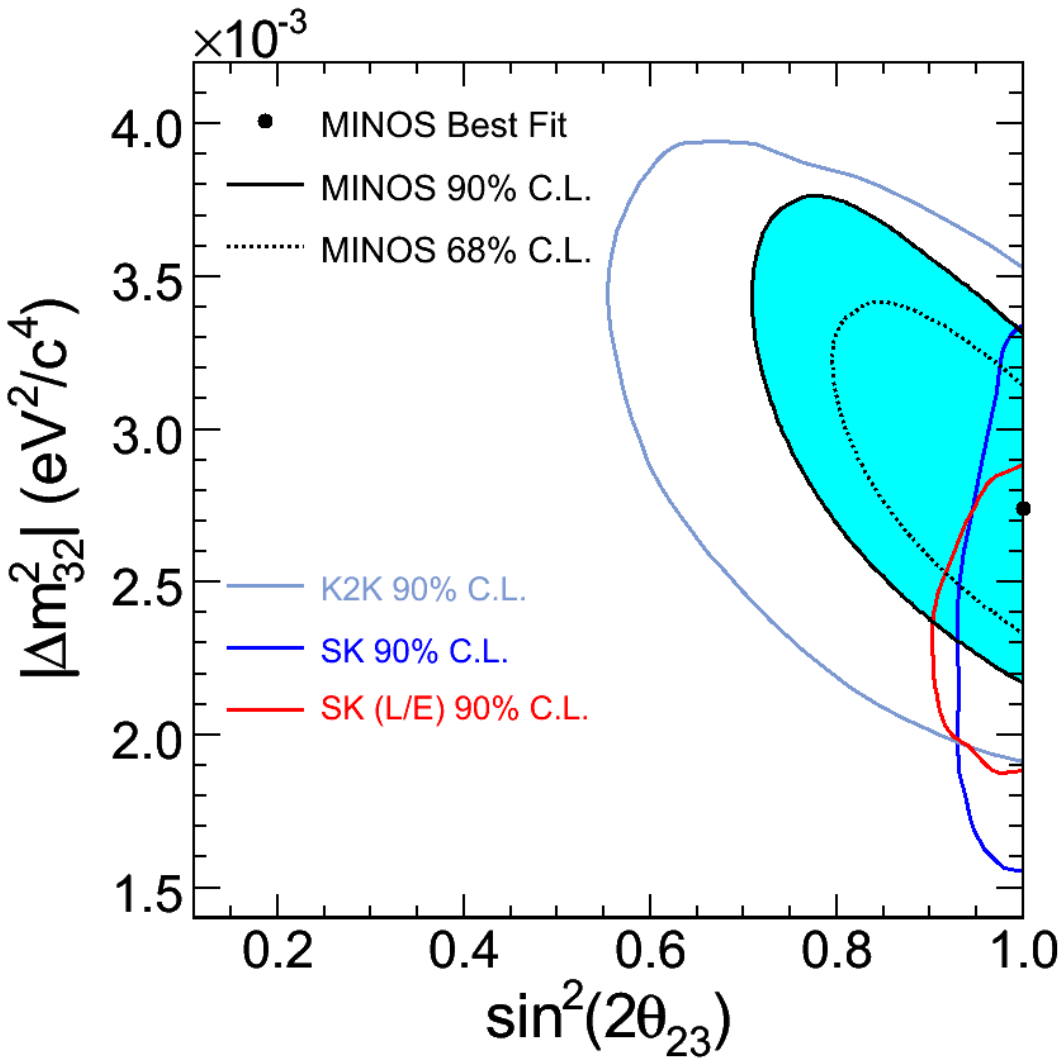
- Constraining the fit to $\sin^2(2\theta_{23}) = 1$ yields:

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



Allowed Region

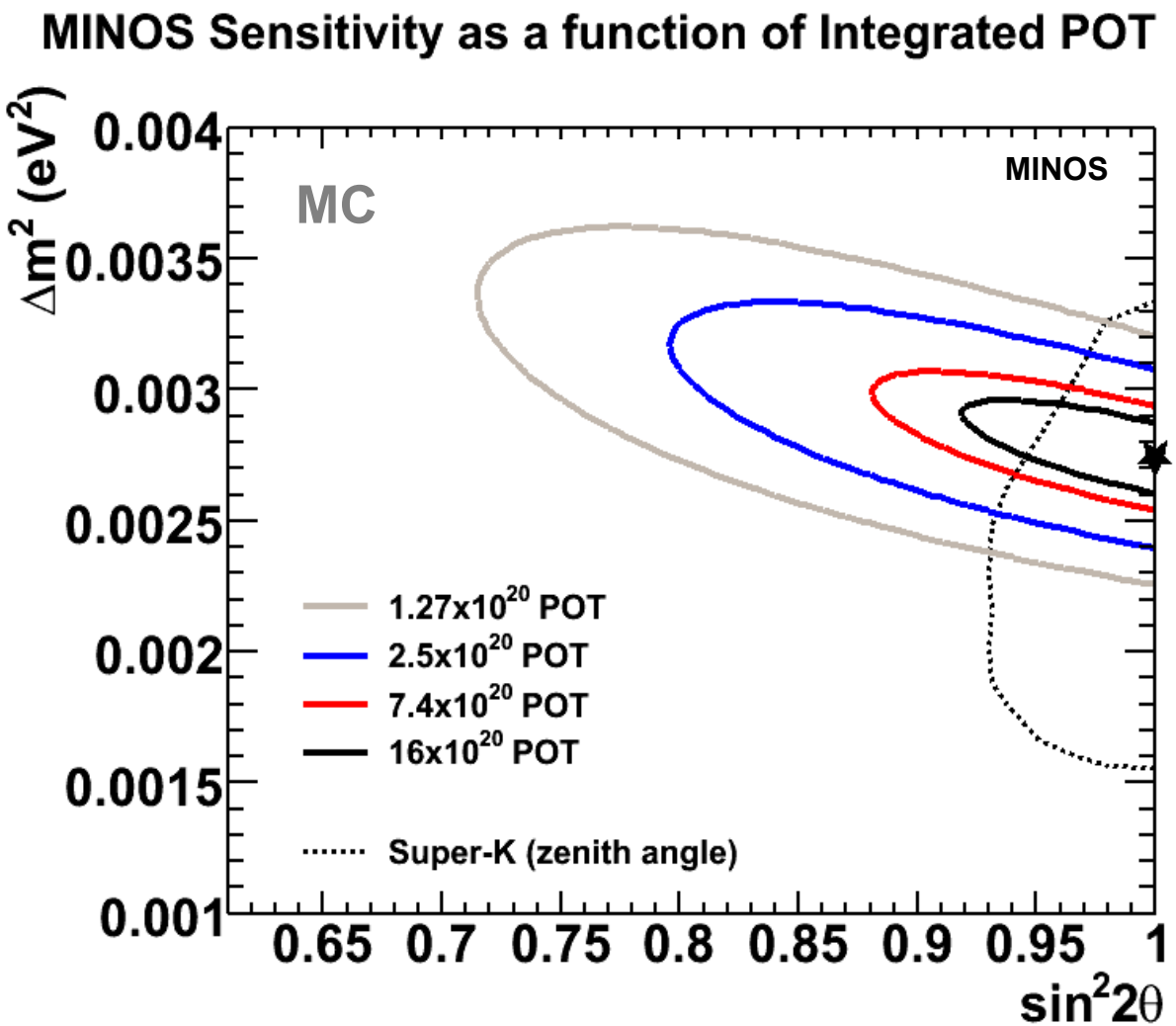
- Consistent with previous experiments
- Already competitive in measurement of $|\Delta m^2_{32}|$



- 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)

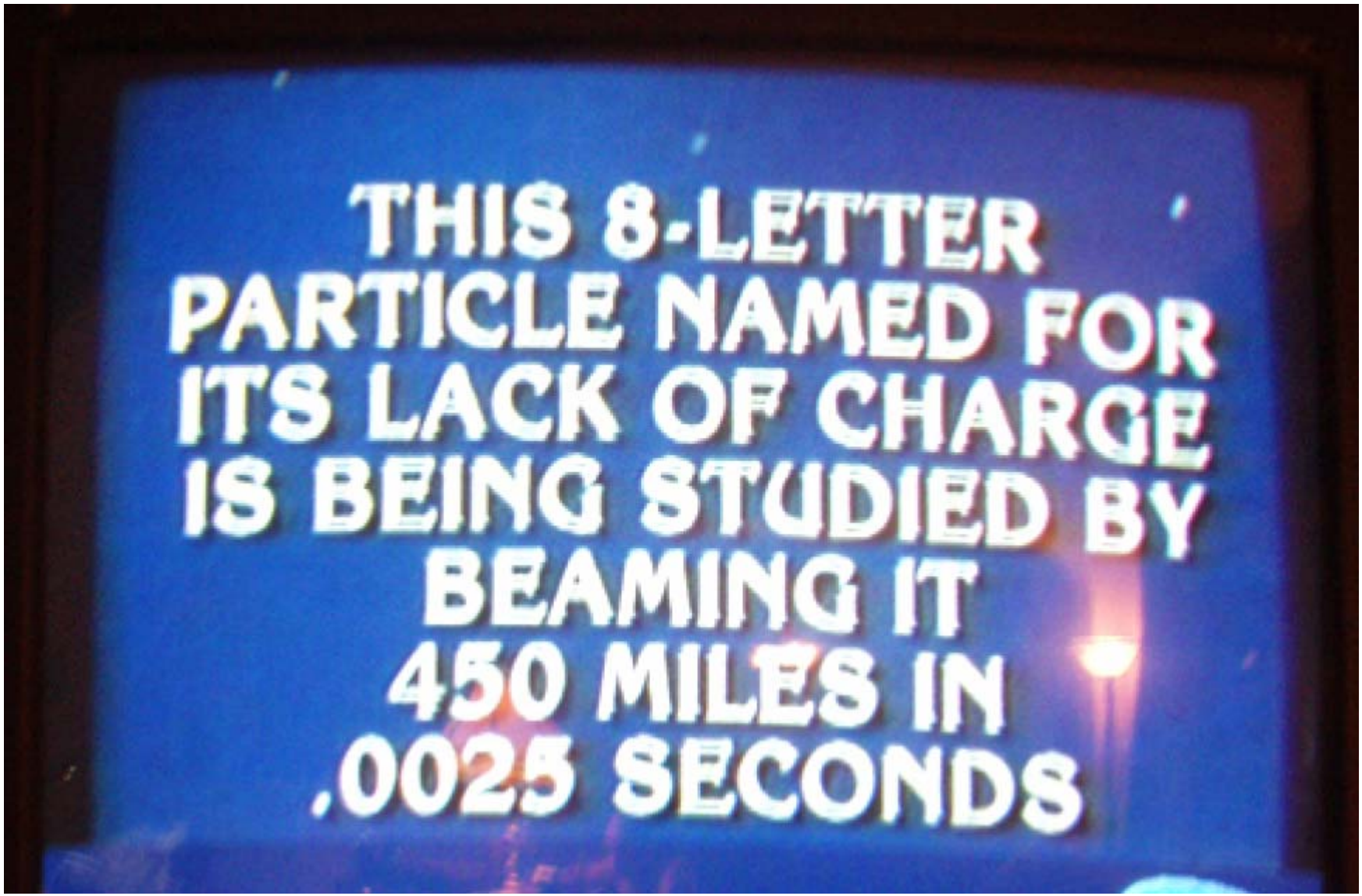
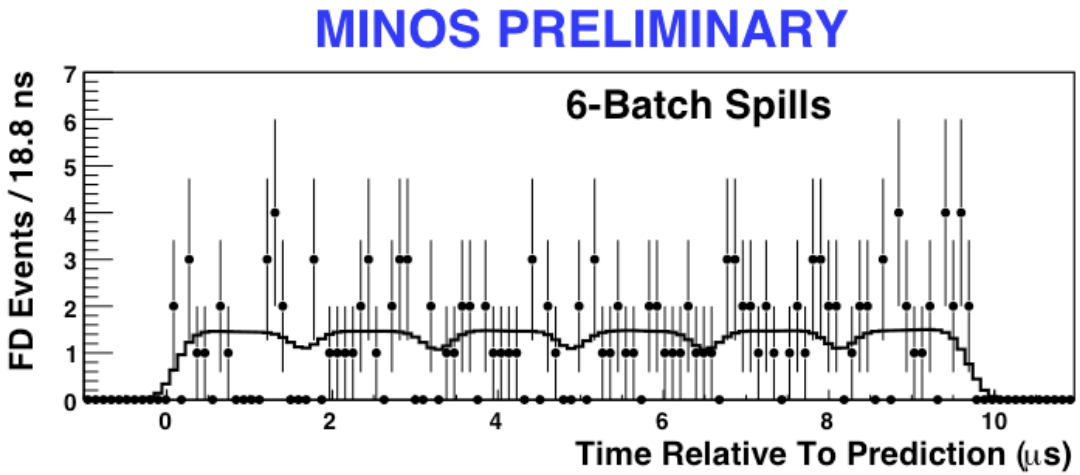


Photo by Jeff Nelson

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!)

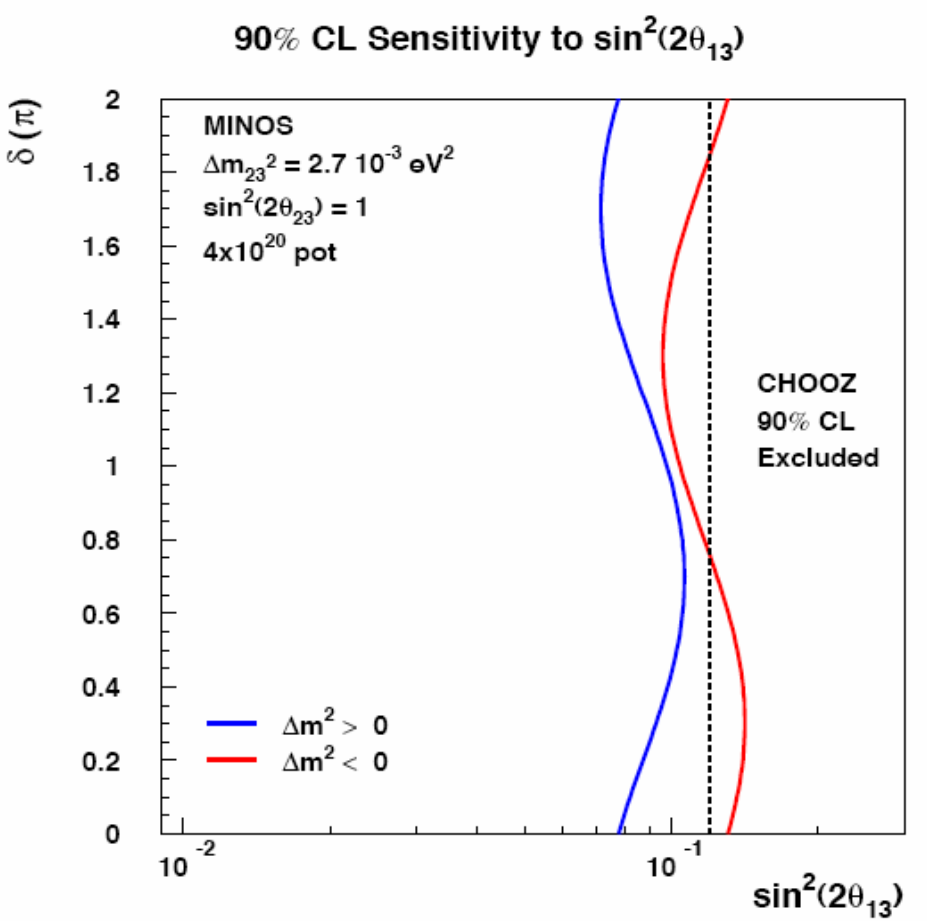
- MINOS T.O.F.:
  - 2449223 +/- 84 (stat.) +/- 164 (syst.) ns 99% C.L.
- Nominal T.O.F.:
  - 2449356 ns (@ c)
- In terms of velocity:
    - $(v-c)/c = 5.4 \pm 7.5 \times 10^{-5}$ (99% C.L.)
- Previous experiment had baseline of ~500 m with timing precision of ~ns, gave result of:
    - $|v-c|/c < 4 \times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

Search for sub-dominant neutrino oscillations

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

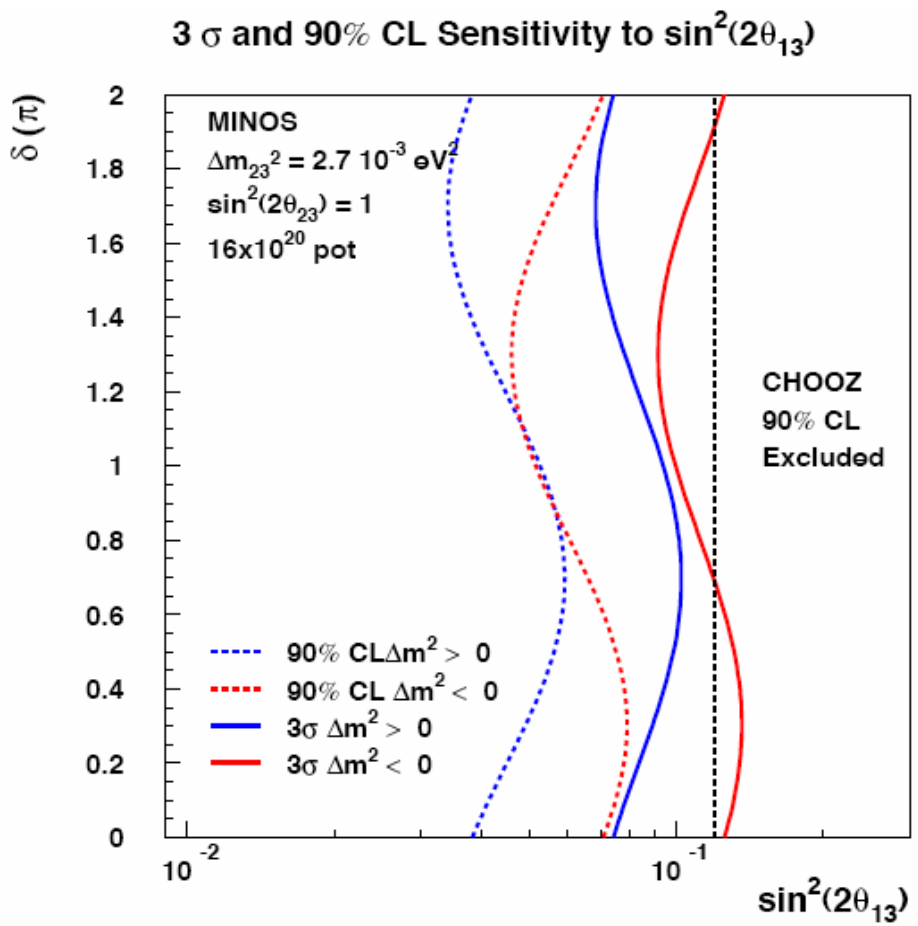
- Sub-dominant neutrino oscillations
  - Look for ν_e appearance
  - $P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$
- Look for events with compact shower and typical EM profile
  - MINOS optimised for ν_μ
  - ν_e signal selection is harder
    - 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} (4×10^{20} POT)



- Can improve on current best limit from CHOOZ
  - Matter effects can change ν_e yield by $\pm 20\%$
  - Reach depends strongly on POT
  - With 16×10^{20} POT can make significant improvements to world's best limit and increase chance of discovery!

Sensitivity to θ_{13} (16×10^{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)
  - 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:

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

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

... and MUCH MORE TO COME

Backup slides

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 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)