MINOS Results from the First Year of NuMI Beam Operation

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(for the MINOS Collaboration)

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June 17th, 2006

The MINOS Experiment

A large detector at Soudan

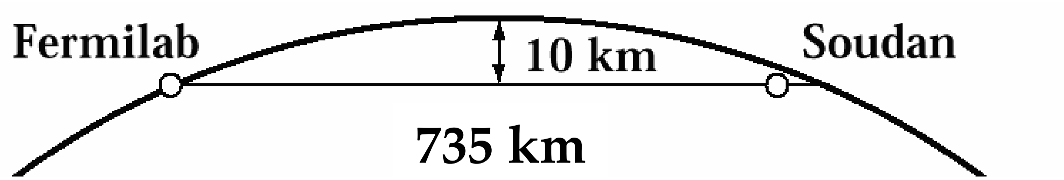
- The "far detector" or FD

A smaller detector at Fermilab

- The "near detector" or ND

Measure the beam and neutrino energy spectrum near the source

- See how it differs far away



Talk Outline

- > Introduction to MINOS
- > Detector and beam performance and modeling
- > Oscillation Analysis
- > Future prospects

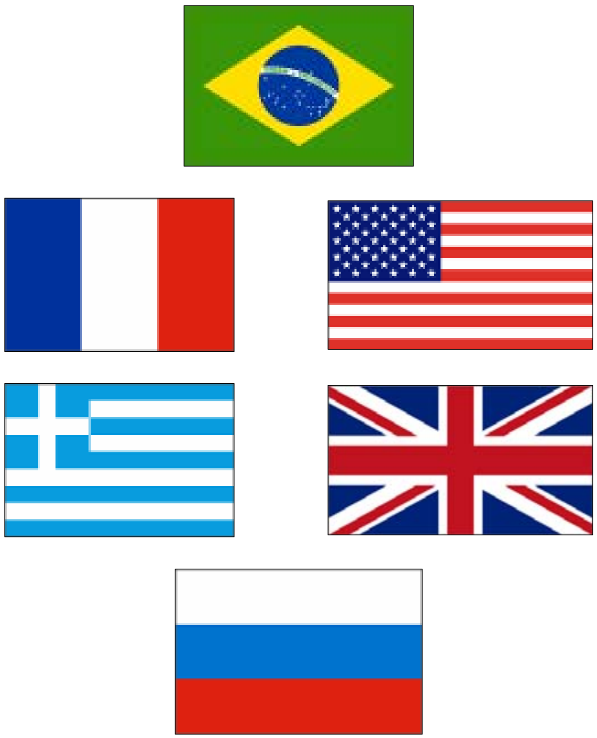
MINOS has been collecting data with the NuMI beam since 3/05

- > Data from 1.27×10^{20} protons on target (POT) was accumulated under nominal beam conditions
- > Previous MINOS results from 0.93×10^{20} POT

We report for the first time preliminary results from the full 1.27×10^{20} POT sample

- > These results supersede our previously reported results

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

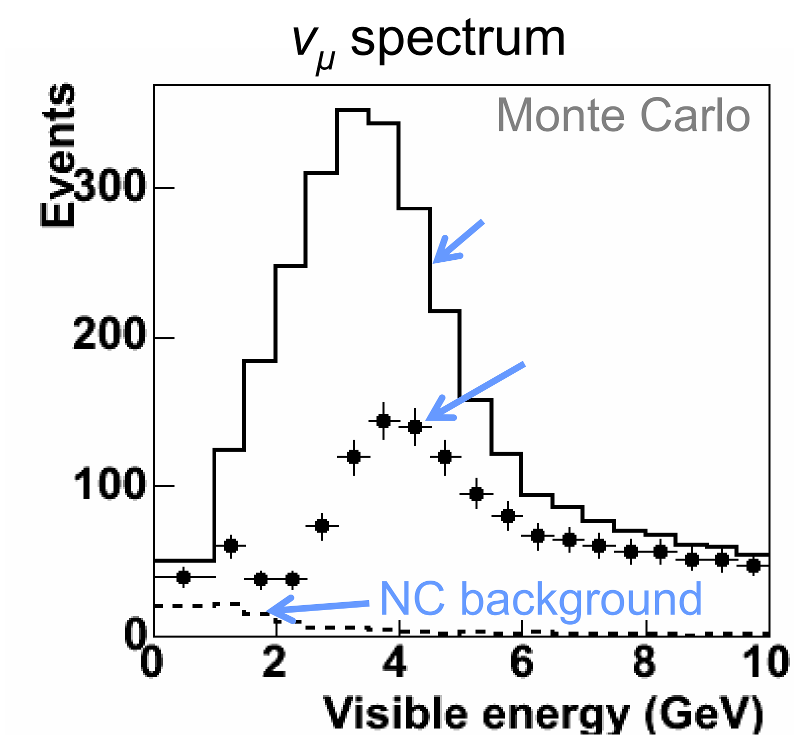
MINOS physics goals

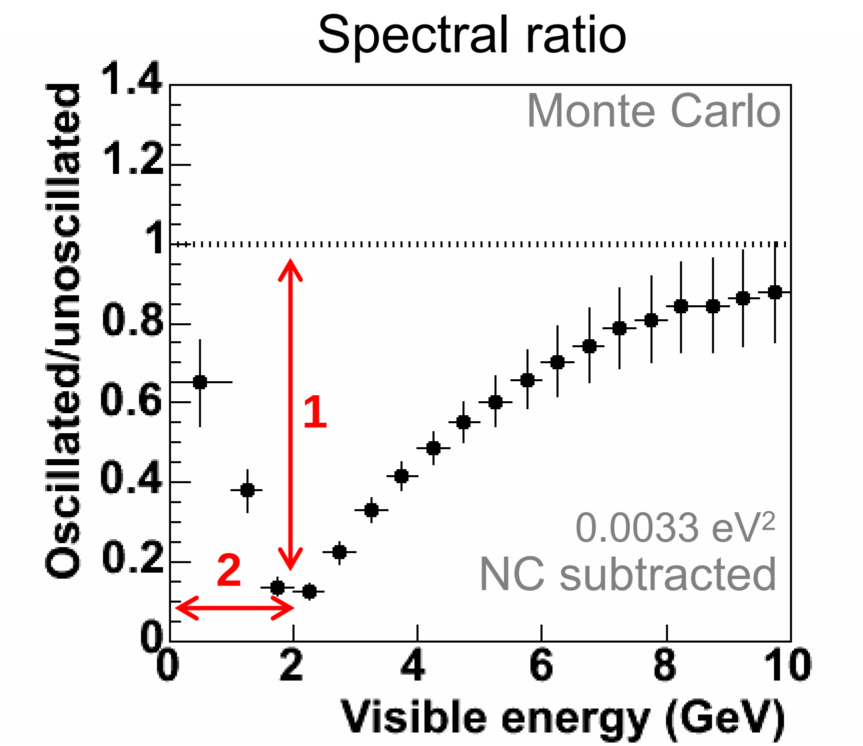
- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - > Precisely measure oscillation parameters $\Delta m^2_{32} = m^2_3 - m^2_2$ and $\sin^2 2\theta_{23}$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ transitions
- High statistics studies of neutrino-nucleus interactions
- Search for/constrain exotic phenomena
- Atmospheric neutrino oscillations
  - > First physics paper Phys. Rev. D73, 072002 (2006)

Example of a disappearance measurement

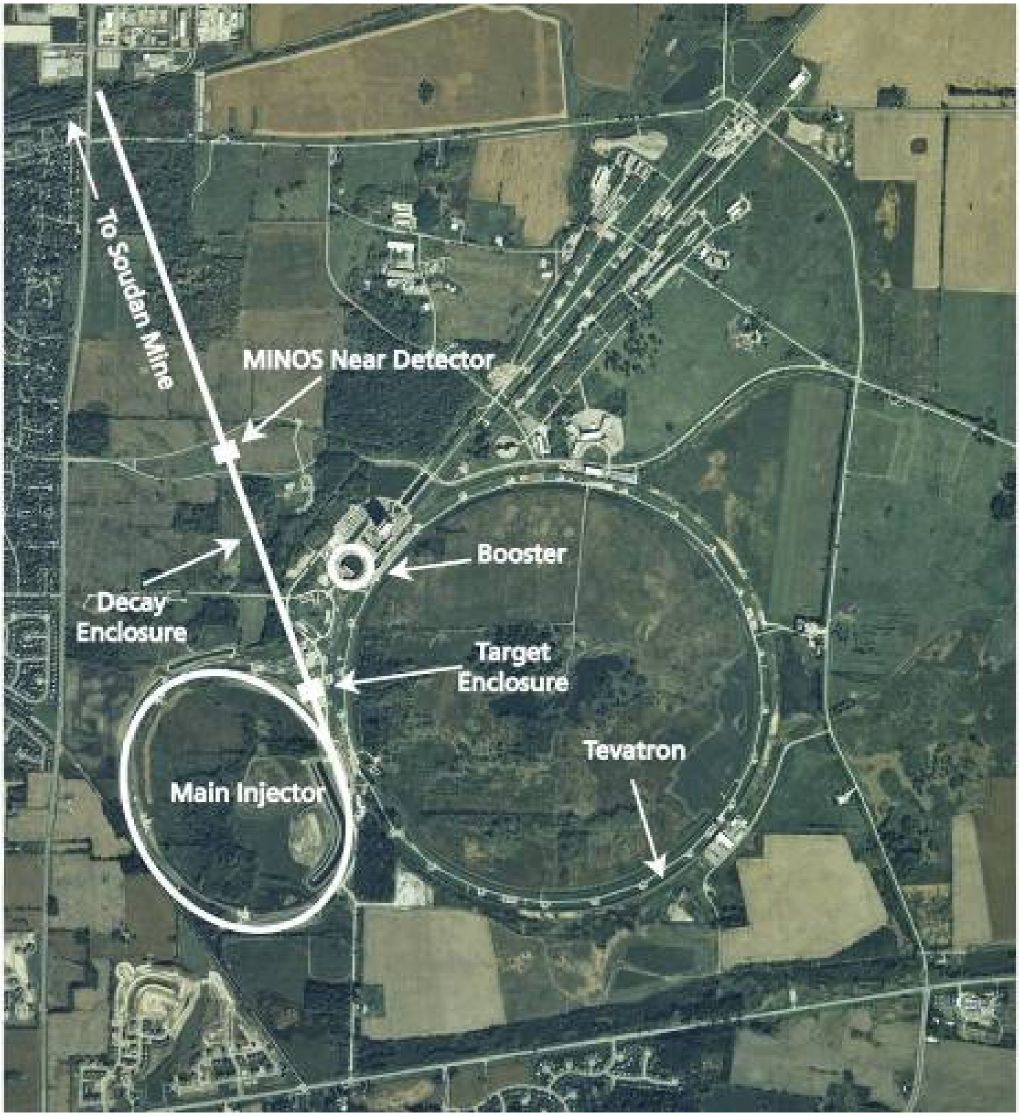
Look for a deficit of ν_μ events at a distance…

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





The NuMI beam at Fermilab



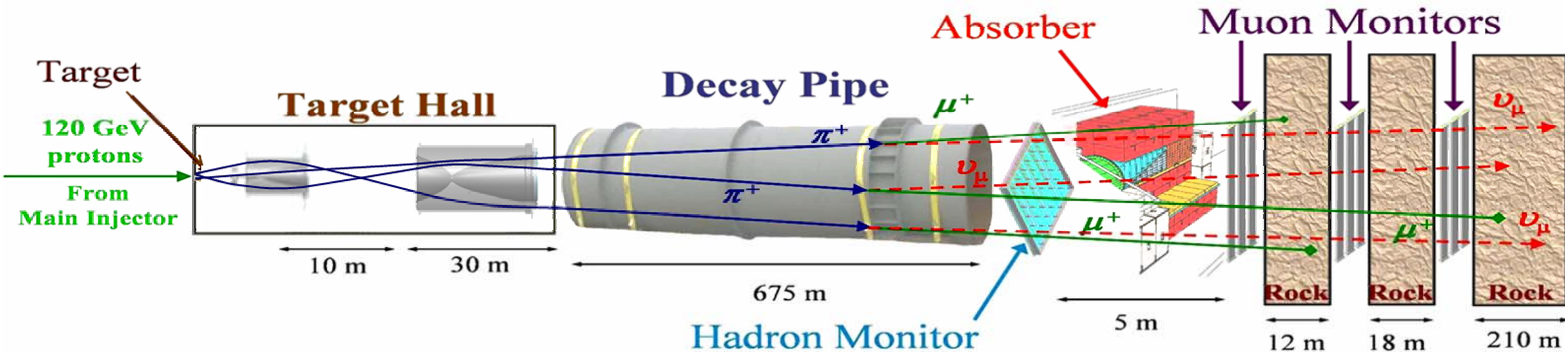
Design parameters

- 120 GeV protons from the Main Injector
- Main Injector can accept up to 6 booster batches per cycle
- 1.87s minimum cycle time
- 4×10^{13} protons/pulse
- 0.4 MW
- 10μs extraction

Averages from 10/05 to 1/06

- 170 kW
- 2.3×10^{13} protons/pulse
- 2.2 s cycle

The NuMI beamline



Water-cooled segmented graphite target

- 47 2.0 cm segments; total length of 95.4 cm

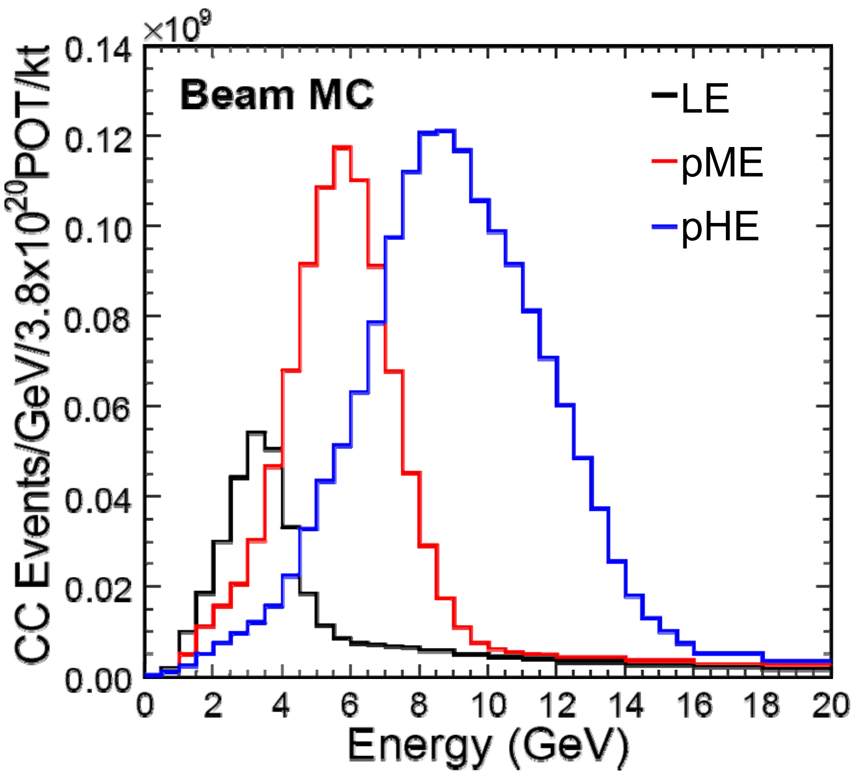
2 parabolic horns carrying

- Up to 200 kA current provides up to 3T fields
- Target can be positioned up to 2.5m upstream of the first horn to change beam energy

The NuMI neutrino beam

Majority of running in the LE-10 configuration

- Beam composition: 98.7% $\nu_\mu+\overline{\nu}_\mu$ (5.8% $\overline{\nu}_\mu$), 1.3% $\nu_e+\overline{\nu}_e$
- Collected data in 5 other beam configurations for systematics studies (roughly 5% of the total exposure)

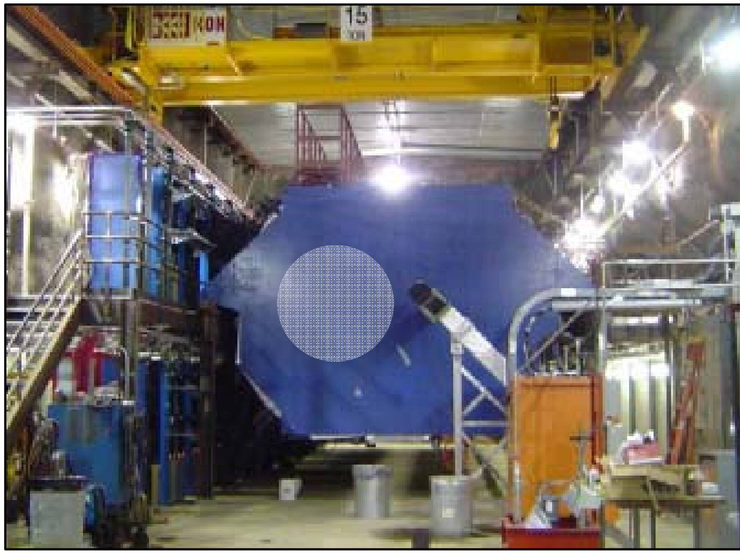


Expected events in Far Detector (no osc.)

Beam	Target - Horn Separation (cm)	FD Events per 10^{20} POT*
LE-10	-10	390
pME	-100	970
pHE	-250	1340

* Events in fiducial volume

MINOS Detectors



Near Detector

1 kton

$3.8 \times 4.8 \times 15\ m^3$

282 steel planes

153 scintillator planes

Iron and Scintillator tracking calorimeters

2.54 cm thick magnetized steel planes <B> = 1.2T

$1\times4.1\ cm^2$ scintillator strips

Multi-anode PMT readout

GPS time-stamping to synchronize FD data to ND/Beam

Software triggering in DAQ PCs

Main Injector spill times sent to the FD for a beam trigger

Far Detector

5.4 kton

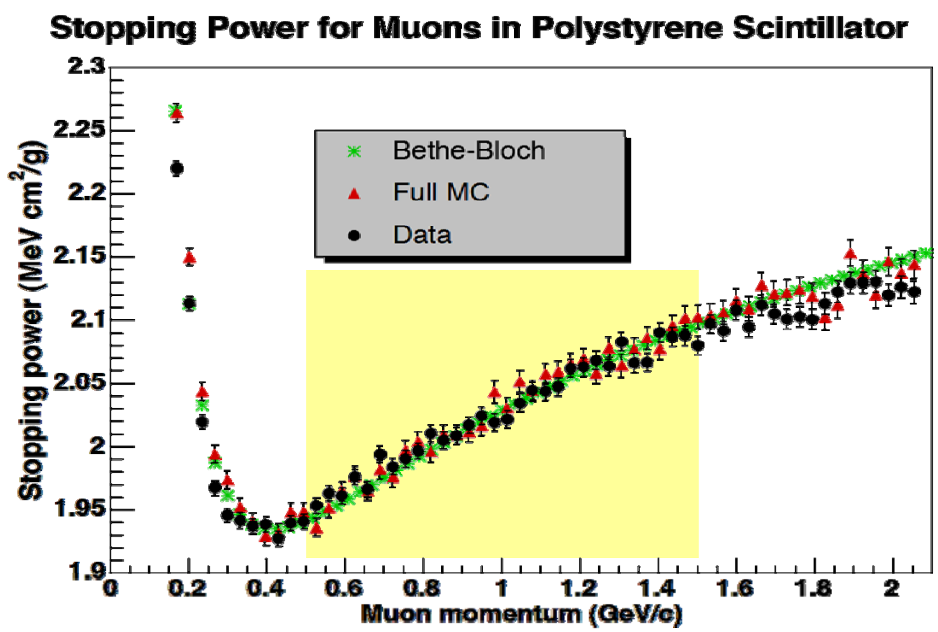
$8 \times 8 \times 30\ m^3$

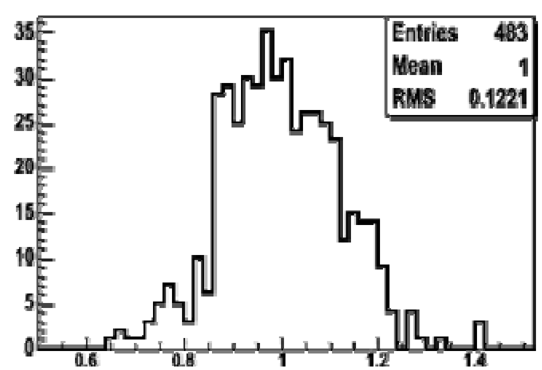
484 planes

MINOS Calibration system

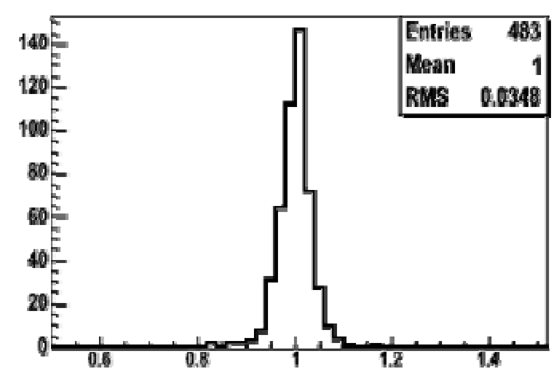
ND & FD response
- Light Injection system (PMT gain)
- Source scan (within a strip)
- Cosmic ray muons (strip to strip)
- Stopping cosmic ray muons (detector to detector)
- Overall energy scale (Test beam)

Energy scale errors
- 5.7% absolute
- 2% ND/FD relative





Raw response



Calibrated response

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

All near detector data was open

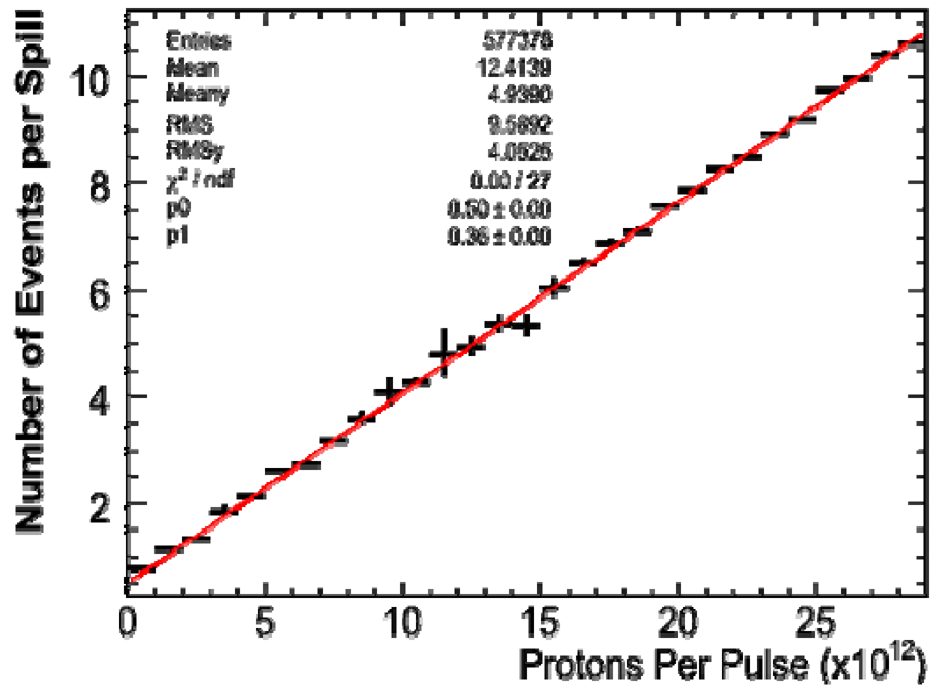
> Used to study beam properties, cross sections, and detector systematics

Analysis procedures defined prior to box opening

Near detector events

- High event rate in the near detector
  - > Over 1×10^7 events in the fiducial volume
- Multiple interactions per main injector spill
  - > 10 μs beam spills
- Events are separated by topology and 19ns timing
  - > Linear response to increasing intensity

Number of events vs intensity



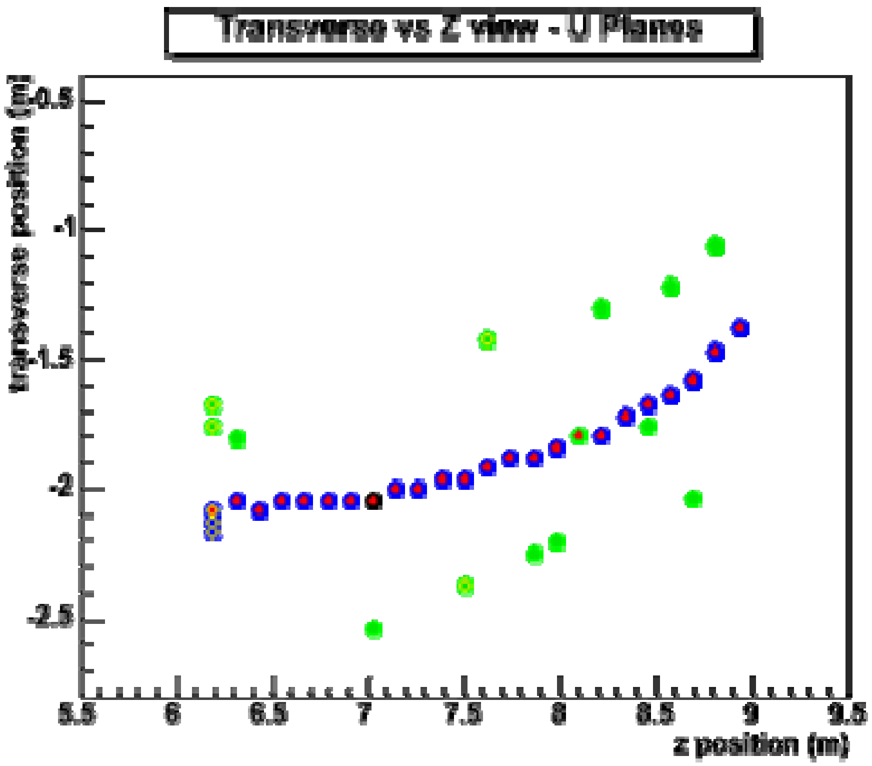
A 2 GeV ν_μ event

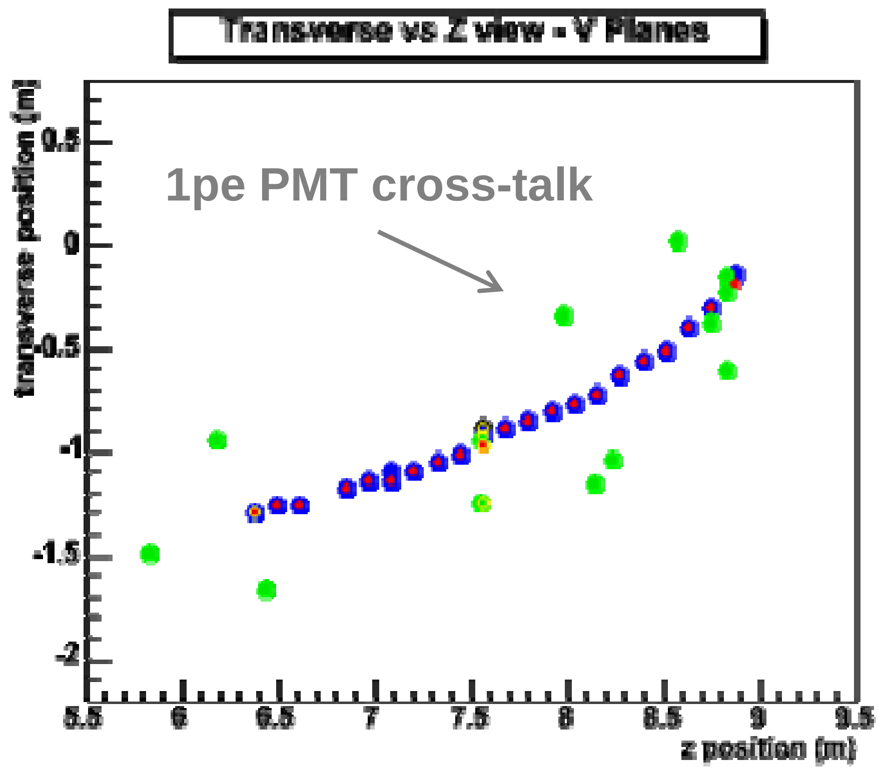
Track Energy 2.04 GeV

Shower energy 0.20 GeV

q/p = -0.52 ± 0.03

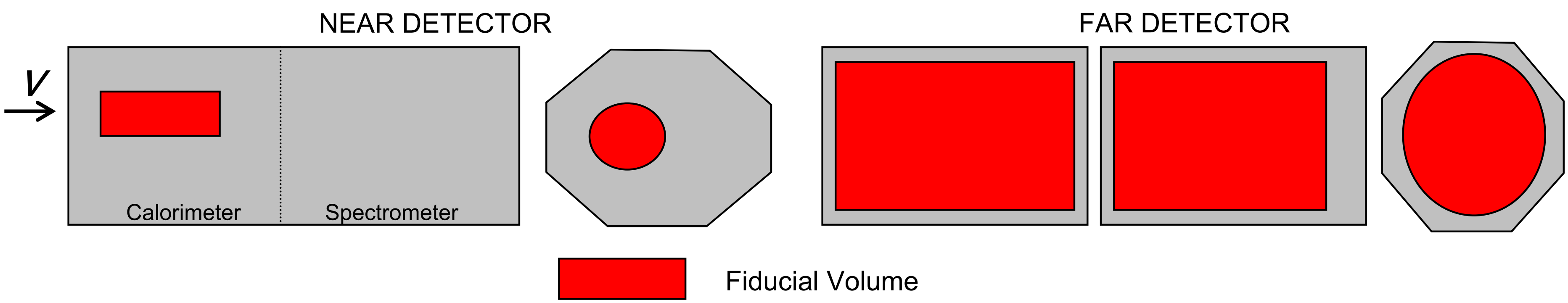
- < 2 PE
- 0<PE < 20 PE
- >20 PE



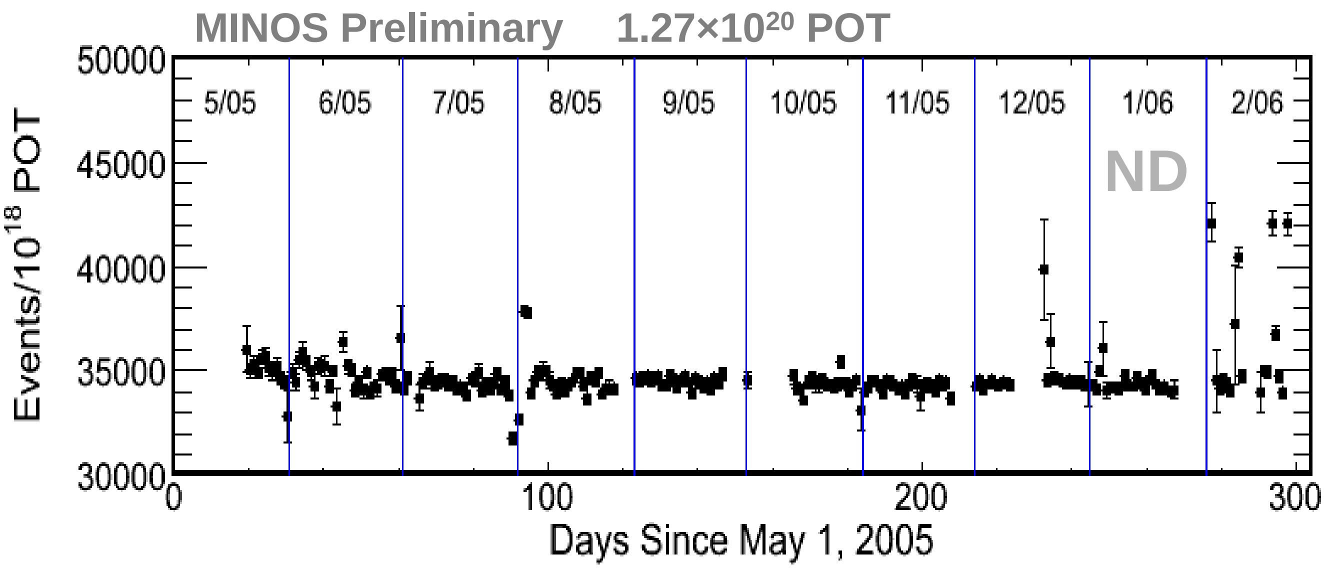


ν_μ CC event pre-selection cuts

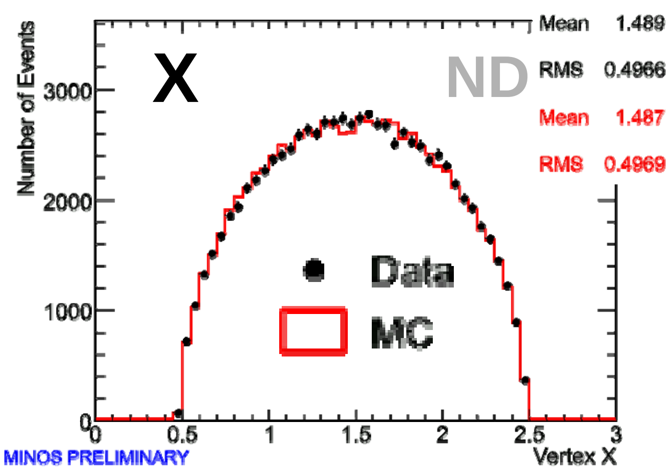
- At least one good track
- Fitted track with negative charge
- Track vertex within the fiducial volume
  - > ND r < 1m from beam center
  - > FD r < 3.7m

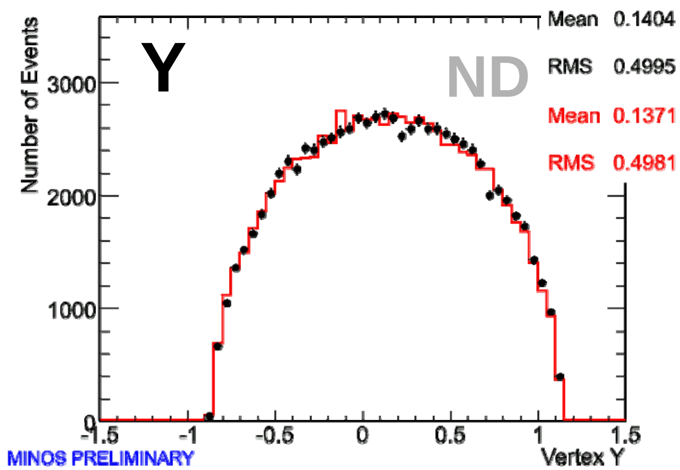


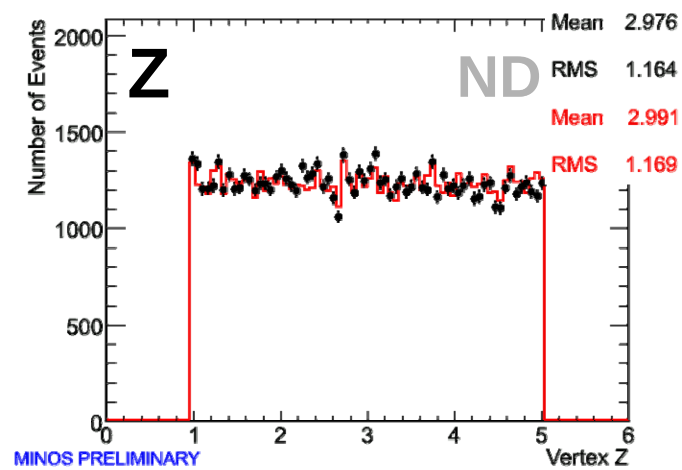
Near detector rate & event vertices



- Event rate is flat as a function of time
- Horn current scans on July 29 – Aug 3
- Different tunes in Feb
- Acceptance well reproduced



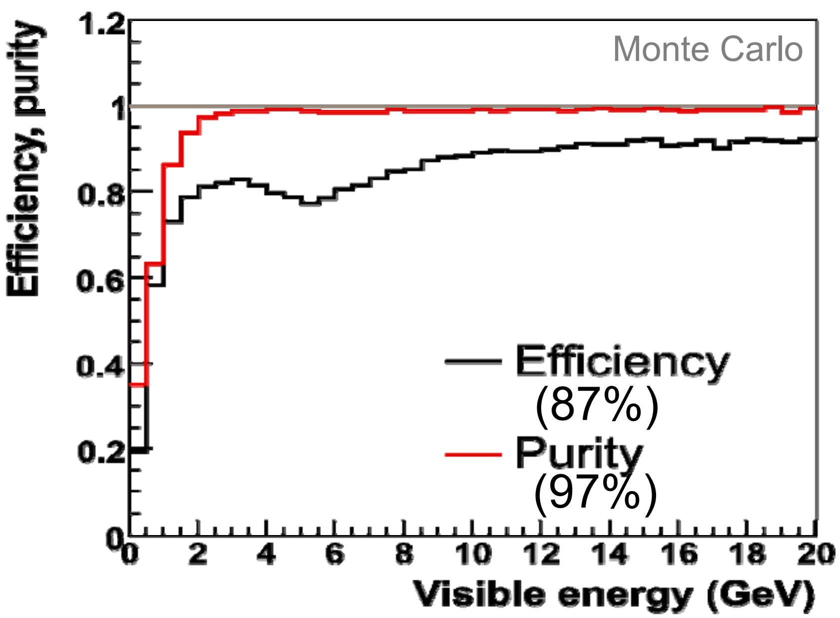


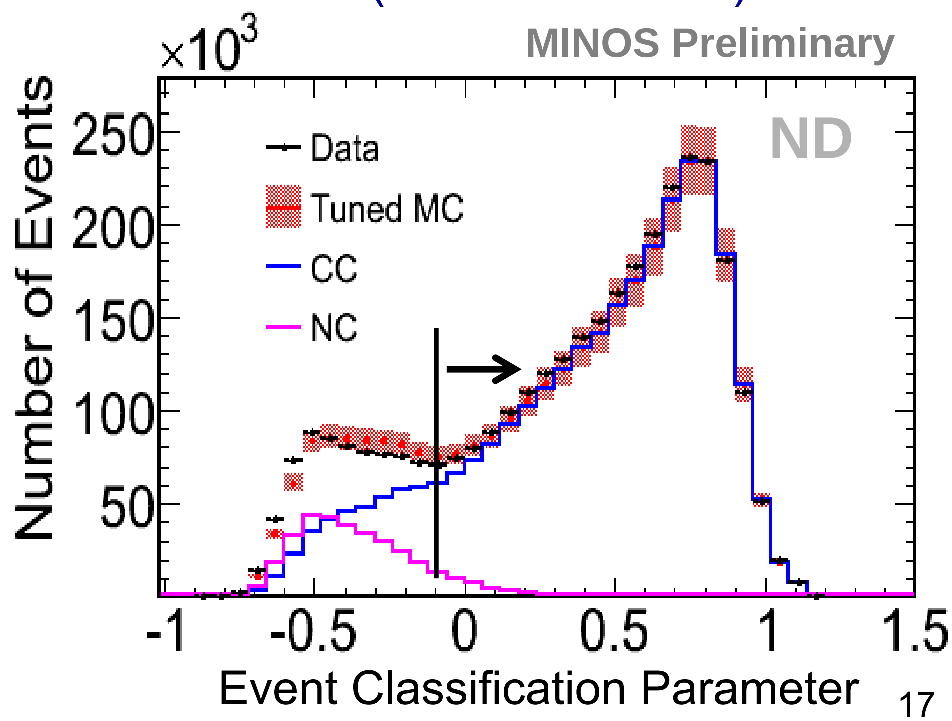


Event selection performance

Charged current events are selected using a likelihood procedure

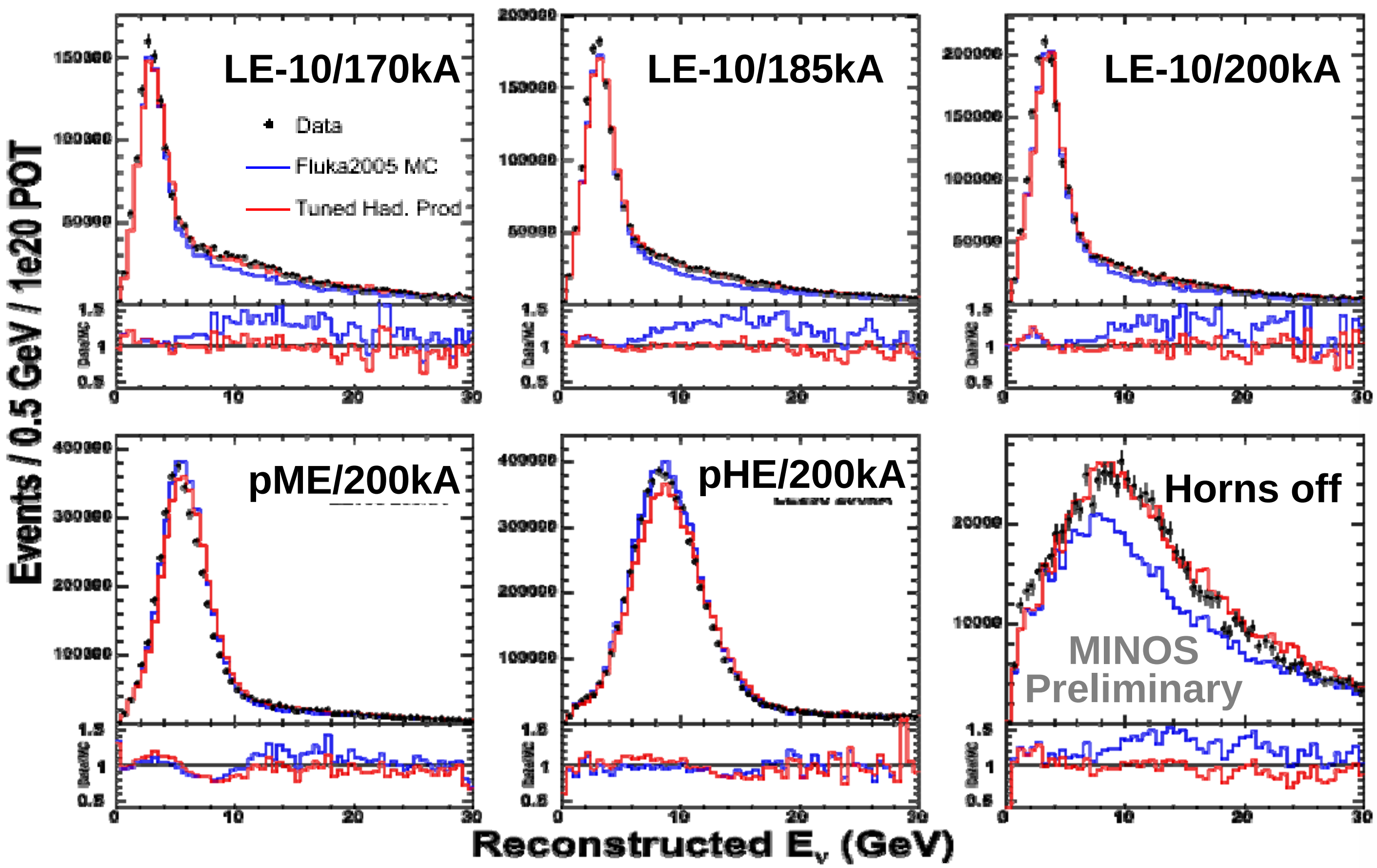
- Combine probability density functions for 3 low level variables to differentiate CC & NC interactions
- Efficiency is reasonably flat vs visible energy over most of the energy range
- NC contamination is limited to the lowest bins (below 1.5 GeV)



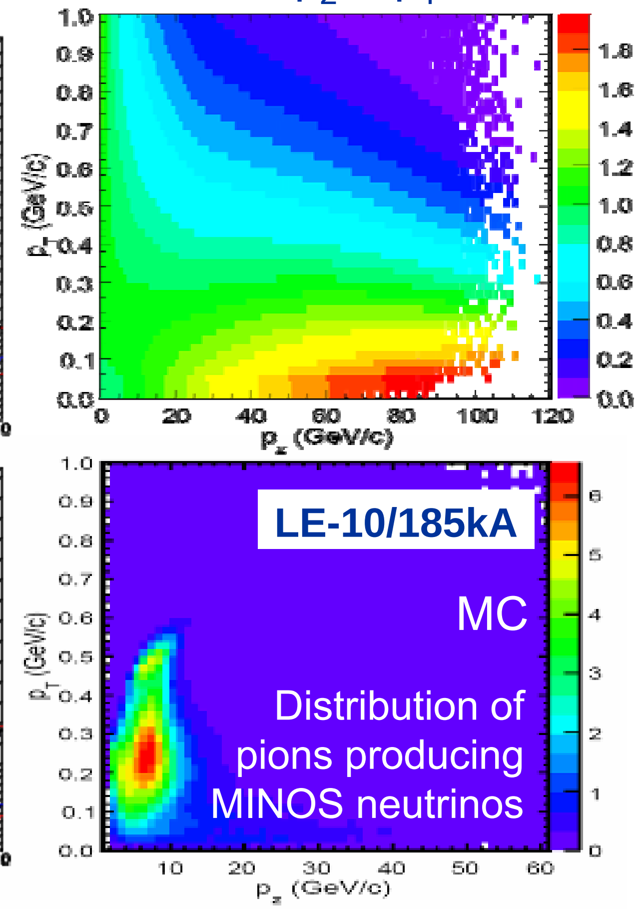


Hadron production tuning

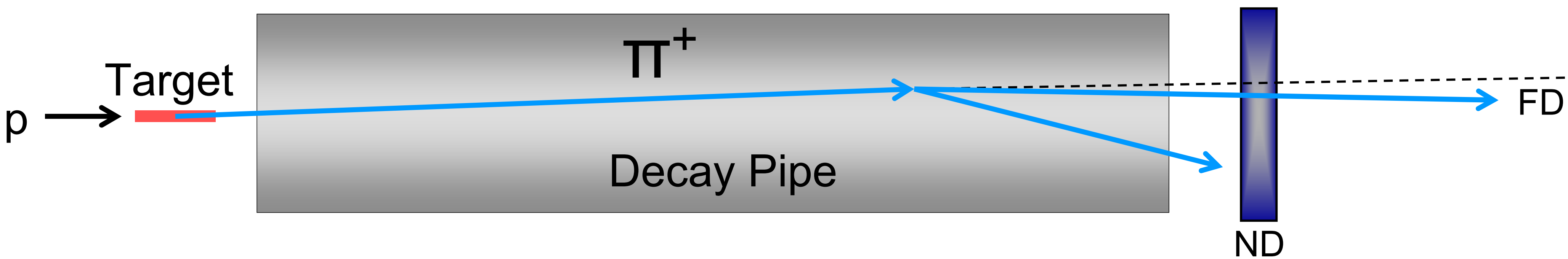
- Varying the dependence on p_T and x_F in FLUKA05
- Also allow small changes in
  - > Cross section parameters
  - > Horn focusing
  - > Neutrino energy scale



Weights applied vs p_z & p_T



Predicting the unoscillated FD spectrum

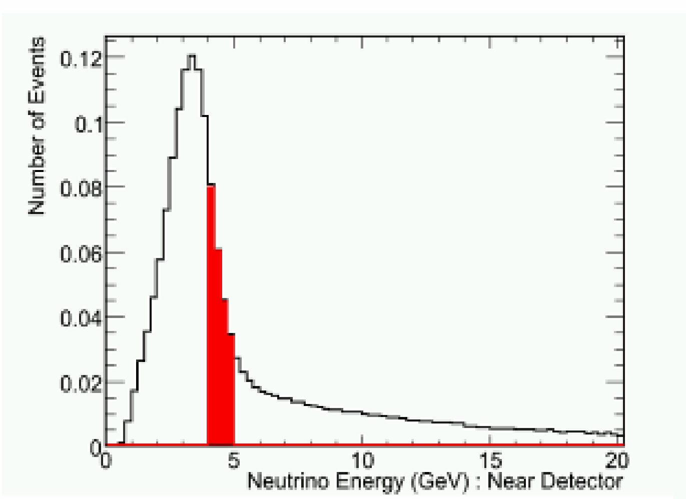


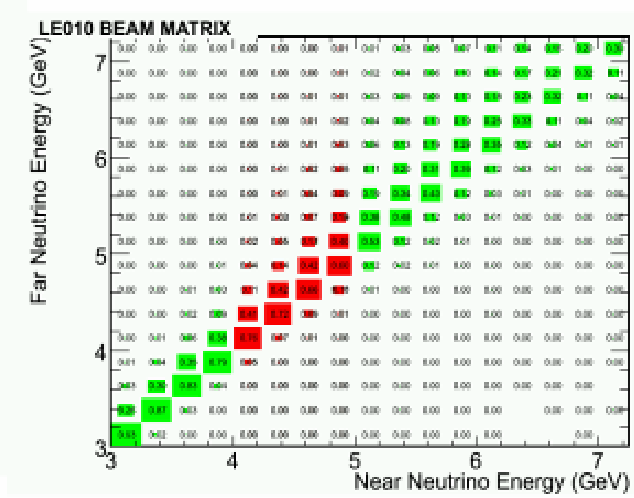
Start with near detector data & extrapolation to the far detector

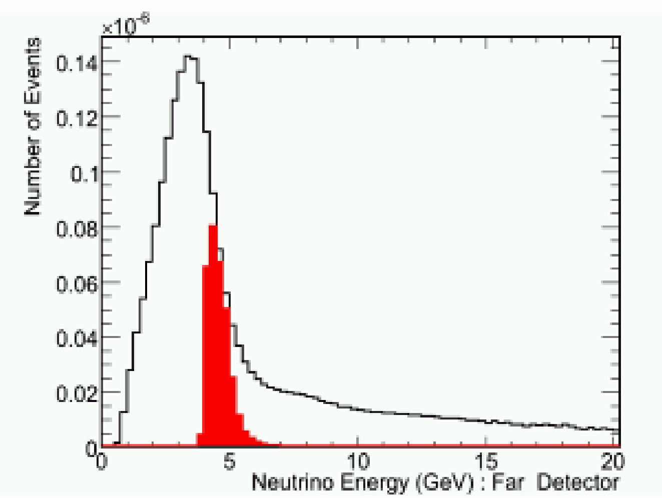
> Use Monte Carlo to provide corrections due to energy smearing and acceptance

> Encode pion decay kinematics & the geometry of the beamline into a matrix used to transform the ND spectrum into the FD energy spectrum

This is the primary method used in our analysis



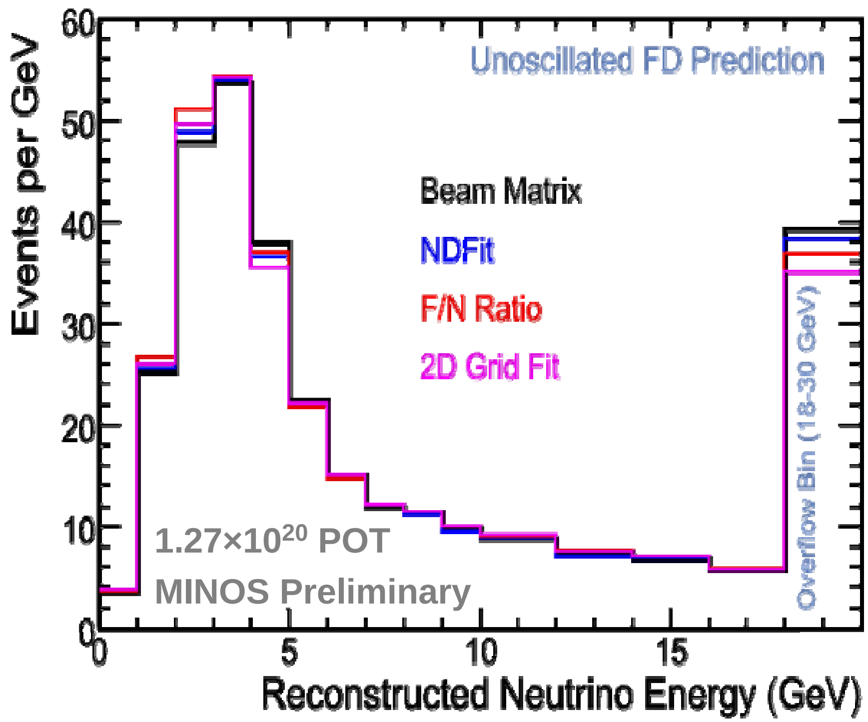




Different methods of predicting the FD spectrum

ND fit methods

- 2 types of fits made to all 6 beams
  - **ND fit to E_ν distribution**
  - **2D fit to (E_ν, y) grid**
- The MC is then used to produce the extrapolation FD spectrum



ND data extrapolation methods

- 2 types of fit used
  - **Beam matrix**
  - **F/N ratio**
    - Events in each ND energy bin are scaled via MC into a number of FD events in the same bin

The methods are robust to different categories of systematics

Selecting far detector beam induced events

GPS time stamping both detector sites

> FD trigger reads out 100μs of activity around beam spills

FD neutrino events have distinctive topology

> They point to Fermilab

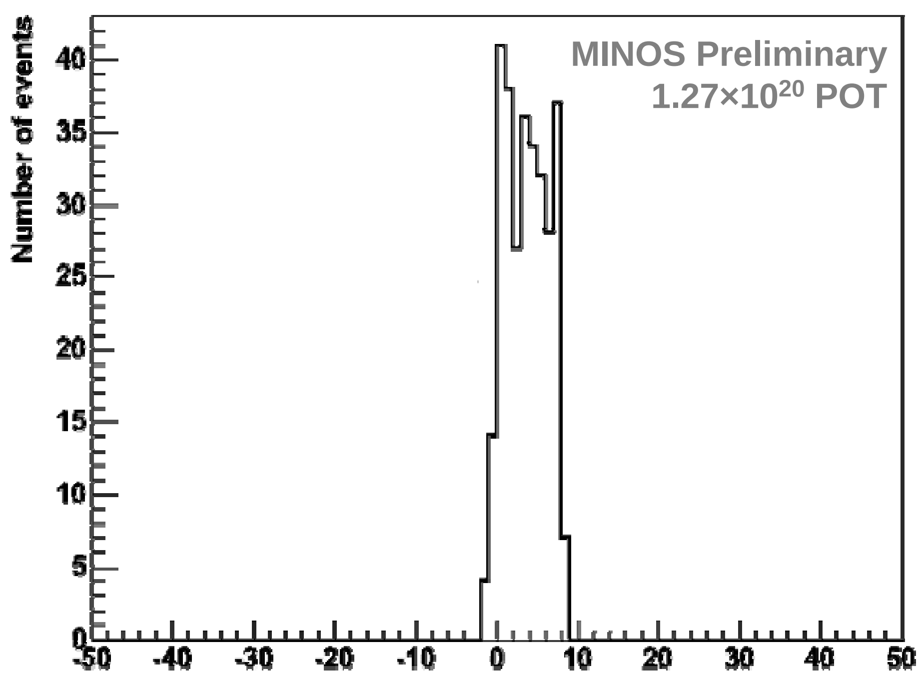
> Easily separated from cosmic muons with 60° cut around the beam axis

Backgrounds estimated from "fake" triggers

> 2.6 million triggers

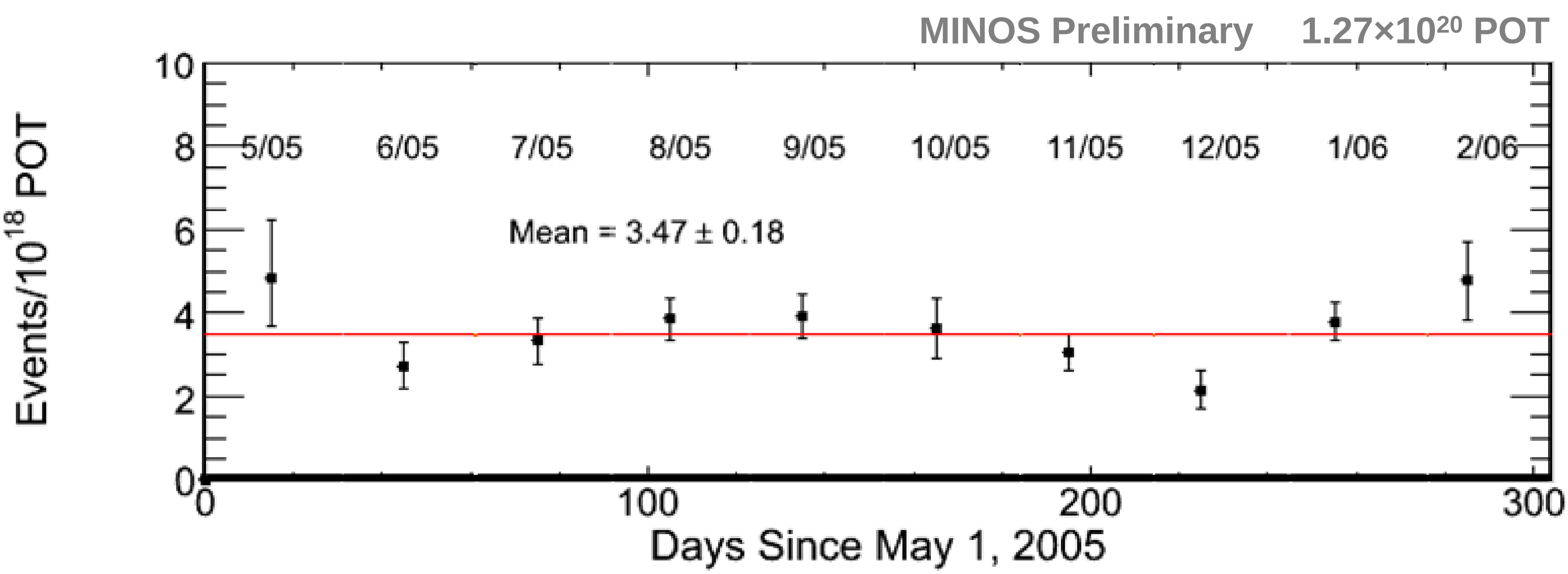
> 0 events survived cuts

> Upper limit of 0.5 events



Time of neutrino interactions from beam spill (μs)

Far detector beam data analysis



This analysis uses data collected from 20 May, 2005 to 3 March, 2006

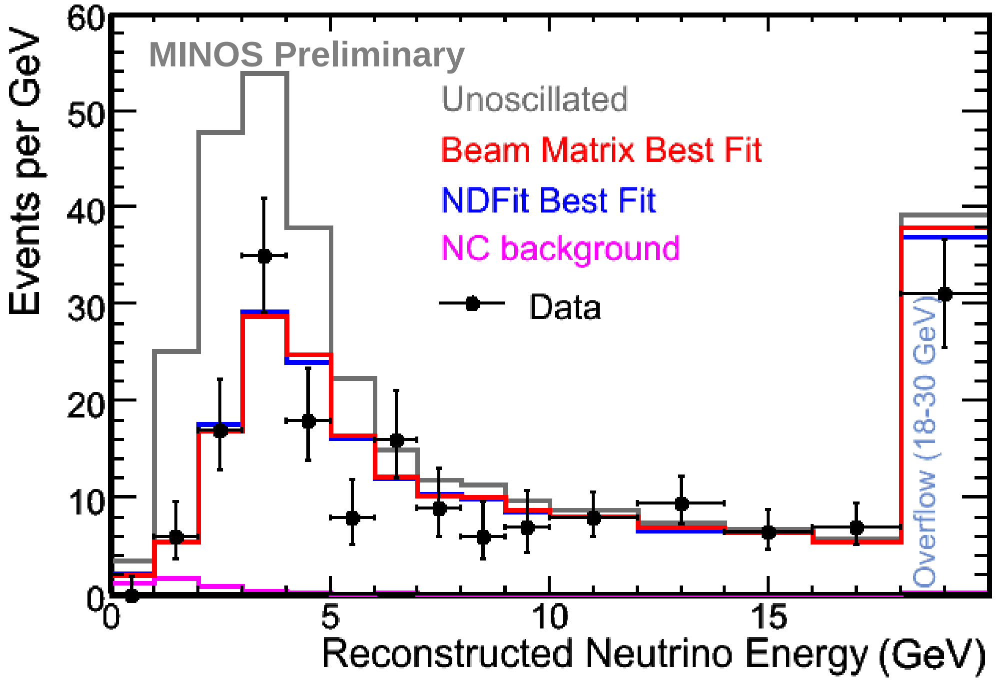
Numbers of observed & expected events

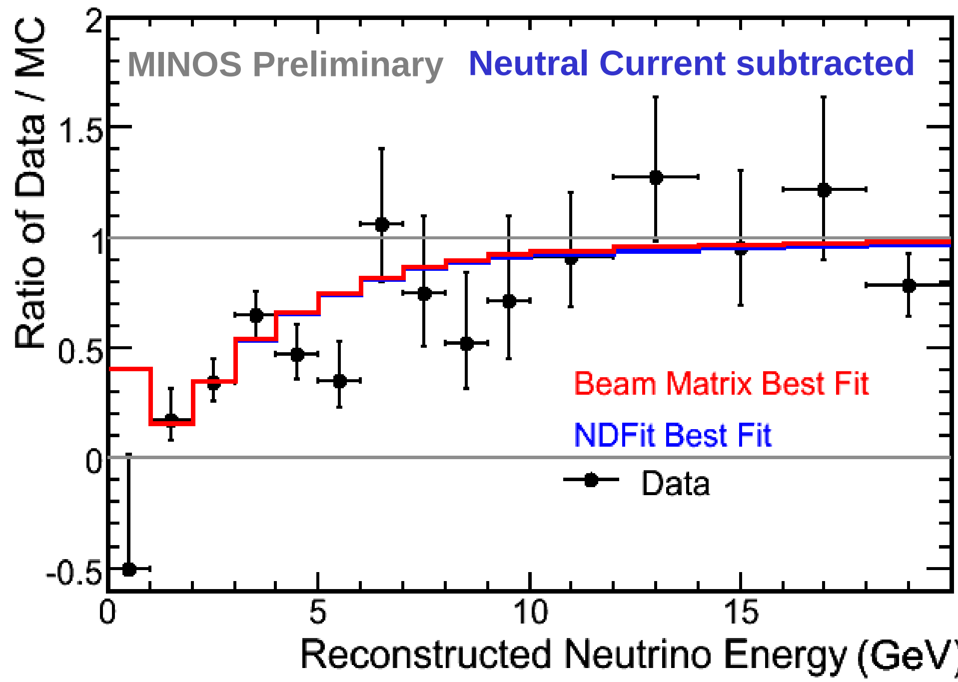
Data sample	Data	Expected (Matrix Method; Unoscillated)	Data/MC (Matrix Method)	Expected (Fit Method; Unoscillated)
ν_μ (<30 GeV)	215	336±21	0.64±0.08	332.8
ν_μ (<10 GeV)	122	239±17	0.51±0.08	237.7
ν_μ (< 5 GeV)	67	168±12	0.45±0.09	168.6

A large energy dependent deficit

- Below 10 GeV the significance of the deficit is 5.9σ (stat+syst)
- Preliminary result from the 1.27×10^{20} POT sample

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





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

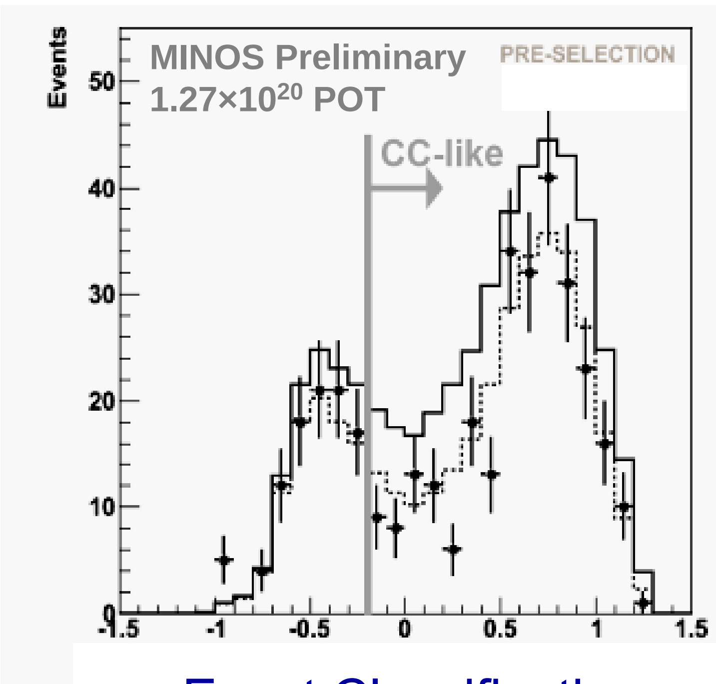
$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat})$$

$$\text{Normalization} = 0.98$$

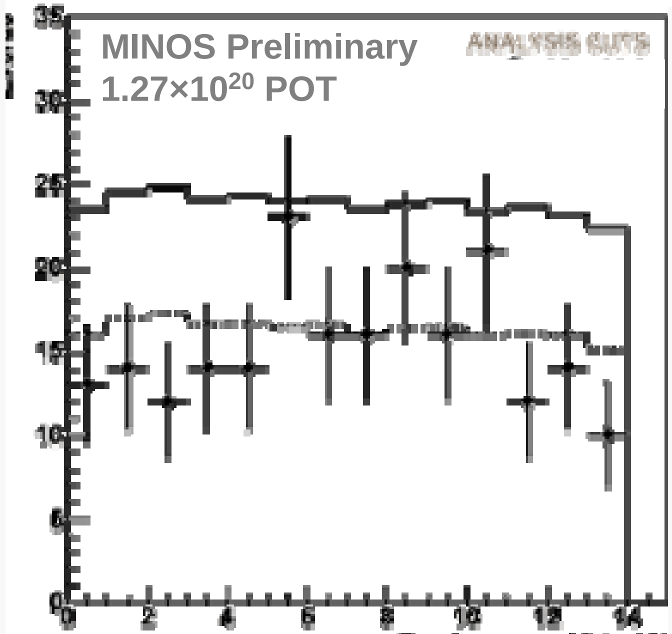
Measurement errors are 1 sigma, 1 DOF

$$\sum_{i=1}^{\text{nbins}} 2(e_i - o_i) + 2 o_i \ln\frac{o_i}{e_i} + \frac{(1-N)^2}{0.04^2}$$

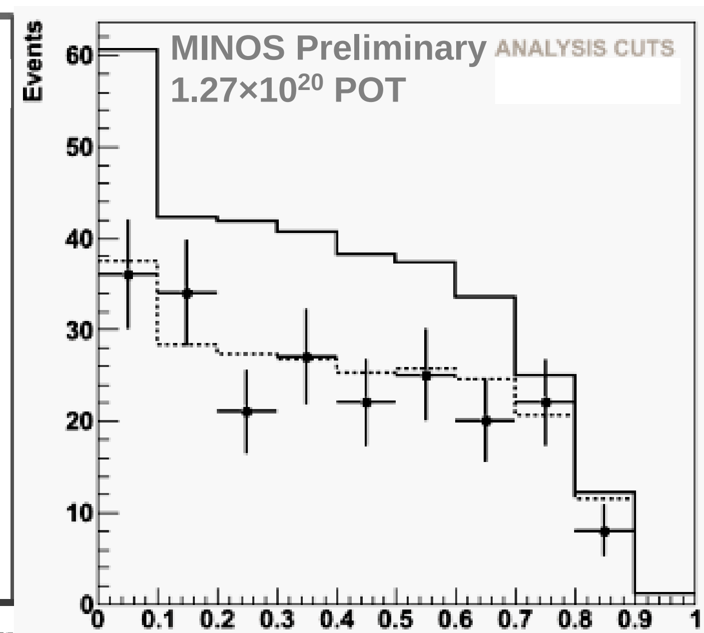
FD distributions



Event Classification Parameter



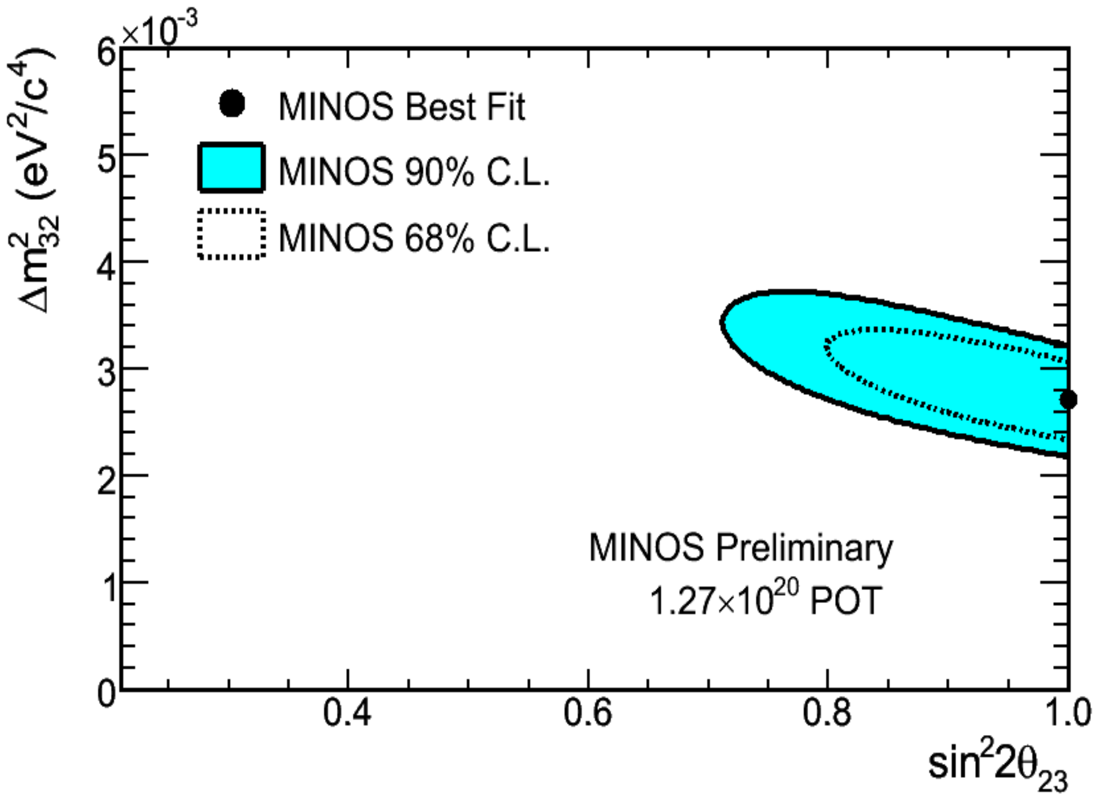
Track Vertex r^2 (m^2)



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

Predicted no oscillations (solid)
Best fit (dashed)

Allowed region



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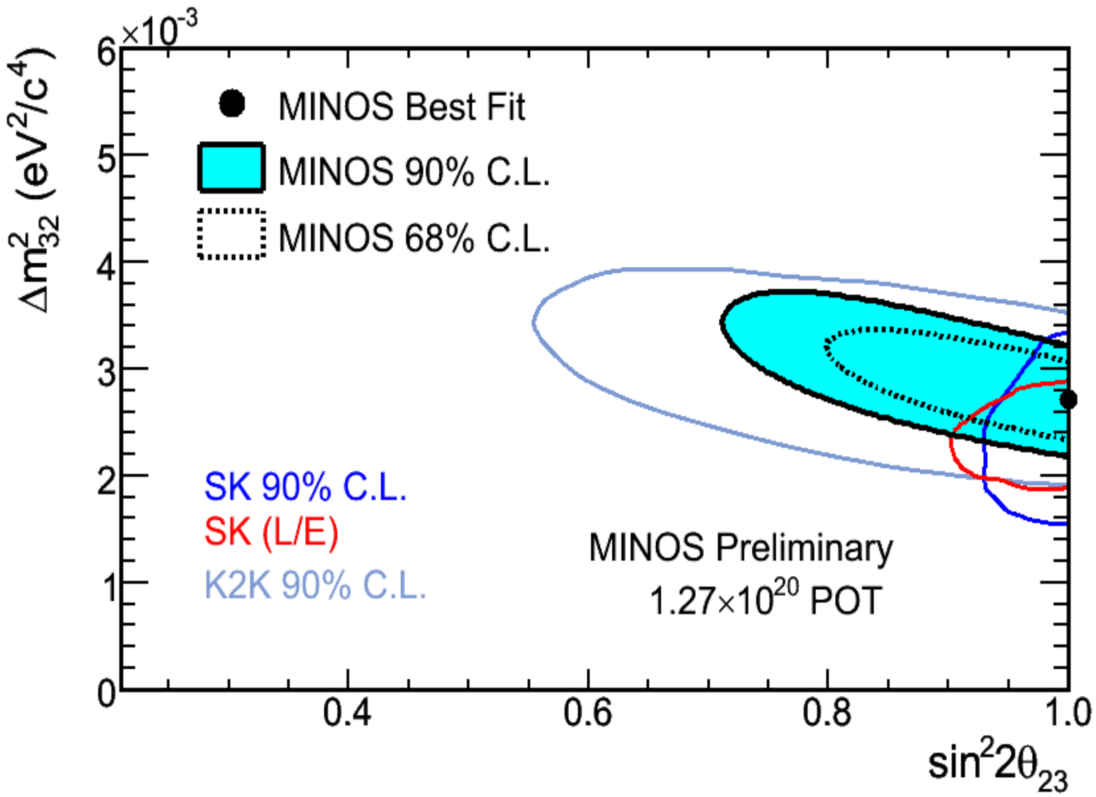
$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat})$

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

Statistical errors

Allowed region



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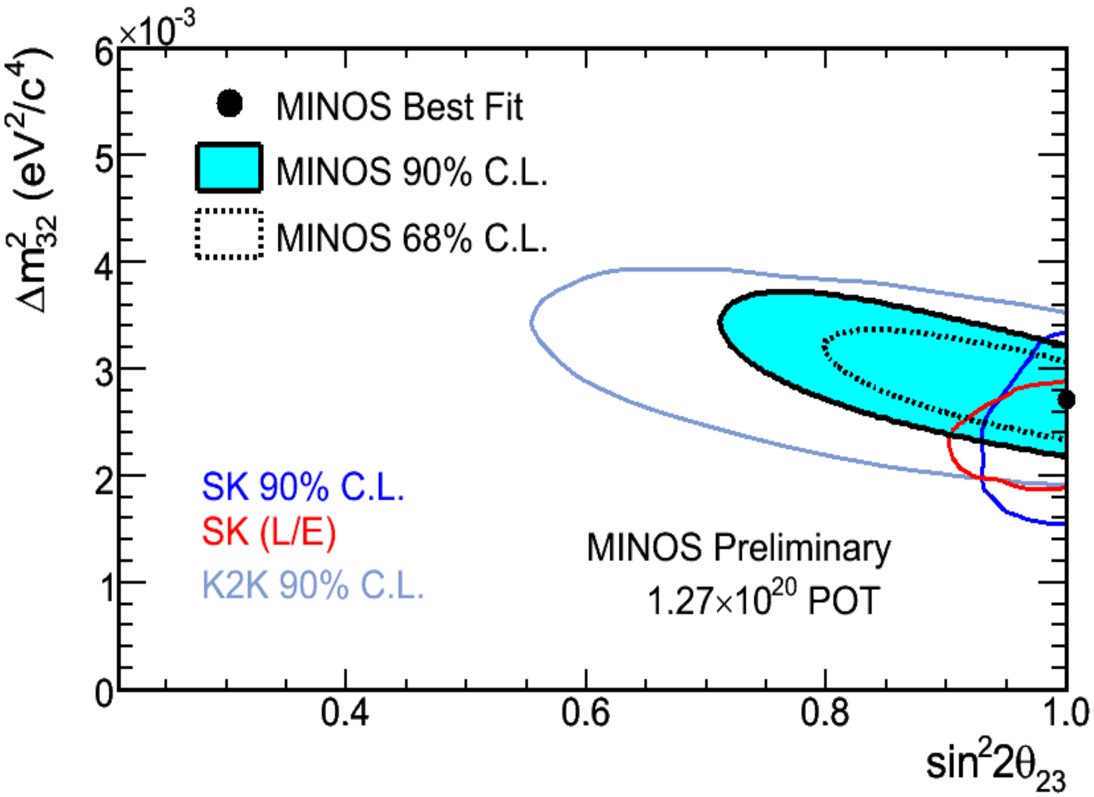

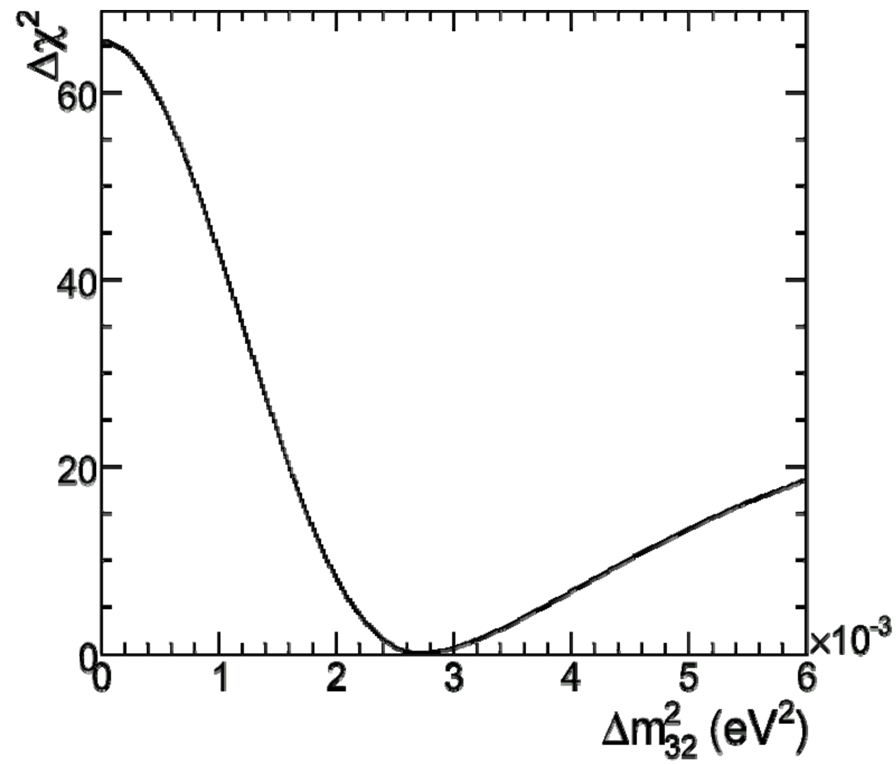

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Constrained to $\sin^2(2\theta_{23}) \leq 1$

Statistical errors

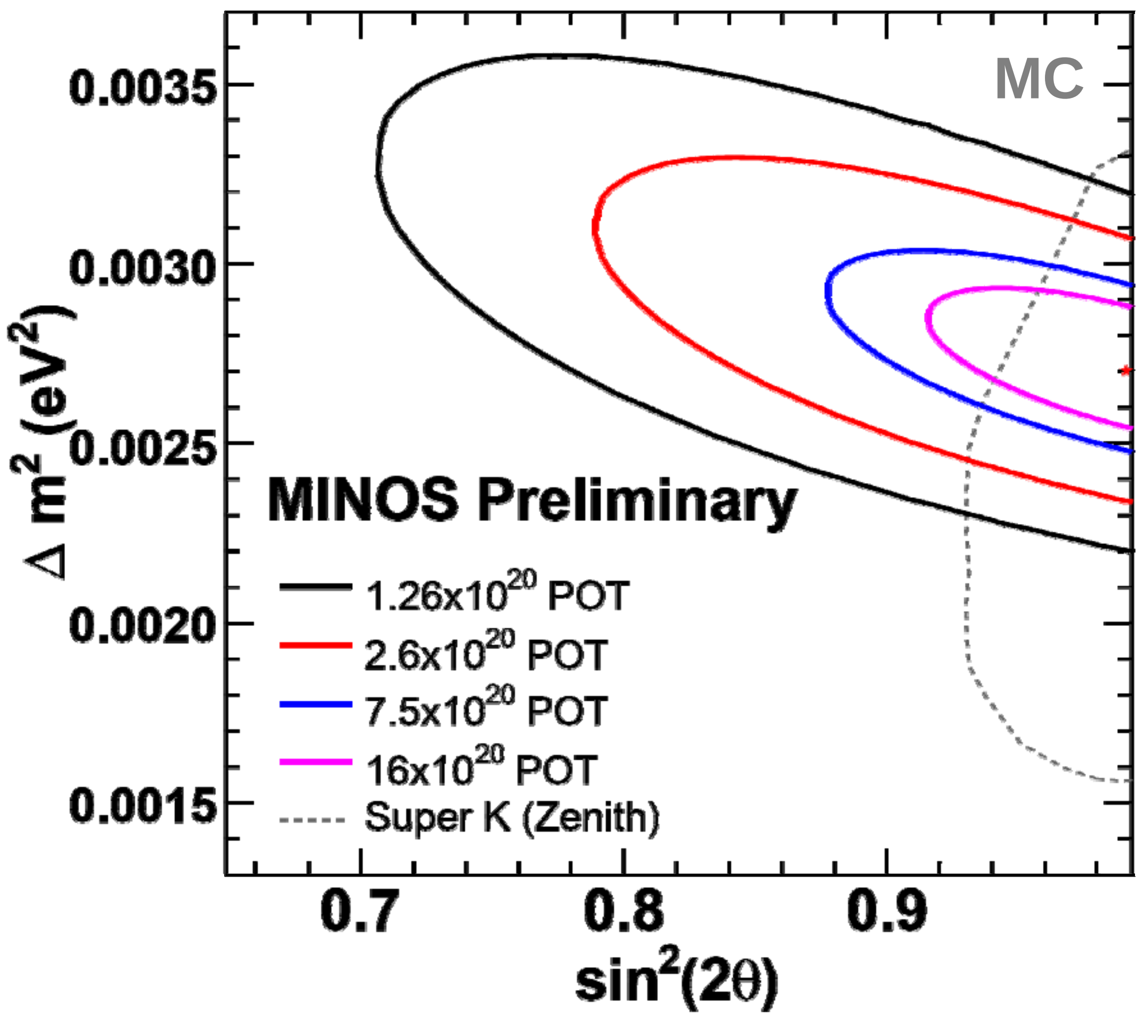
$|\Delta m^2_{32}| = 2.72\,^{+0.25}_{-0.25}\,(\text{stat}) \times 10^{-3}\,\text{eV}^2$

When constrained to $\sin^2(2\theta) = 1$

Systematic errors

Preliminary Uncertainty	Δm^2 (10^{-4} eV^2)	$\sin^2 2\theta$
Near/Far normalization ± 4%	0.03	0.000
Muon momentum scale ± 2%	0.35	0.003
Near/Far shower energy scale ± 2%	0.10	0.003
NC contamination ± 50%	0.88	0.038
CC cross-section uncertainties	0.16	0.004
Intranuclear re-scattering / absolute energy scale (±6%)	0.83	0.018
Reconstruction	0.13	0.005
Fit bias	0.10	0.010
Beam uncertainties	0.25	0.005
Total Systematic (summed in quadrature)	1.31	0.044
Statistical sensitivity	3.6	0.12

Projected sensitivity of MINOS



Input parameters

$\left|\Delta m^2_{32}\right| = 2.72 \times 10^{-3}\,\mathrm{eV}^2$

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

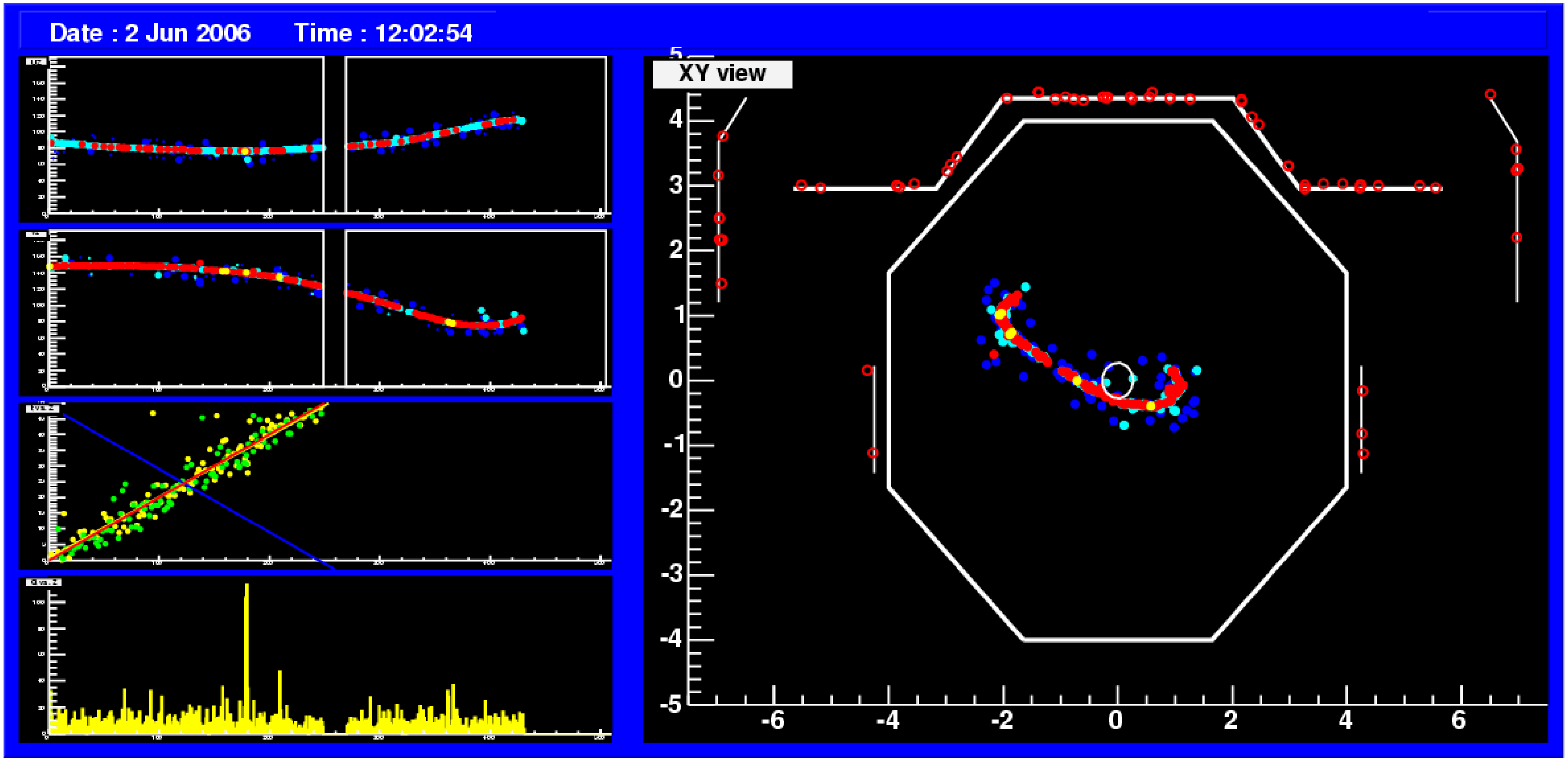
Statistical errors only

90% C.L.

2nd year of MINOS running in the NuMI Beam is underway

The first FD beam event in the new run

> A muon from an interaction in the cavern rock



MINOS Summary

Preliminary results from the first year of accelerator neutrino exposure

- Our exposure to date is 1.27×10^{20} POT
- Disfavors no oscillations at 5.9 σ (rate only)
- It is consistent with ν_μ disappearance with the following parameters

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

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

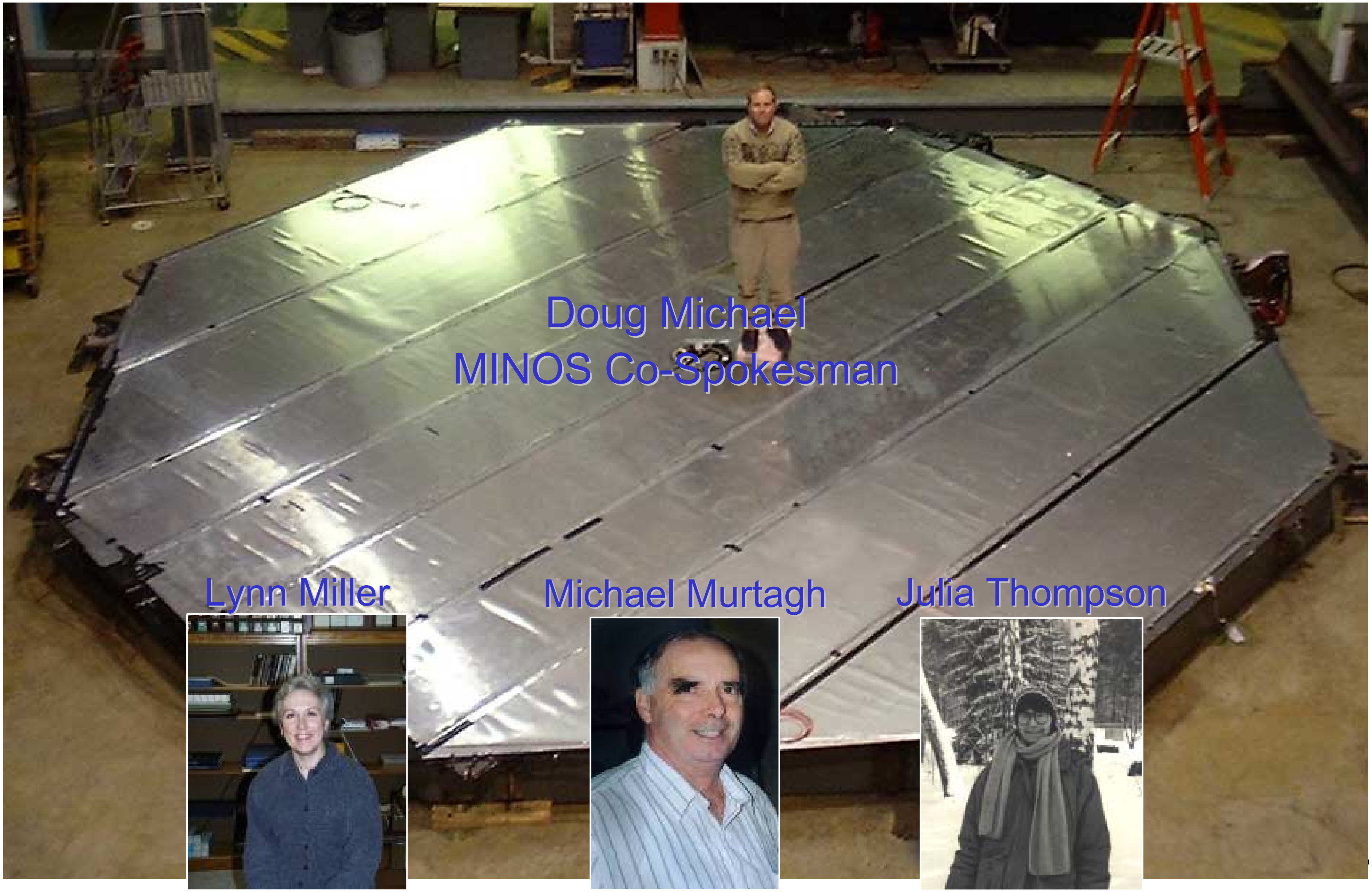
- A fit constrained to the $\sin^2(2\theta)=1$ boundary yields

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

The systematics are under control

- Many systematics are data driven and will improve with increasing statistics and further analysis
- We should be able to make significant improvements in precision with a substantially larger dataset

Dedication



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