How to do a $\nu_e \rightarrow \nu_\mu$ measurement in a MINOS-like detector

Masaki Ishitsuka, Indiana University
for the MINOS collaboration

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Golden channel: $\nu_e \rightarrow \nu_\mu$ at Neutrino Factory

\[ \mu^- \rightarrow e^- + \nu_e + \nu_\mu \rightarrow \mu^- \]

\[ \mu^+ \rightarrow e^+ + \nu_e + \nu_\mu \]

Requirement to the detector

- Detection of $\bar{\nu}_\mu$ ($\nu_\mu$) appearance signal
- Muon change sign identification
- Separation of $\nu_\mu$ CC from $\nu_e$ CC and NC background
- Large detector mass
- (Reduction of the cost)

Magnetized tracking calorimeter detector like MINOS

Distinguished by the charge sign

Excess (Golden ch.)
Concept of MINOS

High intensity muon neutrino beam created at NuMI facility

Near Detector at Fermilab measures un-oscillated $\nu_\mu$ energy spectrum

Study of oscillations in Far Detector at Soudan Mine, Minnesota
MINOS Physics Goals

- Demonstrate $\nu_\mu \rightarrow \nu_\tau$ oscillation behavior

- Precise (<10%) measurements of oscillation parameters: $\Delta m_{23}^2$ and $\sin^2 2\theta_{23}$

- Search for / rule out exotic models:
  - Sterile neutrino in atmospheric $\nu$ oscillation
  - Neutrino decay, decoherence

- Search for $\nu_e$ appearance signal from sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation
  - Sensitivity to non-zero $\theta_{13}$ beyond current limit

- Study of neutrino and anti-neutrino oscillation by magnetized MINOS far detector

Latest results are presented by N. Saoulidou at the plenary session
NuMI Neutrino Beam

- Typical neutrino energy can be tuned by varying the target position relative to horns.
- Peak at 3GeV in low energy configuration.
- Neutrino beam profile in low energy configuration:
  - 92.9% $\nu_\mu$, 5.8% $\bar{\nu}_\mu$, 1.3% $\nu_e + \bar{\nu}_e$
- Performance (Week of 5/12)
  - 10$\mu$s spill of 120GeV protons every 2.2sec
  - Intensity: $3.0 \times 10^{13}$ POT/spill
  - 0.275MW beam power
MINOS Detectors

Magnetized Steel and Scintillator Tracking Calorimeter

- 2.5cm thick Magnetized steel planes: B~1.3T
- 1cm thick x 4.1cm width plastic scintillator strips
  arranged orthogonal orientation on alternate planes

**Near Detector**
- 1kton mass (3.8x4.8x17m³)
- 44ton fiducial mass
- 282 steel and 153 scintillator planes

**Far Detector**
- 5.4kton mass (8x8x30m³)
- 3.9kton fiducial mass
- 484 steel and scintillator planes
MINOS Far Detector
Magnetic Field
Detector Technology

- Single-sided readout for the near detector
- x8 (FD) and x4 (ND after 120th plane) multiplexing
- Downstream of the near detector is used as muon spectrometer with every fifth active plane.

Reduction of cost

- 4.1 x 1 cm co-extruded scintillator strips
- optical fiber readout
- M16 (FD) and M64 (ND) multi-pixel PMT
- GPS time-stamping to synch FD data to ND/Beam
- Continuous untriggered readout during spill time for ND (19nsec sampling)
- Light injection (LI) system for calibration
Reconstruction of a MINOS Event
Near Detector Interactions

- Intense neutrino beam makes multiple neutrino interactions spill in the ND
- Events are separated by topology and timing
- Event rate is linear with beam intensity
Event Topologies

\( \nu_\mu \) charged-current

\( \nu_e \) charged-current

Monte Carlo

\( E_\nu = E_{\text{shower}} + P_\mu \)

- 55%/\sqrt{E}
- 6% range, 10% curvature

Muon momentum is measured by:

- range for contained tracks
- curvature for exiting tracks

Long muon track + hadronic activity at vertex

Short event, often diffuse

Short with EM shower profile
Energy Calibration

Absolute energy calibration by “mini-MINOS”

- Measured in a CERN test beam.
- Study e/μ/hadron response.
- Operated in both ND and FD configurations.
- Test MC simulation of low energy interactions.

Calibration of ND and FD response using:

- Light injection system (PMT gain)
- Cosmic ray muons (strip to strip and detector to detector)

Energy scale calibration:

- 2% error on relative N/F calibration
- 5.7% absolute energy calibration
$\nu_\mu$ Charged-Current Event Selection

$\nu_\mu$ 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:
3. The fitted track should have negative charge (selects $\nu_\mu$)
4. Cut on Particle ID parameter which is used to separate CC and NC events.
Muon Charge Separation

• Muon charge/Momentum in the near detector where high energy muons exit from detector and only the part of track information is available.

• $\mu^-$'s are focused ($\mu^+$'s are diffused) by the magnetic field.

• NC interactions are distinguished by the event topology.
νμ Charged-Current Selection

CC / NC separation based on k-nearest neighbor (kNN) method with track quantities.

1. Track length (planes)
2. Mean pulse height
3. Fluctuation in pulse height
4. Transverse track profile

νμ CC efficiency (including track reconstruction) 81.5%

NC contamination 0.6%
MINOS improved the neutrino oscillation parameter measurement using $3.36 \times 10^{20}$ pot data from NuMI beam.

Magnetized steel and scintillator tracking calorimeter detector is optimized to detect muon tracks from beam $\nu_\mu$ CC interactions.

Performance of MINOS detector and prospect for the “Golden Channel”

- Clear muon tracks are reconstructed in MINOS detectors.
- $\mu^+$ and $\mu^-$ are distinguished with the magnetic field.
- $\nu_\mu$ CC interactions are selected by the event topology.
- Large detector mass with steel planes.
- Reduction of the cost was achieved with some ideas.