First MINOS Results from the NuMI Beam

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for the MINOS collaboration

IOP Particle Physics 2006, Warwick
Overview

Introduction to the MINOS experiment
- Overview of MINOS Physics Goals
- The NuMI facility and the MINOS detectors

Near Detector and beam measurements
- Selecting CC muon neutrino events
- Near Detector distributions and comparison with Monte Carlo

Far Detector analysis
- Selecting beam neutrino candidates in the Far Detector
- Near-Far extrapolation of the neutrino flux
- Oscillation analysis with $0.93 \times 10^{20}$ POT
Neutrino Oscillations

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

\[
\sin^2 2\theta \approx 4U_{\mu 3} (1 - U_{\mu 3})
\]

- Verify $\nu_\mu \rightarrow \nu_\tau$ mixing hypothesis and make a precise (<10%) measurement of the oscillation parameters $\Delta m^2$ and $\sin^2 2\theta$

2 neutrino survival probability:

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{E}\right)
\]
Current knowledge of atmospheric neutrino oscillations

Current best measurements of $\Delta m^2$ and $\sin^2 2\theta$ from 
**Super-Kamiokande**
(atmospheric neutrinos) and 
**K2K** ($9 \times 10^{19}$ POT)

The limits (at 90% C.L.) are:
- $\sin^2 2\theta > 0.9$
- $1.9 < \Delta m^2 < 3.0 \times 10^{-3} \text{eV}^2$

This analysis is for $9.3 \times 10^{19}$ POT, and should provide a competitive measurement of the mixing parameters.

Allowed regions from Super-K and K2K

![](image.png)
The MINOS Collaboration

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas
College de France • Fermilab • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Duluth • Minnesota-Twin Cities • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin
Tufts • UCL • Western Washington • William & Mary • Wisconsin
The MINOS Experiment

MINOS (Main Injector Neutrino Oscillation Search)

- A long-baseline neutrino oscillation experiment:
- Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.
- Far Detector deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations
- Near Detector at Fermilab to measure the beam composition and energy spectrum
MINOS Methodology

Look for a deficit of $\nu_\mu$ events at Soudan

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$
Producing the neutrino beam

- 9μs spill of 120GeV protons every 2s
- 0.2 MW average beam power
- 20 × 10^{12} protons per pulse (ppp)
The NuMI neutrino beam

- Currently running in the LE−10 configuration
- ~$1.5 \times 10^{19}$ POT in pME and pHE configurations early in the run for commissioning and systematics studies

$98.5\% \nu_\mu + \bar{\nu}_\mu \ (6.5\% \bar{\nu}_\mu)$

$1.5\% \nu_e + \bar{\nu}_e$

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target z position (cm)</th>
<th>FD Events per 1e20 pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>LE−10</td>
<td>−10</td>
<td>390</td>
</tr>
<tr>
<td>pME</td>
<td>−100</td>
<td>970</td>
</tr>
<tr>
<td>pHE</td>
<td>−250</td>
<td>1340</td>
</tr>
</tbody>
</table>

Events expected in fiducial volume
/2006/4/10

First year of running

Dataset used for the oscillation analysis
The MINOS detectors

- **Veto Shield**

- **Coil**

- **Far**

- **Near**

5.4 kt mass, 8×8×30m
484 steel/scintillator planes
Divided into 2 super modules
M64 multi-anode PMTs

1 kt mass, 3.8×4.8×15m
282 steel and 153 scintillator plane
Front 120 planes → Calorimeter
Remaining planes → Spectrometer
M16 multi-anode PMTs

Detectors magnetised to 1.2 T
GPS time-stamping to synch FD data to ND/Beam
Flexible software triggering in DAQ PCs: FD triggers from FNAL over IP
Detector technology

MINOS Near and Far Detectors are functionally identical:

- 2.54 cm thick magnetised steel plates
- co-extruded scintillator strips
- orthogonal orientation on alternate planes – U, V
- optical fibre readout to multi-anode PMTs
Reconstruction of a MINOS event
Reconstruction of a MINOS event
Overview

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Event topologies

\[ \nu_\mu \text{ CC Event} \]

- long \( \mu \) track & hadronic activity at vertex

\[ \nu_\mu \text{ NC Event} \]

- short event, often diffuse

\[ \nu_e \text{ CC Event} \]

- short, with typical EM shower profile

\[ E_\mu = E_{\text{shower}} + p_\mu \]

- 55%/\( \sqrt{E/\text{GeV}} \)
- 6% range, 10% curvature
ν_μ CC-like events are selected in the following way:

1. Event must contain at least one good reconstructed track
2. The reconstructed track vertex should be within the fiducial volume of the detector:
   NEAR:
   - 1m < z < 5m (from detector front), \( \nu \rightarrow \) Calorimeter Spectrometer
   - R < 1m from beam centre
   FAR:
   - z > 50cm from front face,
   - z > 2m from rear face,
   - R < 3.7m from detector centre
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
Selecting CC events

Events selected by likelihood-based procedure, with 3 input Probability Density Functions (PDFs)

- event length in planes
- fraction of event pulse height in the reconstructed track
- average track pulse height per plane

Define $P_\mu \, P_{NC}$ as the product of the three CC (NC) PDFs, at the values of these variables taken by the event

**Input variables for PDF based event selection**

![Graphs showing probability distributions for event length, track pulse height fraction, and track pulse height per plane.]
CC selection efficiencies

- Particle ID (PID) parameter is defined:

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

• We observe very large event rates in the Near detector ($\sim 10^7$ events in the fiducial volume for $10^{20}$ POT)
• This provides a high statistics dataset with which we can study how well we understand the performance of the Near Detector and check the level to which our data agrees with our Monte Carlo predictions
Near Detector rate and event vertices (LE-10 beam)

Event rate is flat as a function of time
Horn current scans: July 29 – Aug 3
Particle ID variables (LE−10 Beam)

Event length

Track PH per plane

Track PH fraction
PID parameter

PID cut to select CC-like events is at \(-0.1\)
Error envelopes shown on the plots reflect uncertainties due to cross-section modeling, beam modeling and calibration uncertainties.
Agreement between data and Fluka05 Beam MC is pretty good, but by tuning the MC by fitting to hadronic $x_F$ and $p_T$, improved agreement can be obtained.
Stability of the energy spectrum & reconstruction with intensity

Typical proton intensity ranges from $10^{13}$ ppp - $2.8 \times 10^{13}$ ppp

**Energy spectrum by Month**

- June
- July
- August
- September
- October
- November

**Energy spectrum by batch**

- Reconstructed energy distributions agree to within statistical uncertainties (~1-3%)
- Beam is very stable and there are no significant intensity dependent biases in event reconstruction
Summary of ND data/MC agreement

• The agreement between low level quantities indicates that there are no obvious pathologies introduced by detector modeling and/or reconstruction.

• Agreement between high level quantities is within the expected systematic uncertainties from cross-section modeling, beam modeling and calibration uncertainties (initial agreement improved after applying beam reweighting on the $x_F$ and $p_T$ of parent hadrons in the Monte Carlo).
Introduction to the MINOS experiment (PL)
- Overview of MINOS Physics Goals
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Near Detector and beam measurements (MD)
- Selecting CC muon neutrino events
- Near Detector distributions and comparison with Monte Carlo

Far Detector analysis (TR)
- Selecting beam neutrino candidates in the Far Detector
- Near-Far extrapolation of the neutrino flux
- Oscillation analysis with $0.93 \times 10^{20}$ POT
Far Detector beam analysis

Oscillation analysis performed using data taken in the LE-10 configuration from May 20\textsuperscript{th} 2005 – December 6\textsuperscript{th} 2005

• Total integrated POT: 0.93\times10^{20}

• Excluded periods of “bad data”—coil and HV trips, periods without accurate GPS timestamps. The effect of these cuts are small (~0.7% of our total POT)

• POT-weighted live-time of the Far Detector: 98.9%
Performing a blind analysis

• The MINOS collaboration decided to pursue a blind analysis policy for the first accelerator neutrino results
  – The blinding procedure hides an unknown fraction of FarDet events based on their length and total energy deposition

• No blinding was applied to NearDet data
• Unknown fraction of Far Detector data was open
  – Performed extensive data quality checks

• Unblinding criteria were:
  – No problems with the FarDet beam dataset (missing events, reconstruction problems, etc)
  – Oscillation analysis (cuts and fitting procedures) pre-defined and validated on MC; no re-tuning of cuts allowed after 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 100μs of activity around beam spills
- Far Detector neutrino events easily separated from cosmic muons (0.5 Hz) using topology

Backgrounds estimated by applying selection algorithm on “fake” triggers taken in anti-coincidence with beam spills

In 2.6 million “fake” triggers, 0 events survived the selection cuts (upper limit on background in open sample is 1.7 events at 90% C.L.)
Vertex distributions of selected events

Open dataset

Distributions consistent with neutrino interactions—no evidence of background contamination.
Predicting the unoscillated FD spectrum

- Directly use Near Detector data to perform extrapolation between Near and Far
- Use Monte Carlo to provide necessary corrections due to energy smearing and acceptance
- Use our knowledge of pion decay kinematics and the geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum

This method is known as the Beam Matrix Method
Beam Matrix Method: Near to Far extrapolation

- Beam Matrix encapsulates the knowledge of pion 2-body decay kinematics & geometry
- Beam Matrix provides a very good representation of how the Far Detector spectrum relates to the near one
Predicted true FD spectrum

- Higher than nominal FD MC in high energy tail
- Expected, given that the ND visible energy spectrum is also higher than the nominal MC in this region

Predicted FD true spectrum from the Matrix Method
Vertex distributions of selected events

- 296 selected events with a track—no evidence of background contamination
- Distribution of selected events consistent with neutrino interactions
Track quantities & PID parameter

**Track Length**

- **LE BEAM FAR**
  - Mean: 86.05
  - RMS: 71.48

- **Data**
  - Mean: 79.11
  - RMS: 68.5

chi-square /n.d.f. = 20.9/30 = 0.7

**Track Pulse Height per Plane**

- **LE BEAM FAR**
  - Mean: 824.8
  - RMS: 345.8

- **Data**
  - Mean: 802.6
  - RMS: 311.4

chi-square /n.d.f. = 16.3/20 = 0.8

**Particle Identification Parameter**

- **LE BEAM FAR**
  - Mean: 0.3137
  - RMS: 0.5544

- **Data**
  - Mean: 0.3002
  - RMS: 0.5564

chi-square /n.d.f. = 40.6/50 = 0.8

MINOS PRELIMINARY
Physics distributions

Muon Momentum (GeV/c)

<table>
<thead>
<tr>
<th>Data</th>
<th>LE BEAM FAR</th>
<th>Mean 6.691</th>
<th>RMS 5.959</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td></td>
<td>Mean 6.319</td>
<td>RMS 5.86</td>
</tr>
</tbody>
</table>

chi-square /n.d.f = 22.7/30 = 0.8

Shower Energy (GeV)

<table>
<thead>
<tr>
<th>Data</th>
<th>LE BEAM FAR</th>
<th>Mean 4.418</th>
<th>RMS 4.587</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td></td>
<td>Mean 4.344</td>
<td>RMS 4.569</td>
</tr>
<tr>
<td>MC Un-oscillated</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

chi-square /n.d.f = 10.8/10 = 1.1

\[ y = \frac{E_{\text{shw}}}{E_{\text{shw}} + P_m} \]
### Numbers of observed and expected events

<table>
<thead>
<tr>
<th>Data sample</th>
<th>observed</th>
<th>expected</th>
<th>ratio</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>All CC-like events ($\nu_\mu + \bar{\nu}_\mu$)</td>
<td>204</td>
<td>298±15</td>
<td>0.69</td>
<td>4.1\sigma</td>
</tr>
<tr>
<td>$\nu_\mu$ only (&lt;30 GeV)</td>
<td>166</td>
<td>249±14</td>
<td>0.67</td>
<td>4.0\sigma</td>
</tr>
<tr>
<td>$\nu_\mu$ only (&lt;10 GeV)</td>
<td>92</td>
<td>177±11</td>
<td>0.52</td>
<td>5.0\sigma</td>
</tr>
</tbody>
</table>

- We observe a 33% deficit of events between 0 and 30 GeV with respect to the no oscillations expectation
  - Numbers are consistent for $\nu_\mu + \bar{\nu}_\mu$ sample and for the $\nu_\mu$-only sample
- The statistical significance of this effect is 5 standard deviations
Best-fit spectrum

Oscillation Results for 0.93E20 p.o.t

\[
\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{n\text{bins}} 2(e_i - o_i) + 2o_i \ln \left( \frac{o_i}{e_i} \right), \quad o_i = \text{observed}
\]

\[
e_i = \text{expected}
\]
Ratio of data/MC

Data

Best-fit

NC subtracted

Ratio of Data / MC

Reconstructed Neutrino Energy
Allowed regions

\[ \chi^2 / \text{n.d.f} = 20.5 / 13.0 = 1.6 \]

- MINOS Best Fit: Matrix Method
- MINOS Best Fit: NDfit Method
- MINOS Best Fit: F/N ratio Method
- MINOS Best Fit: 2D Grid Method
- MINOS 68% C.L.
- MINOS 90% C.L.

- SuperK 90% C.L.
- Super-K (L/E)
- K2K 90% C.L.
Systematic shifts in the fitted parameters have been computed with MC “fake data” samples for $\Delta m^2 = 0.003 \text{ eV}^2$, $\sin^2 2\theta = 0.9$ for the following uncertainties:

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\Delta m^2$ shift (eV$^2$)</th>
<th>$\sin^2 2\theta$ shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation $\pm$ 4%</td>
<td>$0.63 \times 10^{-4}$</td>
<td>0.025</td>
</tr>
<tr>
<td>Muon energy scale $\pm$ 2%</td>
<td>$0.14 \times 10^{-4}$</td>
<td>0.020</td>
</tr>
<tr>
<td>Relative Shower energy scale $\pm$ 3%</td>
<td>$0.27 \times 10^{-4}$</td>
<td>0.020</td>
</tr>
<tr>
<td>NC contamination $\pm$ 30%</td>
<td>$0.77 \times 10^{-4}$</td>
<td>0.035</td>
</tr>
<tr>
<td>CC cross-section uncertainties</td>
<td>$0.50 \times 10^{-4}$</td>
<td>0.016</td>
</tr>
<tr>
<td>Beam uncertainty</td>
<td>$0.13 \times 10^{-4}$</td>
<td>0.012</td>
</tr>
<tr>
<td>Intranuclear re-scattering</td>
<td>$0.27 \times 10^{-4}$</td>
<td>0.030</td>
</tr>
<tr>
<td><strong>Total (sum in quadrature)</strong></td>
<td><strong>$1.19 \times 10^{-4}$</strong></td>
<td><strong>0.063</strong></td>
</tr>
<tr>
<td><strong>Statistical error (data)</strong></td>
<td><strong>$6.4 \times 10^{-4}$</strong></td>
<td><strong>0.15</strong></td>
</tr>
</tbody>
</table>
Summary and conclusions

• In this talk we have presented the first accelerator neutrino oscillation results from a $0.93 \times 10^{20}$ POT exposure of the MINOS far detector

• Our result disfavours no disappearance, and is consistent with neutrino oscillations with the following parameters:

\[
\Delta m_{23}^2 = 3.05^{+0.60}_{-0.55} \text{(stat)} \pm 0.12 \text{(syst)} \times 10^{-3} \text{eV}^2 \\
\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15} \text{(stat)} \pm 0.06 \text{(syst)}
\]

• The systematic uncertainties on this measurement are well under control and we should be able to make significant improvements in precision with a larger dataset

  – Our total exposure to date is $1.4 \times 10^{20}$ pot.
Outlook

Improve this measurement:
Sensitivity at $10^{16}$ POT

Search for sub-dominant
$\nu_\mu \rightarrow \nu_e$ oscillations

- Study neutrino/anti-neutrino oscillations
- Search for/rule out exotic phenomena:
  - Sterile neutrinos, Neutrino decay
Back-up slides
Overview of the oscillation measurement

• To perform the oscillation analysis, we need to predict the neutrino spectrum seen by the Far Detector in the absence of oscillations

• Want to minimise uncertainties related to beam modeling and cross-sections (nominal values are built-in to our Monte Carlo)

• Use the Near Detector data to correct the nominal Monte Carlo
  – Measure the beam spectrum
  – Measure neutrino cross-sections
The NUMI facility

- **Design parameters:**
  - 120 GeV protons from the Main Injector
  - Main Injector can accept up to 6 Booster batches/cycle,
  - Either 5 or 6 batches for NuMI
  - 1.867 second cycle time
  - $4 \times 10^{13}$ protons/pulse
  - 0.4 MW
  - Single turn extraction (10ms)
The NuMI beamline

Target Service Building
Main Injector

Carrier Tunnel
Target Hall

MINOS Service Building

Beam Absorber Muon Detectors

Minos Hall Minos Near Detector

To Soudan

±105 M

Primary proton line

Target hall

Decay pipe
Monitoring the NuMI beam

Each spill we monitor:

1) Intensity
2) Beam position
3) Beam profile at the target
4) Hadron and muon profiles at the end of the decay volume

- This information is then used offline to select good beam quality spills
• Help understand energy response to reconstruct $E_v$
  $E_v = p_\mu + E_{had}$
• Measured in a CERN test beam with a “mini-Minos”
  • operated in both Near and Far configurations
  • Study e/μ/hadron response of detector
  • Test MC simulation of low energy interactions
• Provides absolute energy scale for calibration

Single particle energy resolution

- $55\% / \sqrt{E}$
- $23\% / \sqrt{E}$
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:
  - 1.9% absolute error in ND
  - 3.5% absolute error in FD
  - 3% relative
# Breakdown of selected events

<table>
<thead>
<tr>
<th>Cut</th>
<th>Events</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>All events in fiducial volume</td>
<td>331</td>
<td>-</td>
</tr>
<tr>
<td>Events with a track</td>
<td>296</td>
<td>89.1%</td>
</tr>
<tr>
<td>Track quality cuts</td>
<td>281</td>
<td>95.3%</td>
</tr>
<tr>
<td>PID cut (CC-like)</td>
<td>204</td>
<td>72.9%</td>
</tr>
<tr>
<td>Track charge sign cut (negative muons only)</td>
<td>186</td>
<td>91.2%</td>
</tr>
<tr>
<td>Reconstructed energy &lt; 30 GeV</td>
<td>166</td>
<td>89.2%</td>
</tr>
</tbody>
</table>
First year of MINOS running

- High rate in Near Detector results in multiple neutrino interactions per MI spill
- Events are separated by topology and timing

**Near Detector Event Timing**

- Events/19 nsec
- Time in Spill Gate (μ sec)

**Batch structure clearly seen!**

**One near detector spill**

**Snarl 95980 Strip times in microseconds**

- Individual events
- Time (us)
Selected events as a function of time

Open dataset

MINOS PRELIMINARY

Neutrino events per POT are flat as a function of time.
Systematics

- Normalisation: ±4%
  - POT counting, Near/Far selection efficiency
- Relative shower energy scale: ±3%
  - Inter-Detector calibration uncertainty
- Muon energy scale: ±2%
  - Uncertainty in dE/dX in MC
- NC contamination of CC-like sample: ±30%
  - From shape and normalisation of ND PID distribution
- CC cross-section uncertainties:
  - $M_A$ (QEL) and $M_A$ (RES) - ±5%
  - KNO RES-DIS scaling factors - ±20%
- Intranuclear rescattering: ±10% shower energy scale uncertainty
- Beam uncertainty: difference between fits with weighted/unweighted MC
To test the robustness of the method, a “fake dataset” was generated with tweaked beam/generator parameters and unknown oscillation parameters.

Beam Matrix Method yields an accurate estimation of the oscillation parameters despite the large differences between “Mock Data” and Monte Carlo (even for $10^{22}$ protons on target!)
Systematics: Test on $10^{22}$ POT mock data set—step A

MC used to correct for efficiency, purity and unsmearing quite different than the “data”.

Since corrections are relatively small, step A accurately predicts the true Near Detector Spectrum.
The different LE–10 200 kA matrix corresponds to different beam.

The Predicted Far spectrum is within 5% to the “actual” one.

Beam Matrix Method quite robust to beam related uncertainties as well.

NOTE: Red dotted bands are ± 5%.
Systematics: DIS cross sections changed by ± 20% 

fit on fake data.

Fake data Result: Extrapolated Spectrum

\[ \Delta m^2_{23} \chi^2 / \text{n.d.f} = 0.138549/27.000000 = 0.005131 \]
Systematics:
Different beam matrix used
fit on fake data.

\[ \Delta m_{23}^2, \chi^2 / \text{n.d.f} = 0.274709/27.000000 = 0.010174 \]

Fake data Result: Extrapolated Spectrum Beam Matrix

- Un-Oscillated
- Best Fit
- Fake Data

Reconstructed CC-like spectra (GeV)
Alternative methods for predicting the FD spectrum

- We have investigated three other methods of deriving the FD spectrum from the ND data:
  
  - Extrapolation using the Far/Near ratio from the MC
  - Two independent methods of fitting to the ND data in order to derive systematic parameters that are used to reweight the FD Monte Carlo

- These methods have quite different sensitivities to systematic errors, therefore comparing the results obtained with all four checks the robustness of our oscillation measurement
Notice that beam is pointing 3 degrees up at Soudan!
Neutrino-nucleus interactions were generated using the NEUGEN3 neutrino event generator (H. Gallagher, Nucl.Phys.Proc.Suppl. 112: 188-194, 2002).

Quasi-Elastic: dipole parameterisation of form factors with $m_a=1.032$ GeV/c$^2$.


Shower profiles
(LE-10 beam)

- Fairly good agreement between data and MC
- Data showers tend to be slightly shorter and more "dense" than MC showers
Numbers of tracks and showers

- Data
- MC
- MC Un-oscillated

Chi-squared / n.d.f. = 1.2/3 = 0.4

RMS 0.3976
Mean 0.9547

Chi-squared / n.d.f. = 2.8/3 = 0.9

RMS 0.3968
Mean 0.9414

MINOS PRELIMINARY

- Data
- MC
- MC Un-oscillated

Chi-squared / n.d.f. = 2.8/3 = 0.9

RMS 0.467
Mean 1.196

Chi-squared / n.d.f. = 2.8/3 = 0.9

RMS 0.5126
Mean 1.209

MINOS PRELIMINARY
Allowed region
(primary analysis)

$\chi^2 / \text{n.d.f} = 20.5 / 13.0 = 1.6$

$\Delta m^2_{23}$

MINOS Best Fit
MINOS 68% C.L.
MINOS 90% C.L.
SuperK 90% C.L.
Super-K (L/E)
K2K 90% C.L.

$\sin^2(2\theta_{23})$
Allowed region
(extended scale)

\[ \Delta m^2_{23} \]

\[ \chi^2 / \text{n.d.f} = 20.5 / 13.0 = 1.6 \]

- MINOS Best Fit
- MINOS 68% C.L.
- MINOS 90% C.L.

- SuperK 90% C.L.
- Super-K (L/E)
- MACRO
- K2K 90% C.L.
- SOUDAN2

\[ \sin^2(2\theta_{23}) \]
Systematics: DIS-Resonance region cross section factors

Near Detector Ratio of MC to "Data": changes are of the order of 5-6%.

Far Detector Ratio of Predicted to "Data": changes are of the order of < 1%.

- Far Detector Predicted spectrum accurate to within 1%.
- Using the Beam matrix method cross sections cancel out to a large extent.
Energy spectra & Y (CC-like events)

Reconstructed Neutrino Energy (GeV)

Reconstructed Y = $E_{\text{shw}}/(E_{\text{shw}} + E_m)$

These distributions shown after $x_F$, $p_T$ reweighting
The Beam Matrix Method

**step A)**
- measured $E$ (ND) → true $E$ (ND)
  - NC background subtraction
  - correct for selection efficiency and purity
  - correct for detector response

**Beam transport matrix**
Maps true E from ND to FD using
- pion decay kinematics
- beamline geometry

**step B)**

**step C)**
- true $E$ (FD) → predicted visible $E$ (FD)
  - add detector response
  - efficiency
  - background
  - oscillations
Step A, Beam Matrix Method

**Correction for purity**

\[
Purity(bin) = \frac{CCtrue}{CCtrue + NCtrue}(bin)
\]

Reconstructed => True and Correction for efficiency

\[
Efficiency(bin) = \frac{CCtrue}{CCall}(bin)
\]