MINOS Results from the NuMI Beam

Geoff Pearce
Rutherford Appleton Laboratory, UK

(for the MINOS collaboration)

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Talk Overview

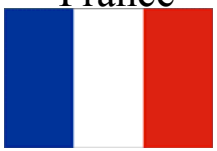
- Introduction to the MINOS experiment
  - Overview of MINOS
  - The NuMI facility
  - The MINOS detectors
- Data and event selection
  - Data taken between May 2005 – Feb 2006
  - Accumulated exposure of 1.27×10^{20} protons-on-target (POT)
    - Update on the 0.93×10^{20} exposure
- Oscillation Analysis
  - Preliminary results from the full 1.27×10^{20} POT sample

    Post Talk Update: Paper now available as hep-ex# 0607088
- Future prospects

The MINOS Collaboration

Brazil

France



U.S.A.

32 institutions
175 scientists

Greece

U.K.

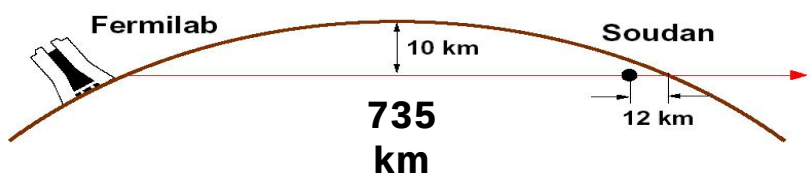
Russia

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 experiment - Overview

Main Injector Neutrino Oscillation Search

- long-baseline neutrino oscillation experiment:
- High power ν_μ beam generated at Fermilab & pointed at Soudan
- A near detector at Fermilab samples the generated neutrino beam
- A far detector in the Soudan Mine samples the neutrino beam after 735km flight
- Compare measurements near & far → oscillations



MINOS experiment: Physics Goals

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis and measure Δm_{32}^2 and $\sin^2 2\theta_{23}$ by ν_μ disappearance *
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for/constrain exotic phenomena
  - Sterile ν, ν decay
- Compare ν, $\bar{\nu}$ oscillations
  - Test of CPT
- High statistics studies of neutrino-nucleus interactions
- Atmospheric neutrino oscillation studies

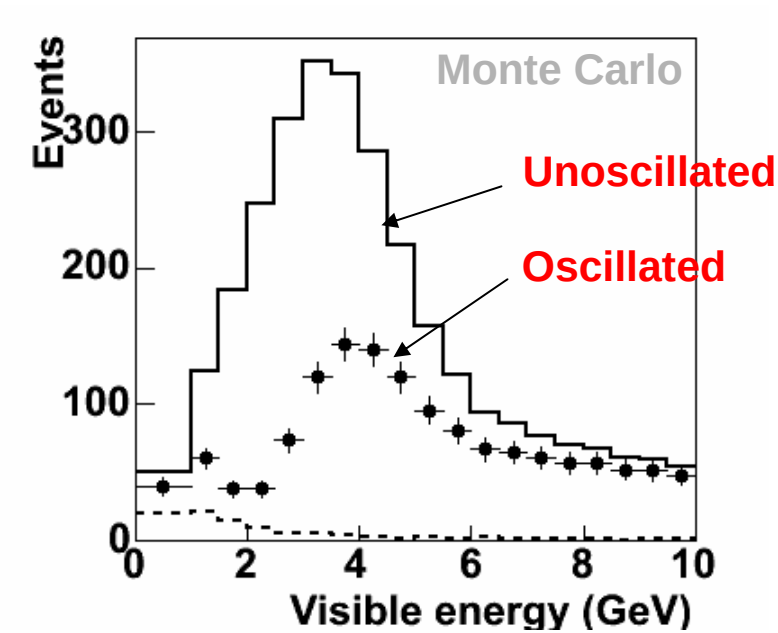
  Phys. Rev. D73, 072002 (2006)

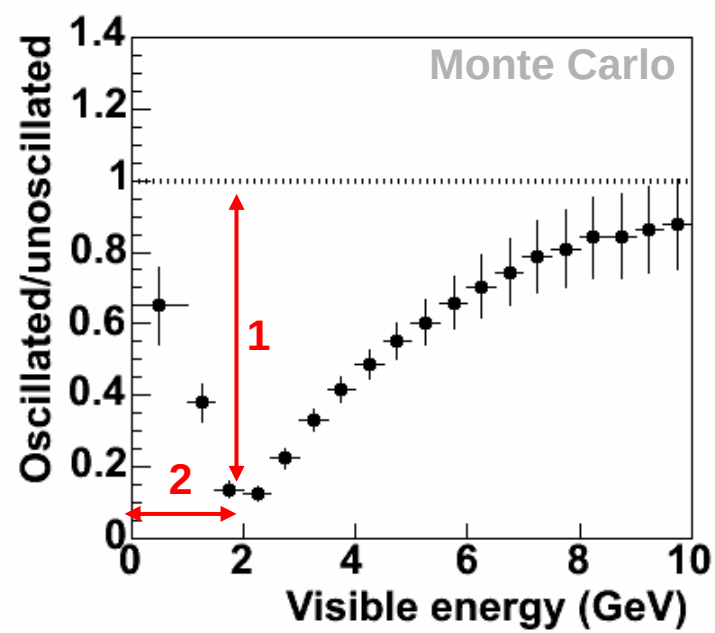
MINOS CC disappearance

Illustration of ν_μ disappearance method

- Predict unoscillated CC spectrum at far detector
  - extrapolate near detector measurement using MC corrections
- Compare with measured spectrum - make oscillation measurement

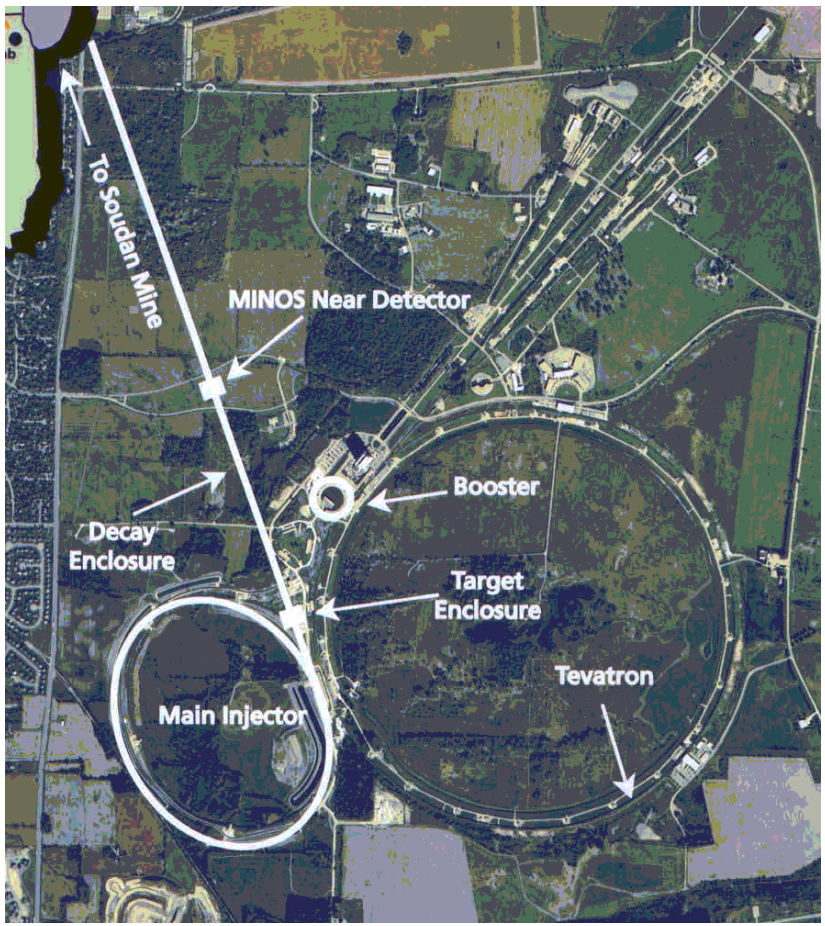
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L/E)$$





The NuMI Facility

New neutrino beam line at Fermilab



Design Parameters

- 120 GeV protons from the Main Injector
- Single turn extraction - 10μs spill
- 1.867 second cycle time
- 4×10^{13} protons/spill
- 400 KW
- Tunable neutrino energy spectrum

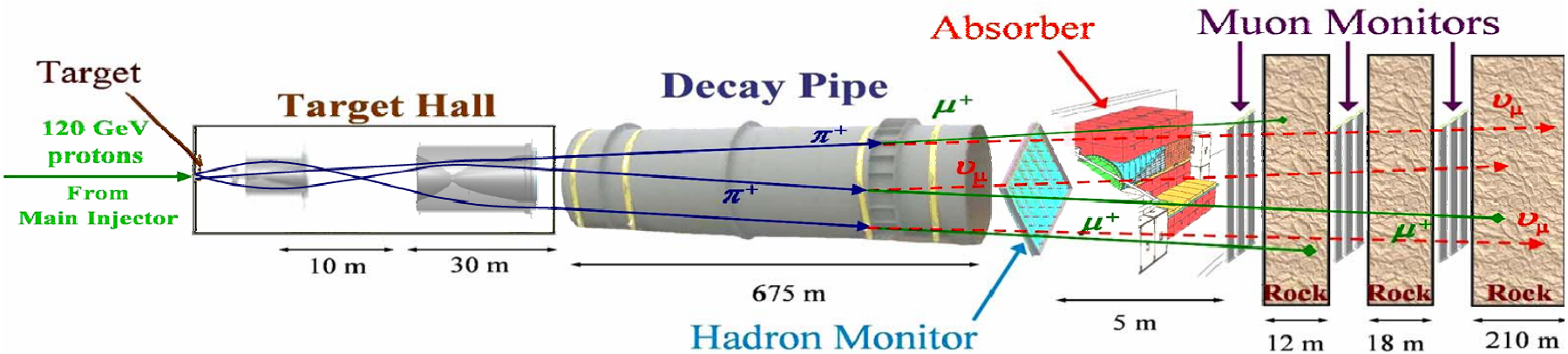
Performance

Averages for period Oct 15-Jan31

- 170kW
- 2.3×10^{13} protons/spill
- 2.2sec cycle

The Neutrino Beam Line

Schematic



Target

- segmented graphite, water cooled
- 954mm long; 47 20mm segments
- Movable: can be positioned up to 2.5m upstream of horn to tune beam energy

Parabolic horns

- Pulsed at up to 200kA; 3T peak field
- Focus π's into decay tunnel

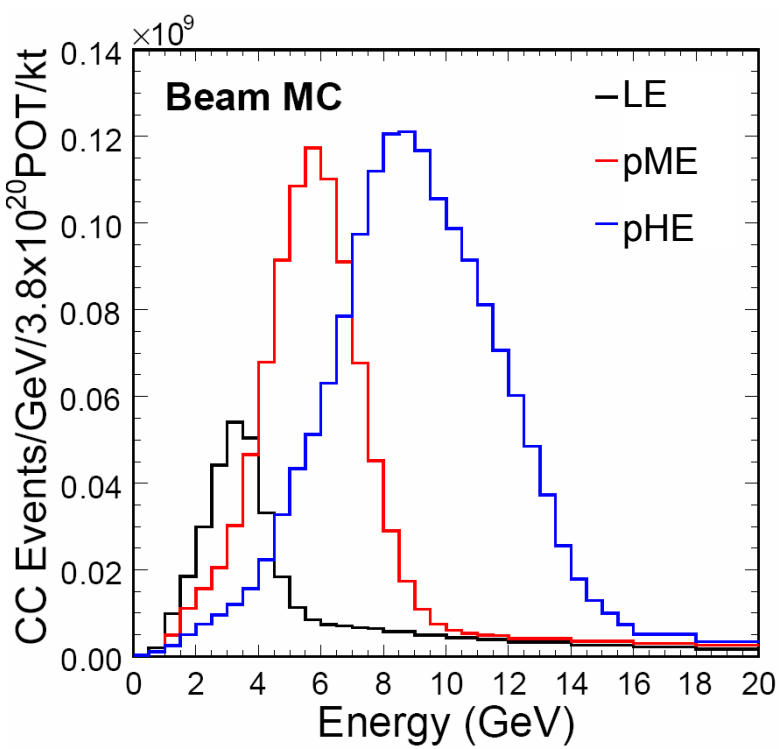
Neutrinos for MINOS

By moving the target we can choose our neutrino spectrum

Majority of data (~95%) taken in low energy configuration (LE-10)

High purity beam: 92.9% ν_μ , 5.8% $\bar{\nu}_\mu$, 1.3% $\nu_e + \bar{\nu}_e$

Data taken in 5 other beam configurations for systematics studies



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

MINOS Detector Technology

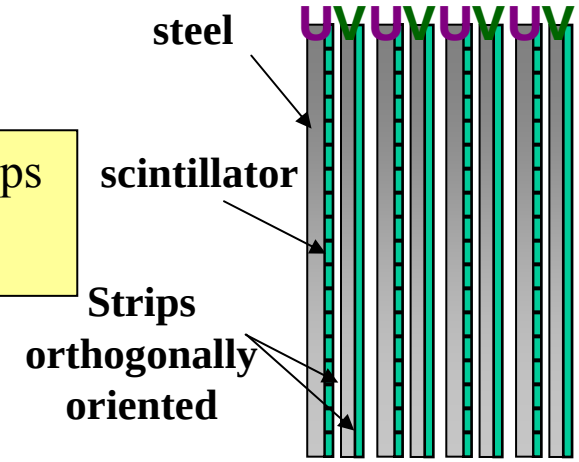
Magnetised tracking calorimeters

near and far detectors are functionally identical

share same basic detector technology and granularity

4.1x1 cm extruded scintillator strips

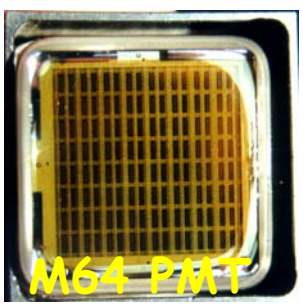
Light collection with WLS fibres

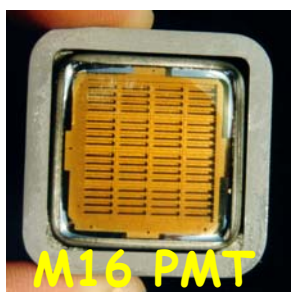


Strips assembled in modules

Mounted on 2.54cm thick magnetised steel plates

Orthogonal orientation on alternate planes (U,V)





Optical readout using multi-anode PMTs

The MINOS Detectors

Near Detector

Site: Fermilab, 1km from target

1kton mass

282 steel planes, 153 scintillator planes, 3.8 x 4.8 x 15m^3

QIE electronics : continuous (19ns) sampling in spill

Data GPS time-stamped to synchronise FD-ND-Beam

Software triggering performed in DAQ PCs

Far Detector

Site: Soudan, Minnesota, 735km from target

5.4kton mass

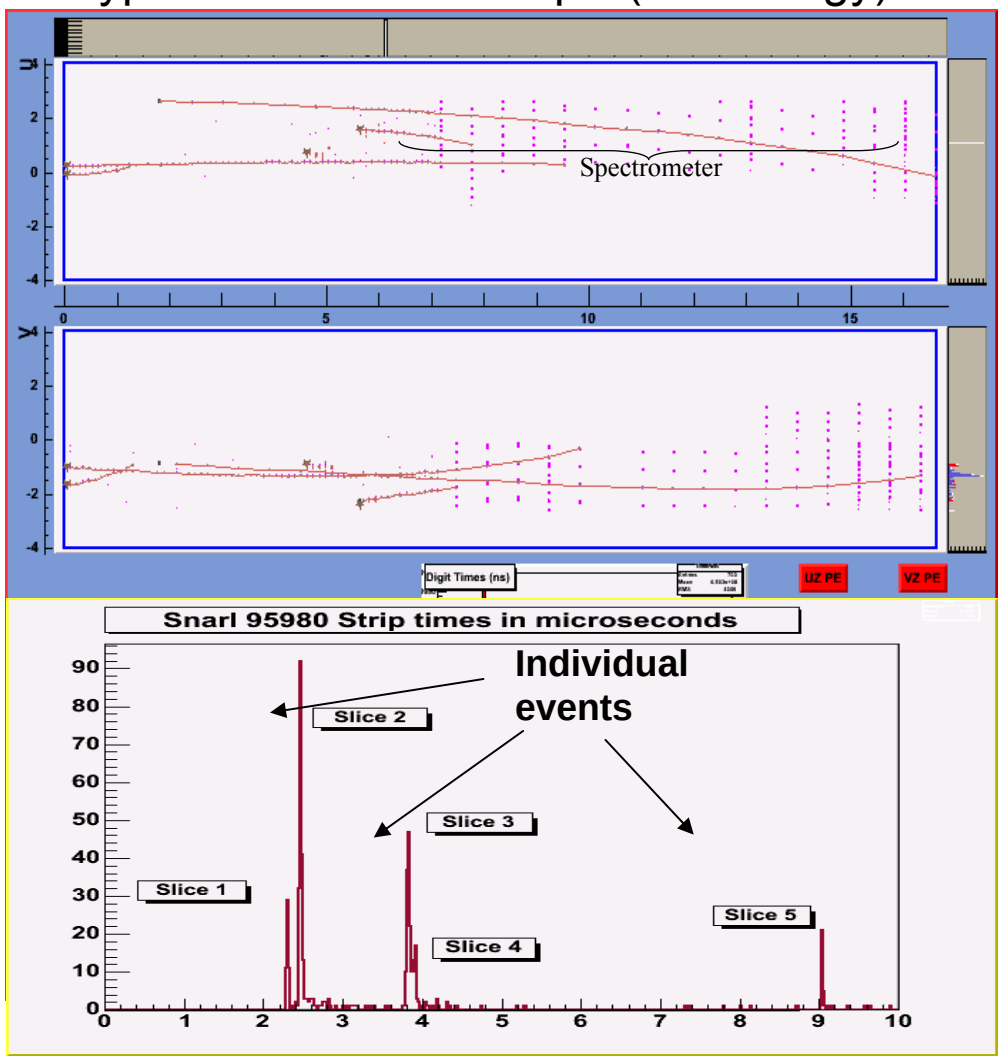
484 steel/scintillator planes, 8 x 8 x 30 m^3

Spill times sent from Fermilab for beam trigger

Event Selection

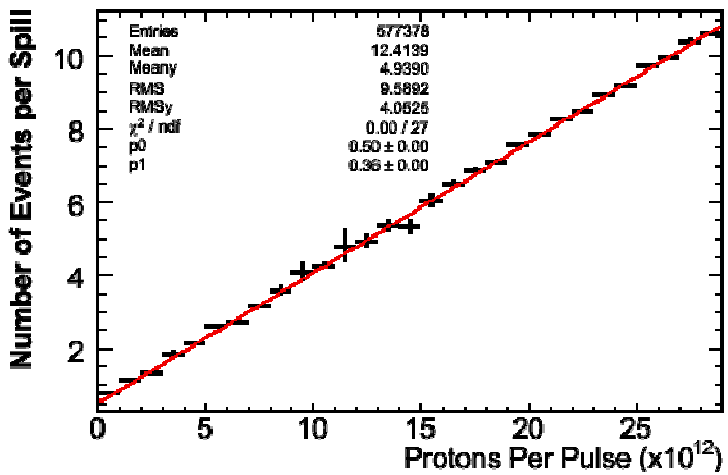
Near Detector Beam Events

Typical near detector spill (low energy)



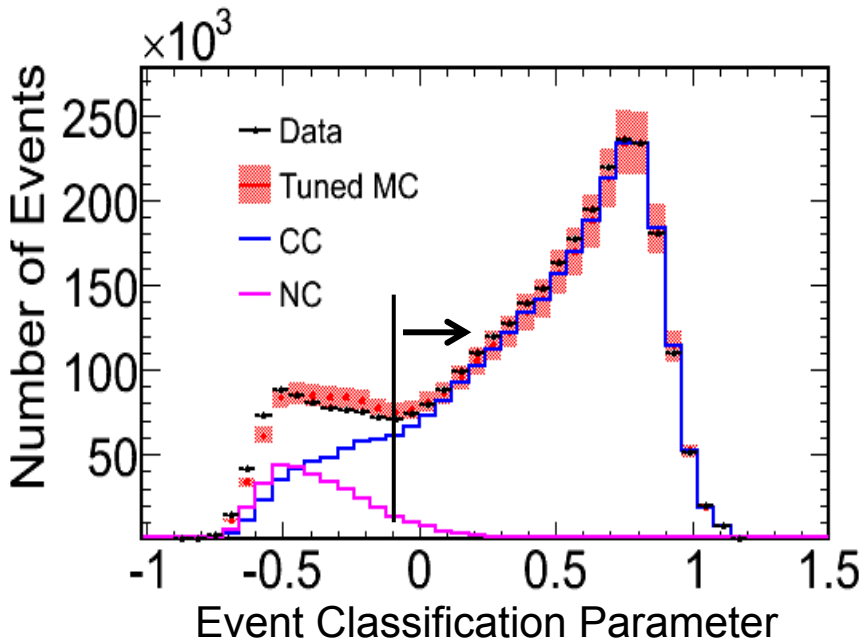
- Near detector has a high event rate
  - over 10^7 events in fiducial volume
- Multiple interactions per spill
  - separated by topology and timing
  - linear with intensity

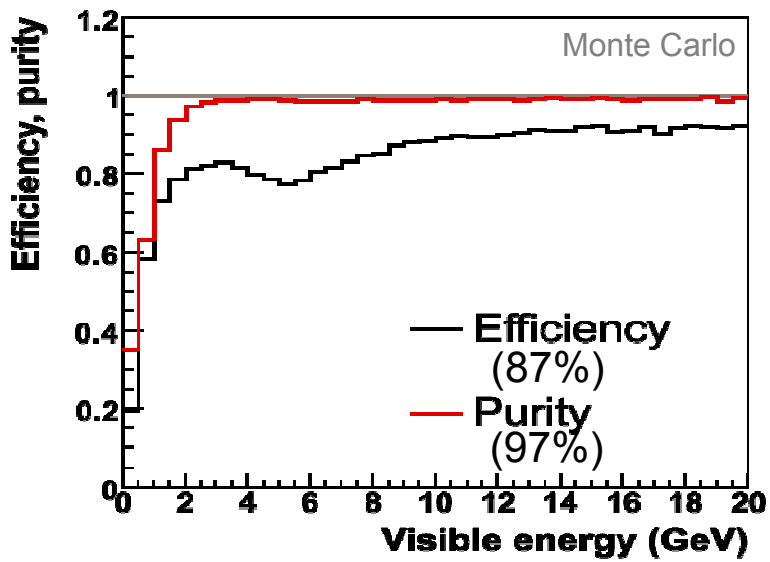
Number of events vs intensity



Charged Current event selection

- At least one good reconstructed track with –ve charge
- Vertex is within fiducial volume
- CC-like events are selected using a likelihood procedure
  - Combine probability density functions (PDF) for 3 low level variables
    - Event length, track pulse height, pulse height/plane
  - 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



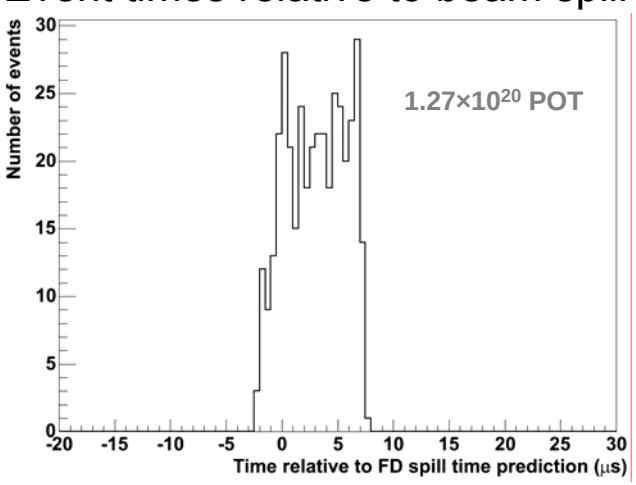


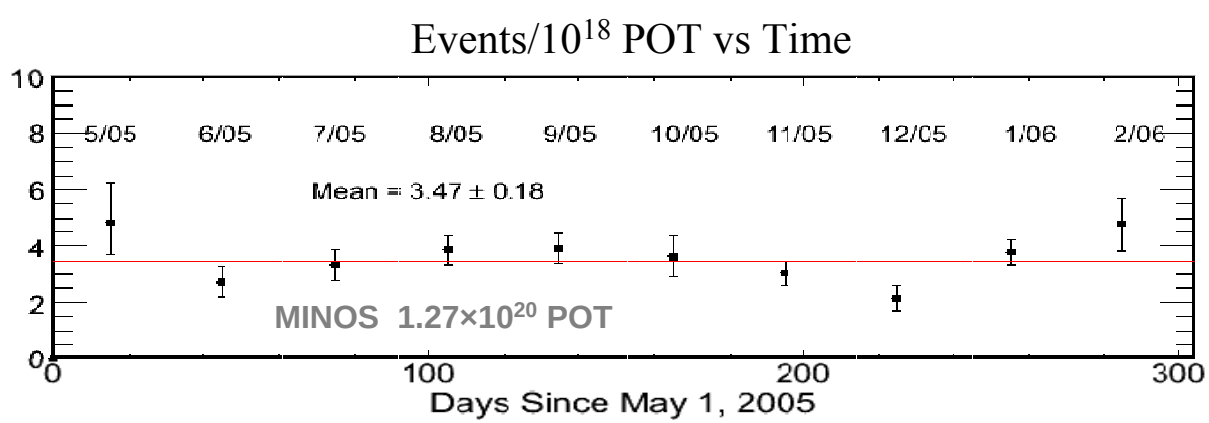
Far Detector Data

Selecting Beam Events

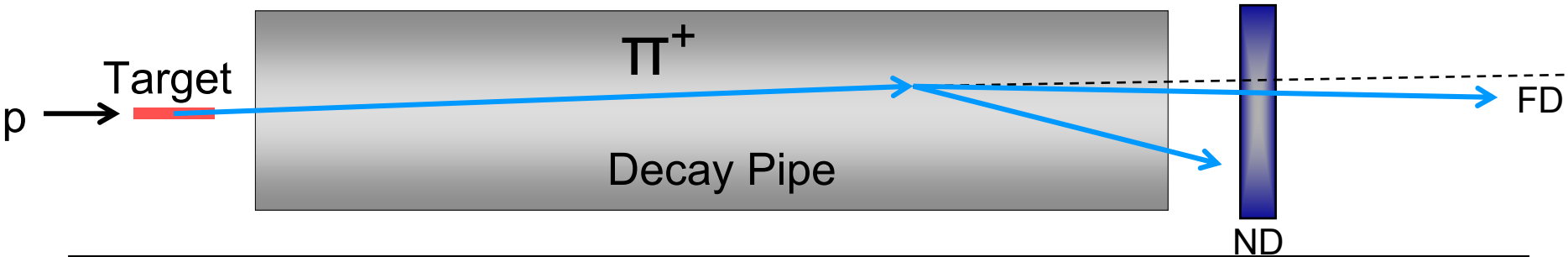
- Blind analysis – hide fraction of FD data as a function of event length & energy
  - "open" data used to check FD data quality; box opened when analysis procedures defined
- FD neutrino events have distinctive topology
  - They point to Fermilab - easily separated from cosmics with 53º cut around beam axis
- Timing
  - FD DAQ spill trigger reads out 100μs of activity around (10μs) beam spills
- Event times consistent with spill times; event rate shows no time dependence
- Backgrounds estimated using fake spill triggers
  - In 2.6M fake spill triggers, NO events survived the event selection cuts
  - Upper limit of 0.5 events

Event times relative to beam spill (μs)





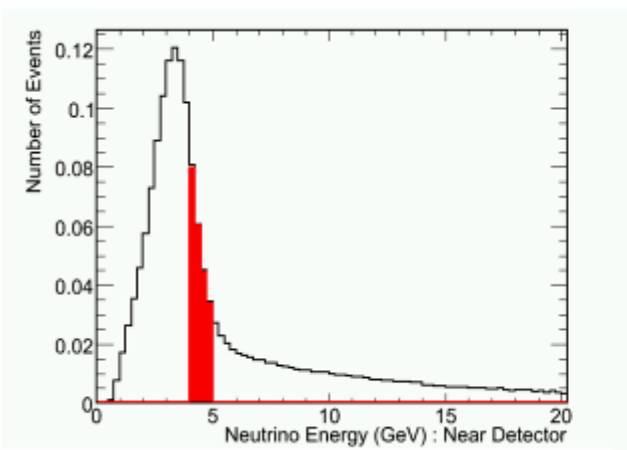
Predicting the unoscillated FD spectrum

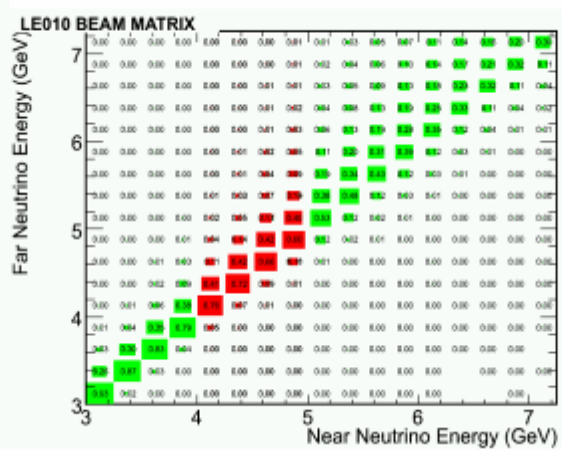


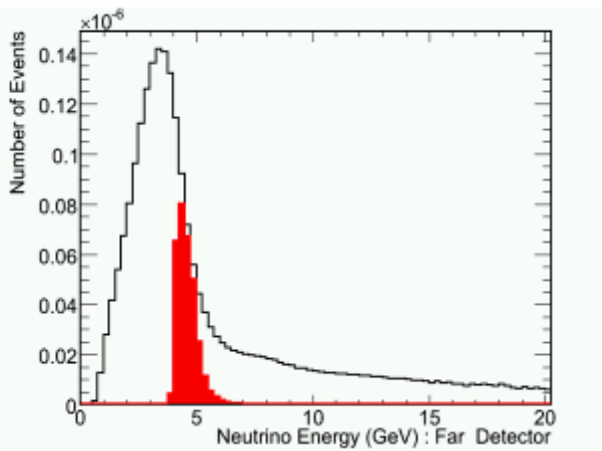
Start with near detector data & extrapolate to the far detector

- Measure beam spectrum in the ND - use MC to provide corrections for energy smearing and acceptance
- Beam MC encodes pion decay kinematics & beamline geometry : construct a beam transport matrix to transform the ND spectrum into the FD energy spectrum
- Apply detector MC corrections to provided predicted observed FD spectrum

This is the primary method used in our analysis







Different methods of predicting the FD spectrum

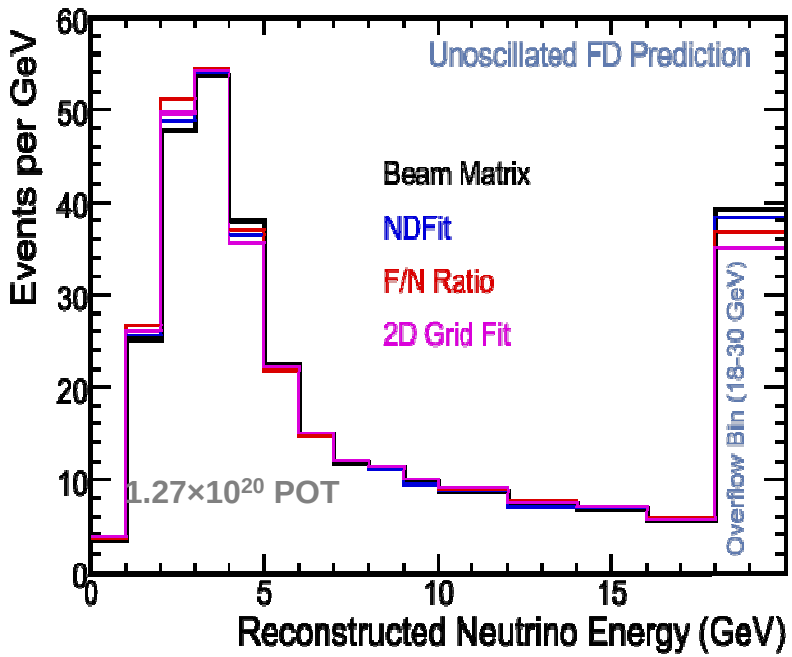
3 other extrapolation methods investigated

ND fit methods

- Fit ND MC prediction to ND observed spectrum
  - **1D fit to E_ν distribution**
  - **2D fit to (E_ν, y) grid**
- Use these fits to re-weight the FD MC

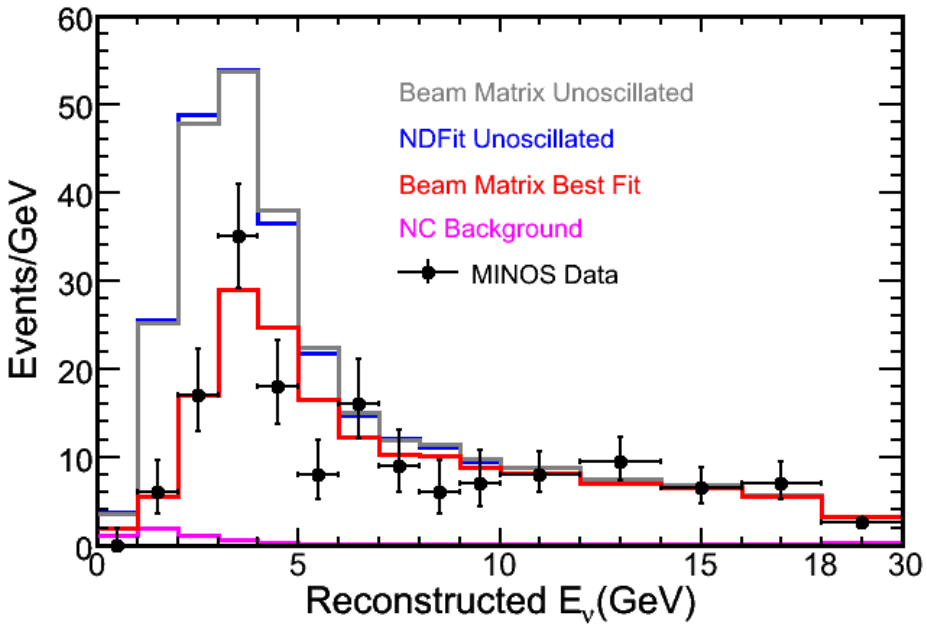
ND data extrapolation methods

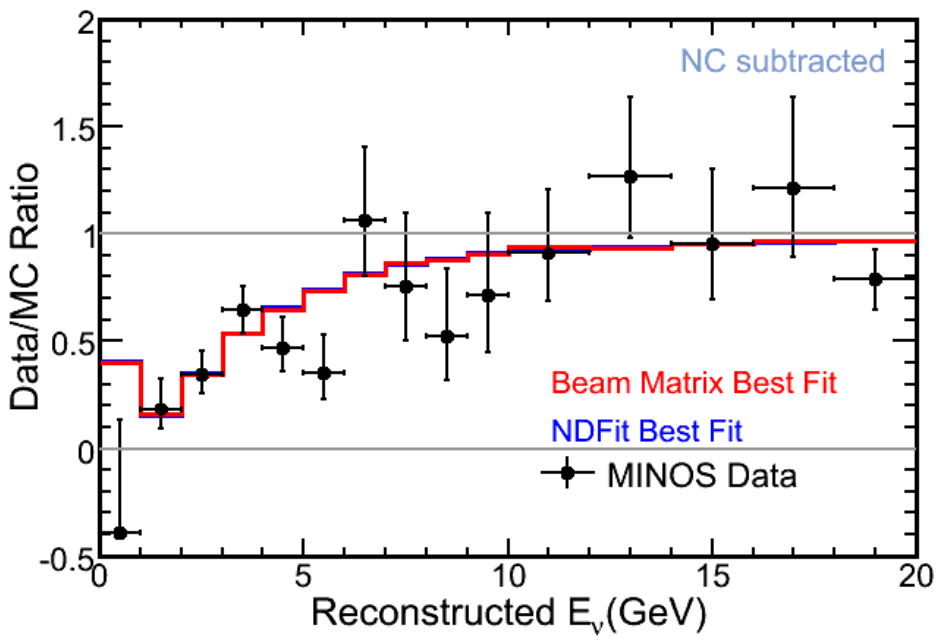
- Beam Matrix method (prev. slide)
- Extrapolate using Far/Near spectrum ratio
  - Events in each ND energy bin scaled via MC into a number of FD events in the same bin



The methods are robust to different categories of systematics and give consistent predictions

MINOS best-fit spectrum for 1.27×10^{20} POT





49% deficit below 10GeV : 6.2σ significance

Fit made to oscillation hypothesis yields:

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

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

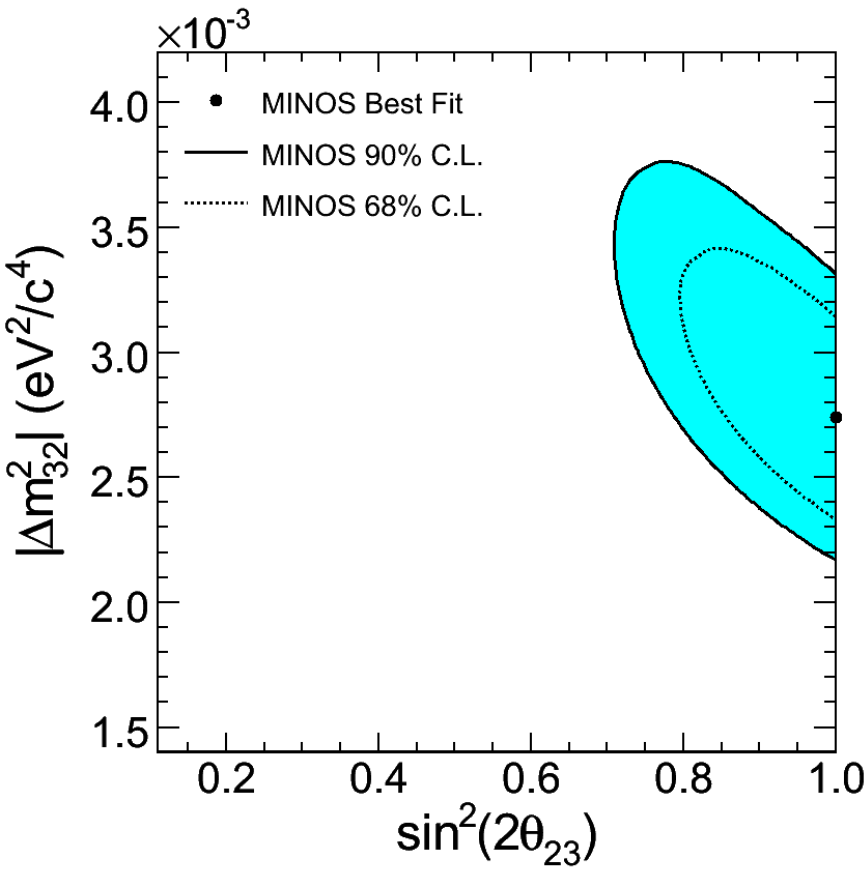
Normalization = 0.98

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	0.05
All other systematic uncertainties *(μ momentum, CC xsects, ND/FD energy calibration, reconstruction, remaining beam uncertainties)*	0.044	0.011
Total Systematic (summed in quadrature)	0.12	0.07
Statistical Error (data)	0.36	0.12

- Main uncertainties included as nuisance parameters in fit
- Many systematic uncertainties are data driven
  - improve with more data and further study

Allowed Region

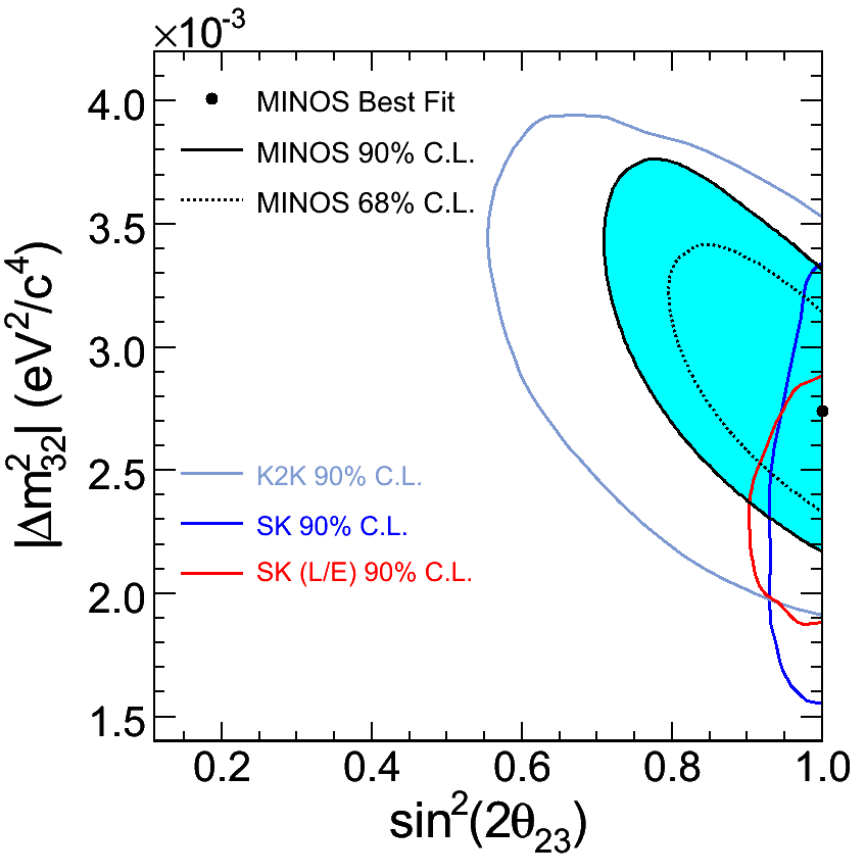


$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\,(\text{stat} + \text{syst}) \times 10^{-3}\,\text{eV}^2$$

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

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

Allowed Region



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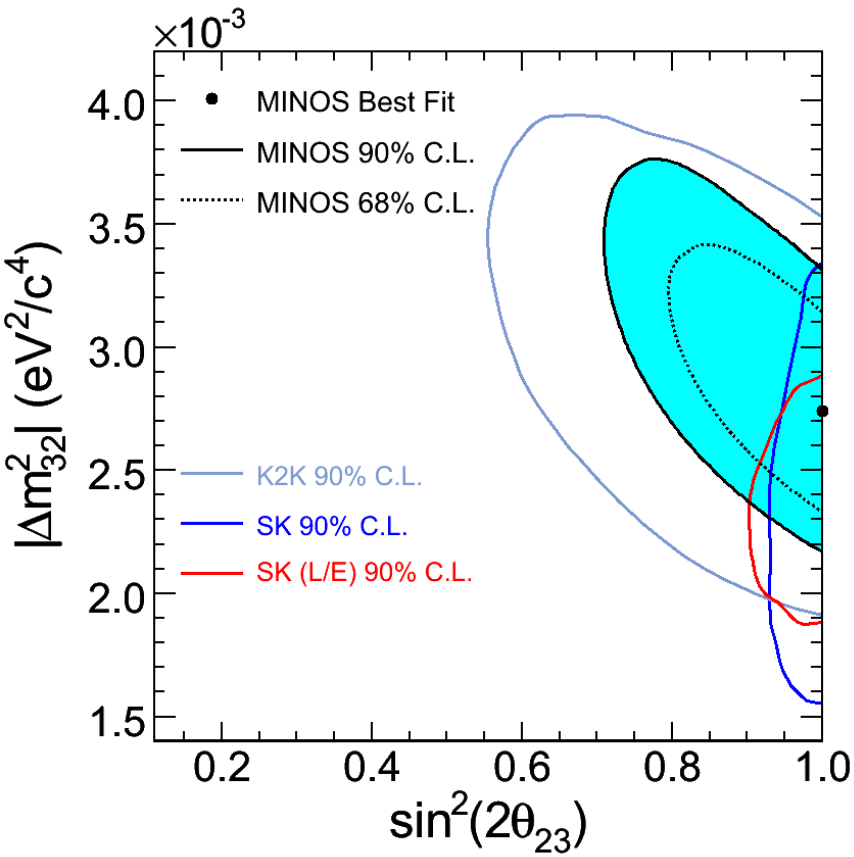
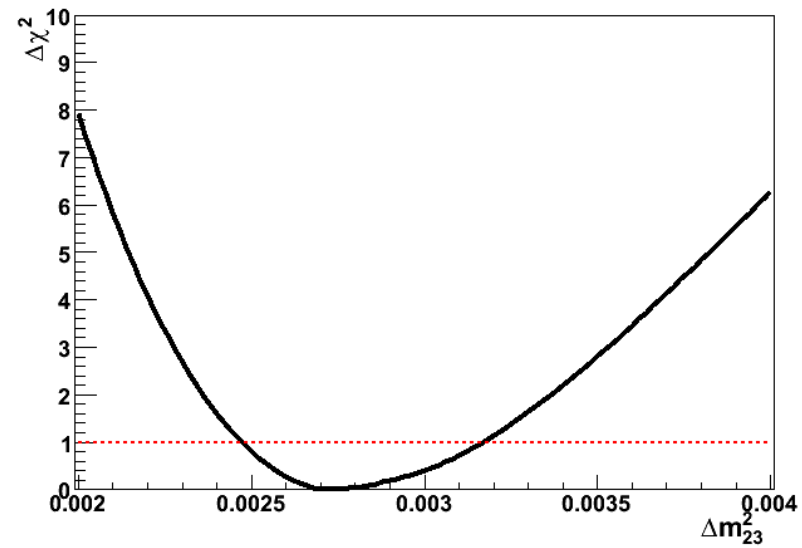




When fit is constrained to $\sin^2 2\theta = 1$

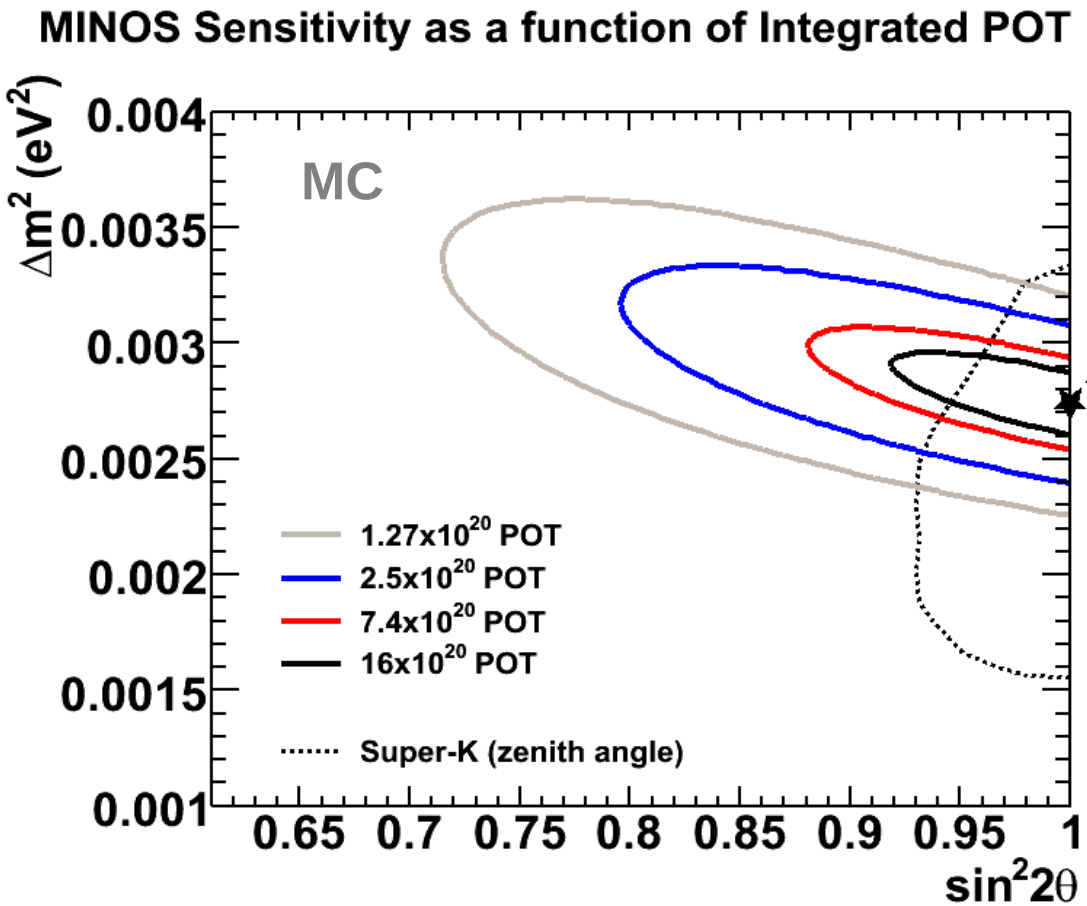
$$\left|\Delta m^2_{32}\right| = 2.74 \pm 0.28\,(\text{stat}) \times 10^{-3}\,\text{eV}^2$$

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

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

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

Projected sensitivity of MINOS



Input parameters

$$\left|\Delta m^2_{32}\right| = 2.74 \times 10^{-3}\,\mathrm{eV}^2$$

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

90% contours

Statistical errors only

Summary and Conclusions

- MINOS has completed an analysis of the first years beam exposure
  - Our exposure to date is 1.27×10^{20} pot
  - We exclude no oscillations at 6.2σ
  - Our results are consistent with the oscillation hypothesis with:

$$\left|\Delta m^2_{32}\right| = (2.74^{+0.44}_{-0.26})\times10^{-3}\,\mathrm{eV}^2$$
$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

- The systematic uncertainties are under control
  - Significant improvements with a substantially larger dataset
- The second run is currently under way
- Other oscillation analyses under way
  - Search for $\nu_\mu \rightarrow \nu_e$ oscillation
  - Search for sterile neutrinos
  - Anti neutrino oscillations