Recent neutrino oscillation results from MINOS

Istvan Danko
University of Pittsburgh
(on behalf of the MINOS collaboration)
Outline

- MINOS and NuMI beam
- Recent results:
  - $\nu^\mu$ disappearance
  - $\bar{\nu}^\mu$ disappearance
  - search for sterile neutrino
  - $\nu^e$ appearance
- Conclusion and future
MINOS experiment

- Main Injector Neutrino Oscillation Search
- Long baseline (735 km)
- NuMI neutrino beam from Fermilab
  - $L/E \sim 1/\Delta m^2_{32}$ (atmospheric osc.)
- Near detector (1 km from target)
- Far detector in Northern Minnesota
- Taking data since 2005
MINOS detectors

- Functionally identical detectors to reduce systematics (neutrino flux, cross section, efficiency)
  - Tracking/sampling calorimeters: alternating steel and scintillator planes, magnetized (~1.3 T)
- Near detector (1 kt, 1 km from target): measures beam composition before oscillation
- Far detector (5.4 kt, 735 km from target): looks for oscillation signal
120 GeV/c protons strike a graphite target
10 µs spill/2.2 s; 3.3e12 p/spill (300 kW)
Secondary mesons (π⁺ and K⁺) are focused by two magnetic horns
π/K (and μ) decays produce neutrinos
\[ 91.7\% \nu_\mu + 7\% \bar{\nu}_\mu + 1.3\% \nu_e/\bar{\nu}_e \]
Neutrino energy spectrum can be tuned by changing target position and horn current (most data is LE) – tune beam simulation
MINOS data

- Reached $1 \times 10^{21}$ PoT earlier this year
- $7.2 \times 10^{20}$ PoT $\nu_\mu$ and $1.7 \times 10^{20}$ PoT $\bar{\nu}_\mu$ analyzed
Neutrino event topologies in MINOS

- **Charged current (CC) $\nu_\mu$ interactions**: produce muon that typically leaves a long prominent track in the detector plus a hadronic shower
- **Neutral Current (NC) events**: short, diffuse shower
- **CC $\nu_e$ interactions**: compact shower with EM core
 Measure $\nu_\mu$ disappearance as a function of energy:

- precision measurement of atmospheric oscillation parameters: $\Delta m^2_{32}$ and $\theta_{23}$
- updated with more data and improved analysis
Analysis technique

- Measure $\nu_\mu$ energy spectrum in the far detector and compare it to the un-oscillated prediction extrapolated from the near detector spectrum.

\[ P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m_{23}^2 L}{E_\nu} \right) \]
The neutrino spectrum shape in far detector and near detector are similar but not identical

- The neutrino energy depends on the decay angle and energy of the parent particle
- Higher energy pions travel further down the decay pipe before decaying
- The near detector sees a line source while the far detector sees a point source
Near to Far extrapolation

- Measured near detector spectrum is used to predict the expected far detector spectrum (without oscillation)
- Detailed beam simulation (beam-line geometry and the decay kinematics) is used to calculate the beam-transport matrix (or far/near spectrum ratio)
  - hadron production from target (the dominant source of flux uncertainty) is tuned to the near detector data at 6 different beam configurations
- energy smearing and acceptance correction from detector simulation
Analysis improvements

- More data: $3.4 \times 10^{20} \rightarrow 7.25 \times 10^{20}$ PoT

- Analysis improvements:
  - updated reconstruction and simulation
  - improved selection for low energy muons
  - improved shower energy resolution
  - no charge sign cut
  - simultaneous fits in bins of energy resolution
  - improved systematic uncertainties
νμ oscillation result

Expected (no osc.): 2451 events
Observed: 1986 events

Test alternative models:
- pure decay: +6σ (7.8σ if NC events included)
- pure decoherence: +8σ
\( \nu_\mu \) oscillation parameters

- Best measurement of \( \Delta m_{32}^2 \) (<5%)

\[
|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{eV}^2
\]

\[
\sin^2(2\theta) > 0.91 \ (90\% \ C.L.)
\]

- Dominant systematic uncertainties included in contours:
  - hadronic energy scale
  - track energy
  - normalization
  - NC background
  - Statistical uncertainty dominates

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**MINOS Preliminary**

- MINOS best fit
- Super-K 90%
- MINOS 90%
- Super-K L/E 90%
- MINOS 68%

7.2\times10^{20} \text{POT} - fiducial events

\( \sin^22\theta \)
New: measure $\overline{\nu}_\mu$ disappearance directly

- measure $\Delta m^2_{32}$ and $\theta_{23}$
- test CPT and exotic models
Producing $\bar{\nu}_\mu$ beam

In normal neutrino mode $\pi^-$ is de-focused:
- $\bar{\nu}_\mu$ contributes $\sim 7\%$ of total CC interactions
- Higher average energy $\rightarrow$ less sensitive to atm. oscillation
- First analysis in 2009
Antineutrino mode

Neutrino mode
Horns focus $\pi^+, K^+$

- $\nu_\mu$: 91.7%
- $\bar{\nu}_\mu$: 7.0%
- $\nu_e + \bar{\nu}_e$: 1.3%

Anti-neutrino Mode
Horns focus $\pi^-, K^-$

- $\bar{\nu}_\mu$: 39.9%
- $\nu_\mu$: 58.1%
- $\nu_e + \bar{\nu}_e$: 2.0%

Target
120 GeV $p$'s from MI

Focusing Horns
$\pi^+$

$2 \text{ m}$

15 m

30 m

675 m
\( \bar{\nu}_\mu \) selection

Selection follows 2008 neutrino analysis

- **Charge-sign selection** based on direction of bend in magnetic field (det. B field is also reversed to focus \( \mu^+ \) from \( \bar{\nu}_\mu \) CC)

- **NC/CC discrimination**: kNN algorithm in 4D variable space (track length, transverse profile of track, energy deposition and its fluctuation along the track)
Near detector spectrum

- 94.3% purity after charge sign selection and NC discrimination (98% purity below 6 GeV)
- 93.5% efficiency
- Good data MC agreement in ND
\[ \bar{\nu}_\mu \text{ result} \]

- Expected (no osc.): 155 events
- Observed: 97 events
- No oscillation is disfavored at 6.3\(\sigma\)
\[ |\Delta m^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2(2\theta) = 0.86 \pm 0.11 \]
\[ |\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{eV}^2 \]
\[ \sin^2(2\theta) > 0.91 \text{ (90\% C.L.)} \]

- \(~2\sigma\) inconsistency
- more antineutrino running is under way to improve nu-bar measurement
Search for sterile neutrinos

Measure Neutral Current (NC) rate in near and far detector

- sensitive to mixing with sterile $\nu$: $\Delta m_{43}^2 \sim \Delta m_{32}^2$ or $\Delta m_{43}^2 \sim O(1\text{eV}^2)$
- update with 2x more data and minor improvements
Neutral current analysis

- Total Neutral Current rate should not change between near and far detector in standard 3-flavor mixing
- A deficit in the far detector could indicate mixing with sterile neutrinos

- Reject CC events with long muon like track
  - 89% efficiency
  - 61% purity
- $\nu_e$ events are included in NC sample
  - result depends on $\sin^2 2\theta_{13}$
NC result

- Expect 757 events
- Observe 802 events
- No significant deficit

Far detector

\[ R = \frac{N_{\text{data}} - BG}{S_{NC}} \]

\[ = 1.09 \pm 0.06 \text{ (stat.)} \pm 0.05 \text{ (syst.)} \]

\[ \text{w/o } \nu_e \text{ appearance} \]

\[ = 1.01 \pm 0.06 \text{ (stat.)} \pm 0.05 \text{ (syst.)} \]

with \( \nu_e \) appearance

Fraction of the disappearing \( \nu_\mu \) that turns to sterile:

\[ f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} < 0.22 \ (0.40) \text{ at } 90\% \text{ C.L.} \]

no (with) \( \nu_e \) appearance
Search for $\nu_e$ appearance

- Sensitive to $\sin^2(2\theta_{13})$ – the only unknown mixing angle
- Non-zero $\theta_{13}$ opens the way to study CPV in the lepton sector
- Double the data from 2009

\[ \nu_\mu \rightarrow \nu_e \]
**$\nu_e$ selection and background**

- $\nu_e$ selection using an artificial neural net (ANN) with 11 input variables
  - characterizing longitudinal and transverse energy deposition
  - 41.6% signal efficiency
- Selected events in the near detector are decomposed
  - $\nu_\mu$ CC, NC, and beam $\nu_e$ components are determined using three different beam configuration each with different background composition:
    - two target positions with horn on and one with horn off

![Graphs showing $\nu_e$ selection and background](image-url)
Signal region (ANN>0.7):
- Expected: $49.1 \pm 7\text{(stat.)} \pm 3\text{(syst.)}$
- Observe: 54 events
- No significant excess ($0.7\sigma$)

Each background component is extrapolated separately to the FD
Check side-band (ANN<0.5):
- predicted: 313.6 events
- observed: 327 events
Oscillation probability calculated with 3-flavor mixing and matter effects included ($|\Delta m^2_{32}| = 2.43 \times 10^{-3} \text{ eV}^2$)

- Feldman-Cousin confidence intervals

90% C.L. at $\theta_{23} = 45^\circ$ and $\delta_{\text{CP}} = 0$

- $\sin^2(2\theta_{13}) < 0.12$ normal hierarchy

- $\sin^2(2\theta_{13}) < 0.20$ inverted hierarchy

Best limit for nearly all values of $\delta_{\text{CP}}$ (with normal hierarchy and maximal $\theta_{23}$)

$\Delta m^2 > 0$

\[ \Delta m^2 > 0 \]

- MINOS Best Fit
- 68% CL
- 90% CL
- CHOOZ 90% CL

$\Delta m^2 < 0$

\[ \Delta m^2 < 0 \]

- MINOS 7.01 $\times 10^{20}$ POT

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Summary

- $\nu_\mu$ disappearance:

\[
|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2 \\
\sin^2 (2\theta) > 0.91 \ (90\% \ C.L.)
\]

- $\nu_e$ appearance:

\[
\sin^2 (2\theta_{13}) < 0.12 \ (0.20) \ at \ 90\% \ C.L.
\]

- Sterile neutrino mixing:

\[
f_s \equiv \frac{P_{\nu_\mu \rightarrow \nu_s}}{1 - P_{\nu_\mu \rightarrow \nu_\mu}} < 0.22 \ (0.40) \ at \ 90\% \ C.L. \ \\
\text{no (with) } \nu_e \text{ appearance}
\]

- $\overline{\nu}_\mu$ disappearance:

\[
|\Delta m^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3} \text{ eV}^2 \\
\sin^2 (2\bar{\theta}) = 0.86 \pm 0.11
\]

Doubling data will reduce the uncertainty by 30%
Tuning the beam MC

Absolute neutrino flux uncertainty in the beam simulation is up to ~30%

- due to uncertainty in hadron production off the target (lack of data)

Although the extrapolation is not sensitive to the uncertainties in the absolute flux (only the much smaller relative flux is important)

Improve the beam simulation by tuning the hadron production (parametrized as a function of $p_t$ and $p_z$) to the near detector data at 6 different beam configurations

$\nu_\mu$ are constrained by the NA61 measurement of the $\pi^+/\pi^-$ ratio
Shower energy

- Estimated as the average true hadronic energy of the k-nearest-neighbour MC events in 3D space (total energy deposit in 1m radius around vertex, sum of the energy in the two largest showers, and the length of the longest shower):

MINOS Preliminary

![Graph showing shower energy distributions](image)
Energy resolution binning

- 5 bins in energy resolution for events with negative track
- 1 bin for events with positive track
CC systematic uncertainties

- Effect of varying the systematic parameters by $\pm 1\sigma$ on the oscillation parameters
- Statistics still dominates
Partially reconstructed events

- Partially reconstructed events originating outside the fiducial volume, mainly in the surrounding rock: doubles the FD data, but worse energy resolution (helps to establish overall event rate)
- They will be included in the final result
\( \bar{\nu}_\mu \) in MINOS detector

- Charged current (CC) \( \nu_\mu \) and \( \bar{\nu}_\mu \) interactions produce a muon that typically leaves a long prominent track in the detector.
- The \( \bar{\nu}_\mu \) and \( \nu_\mu \) CC interactions can be separated event-by-event using the charge sign of the muon in the magnetic field of the detector.

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

\[ \bar{\nu}_\mu \text{ CC} \]

\[ \text{Neutral Current (NC)} \]

\( \nu_\mu \) and \( \nu_\mu \) CC interactions produce a muon that typically leaves a long prominent track in the detector. The \( \bar{\nu}_\mu \) and \( \nu_\mu \) CC interactions can be separated event-by-event using the charge sign of the muon in the magnetic field of the detector.
Far detector data/MC agreement

MINOS Preliminary
- Data
- Oscillated MC
- No Oscillations

Far Detector
$1.71 \times 10^{20}$ POT
Antineutrino Running

Reconstructed $\mu^+$ Energy (GeV)

Reconstructed Shower Energy (GeV)

Q/P

CC/NC Separation Parameter
Comparison with 2009 $\bar{\nu}_\mu$ result

$\nu_\mu$ mode:
- $\nu_\mu$ beam with 7% $\bar{\nu}_\mu$
- higher average energy
$\nu_e$ systematics

- Statistical uncertainty 14.3%
NC background rejection check

- MRCC (muon-removed CC sample) used to check background rejection on shower remnant
Electron simulation

Test beam measurement demonstrate that electrons are well simulated.

Selection efficiency on muon-removed + simulated electron added data and MC agrees.