MINOS Experiment Overview

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Neutrino Mixing and Oscillation

- Can be explained by the non-coincidence of the mass eigenstates and the flavor eigenstates.
- In 2 flavor case, the transition probability is

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E).$$

- In 3 neutrino flavor case, the neutrino mixing and oscillation can be described by 3×3 PMNS matrix, mass splitting (Δm^2_{32} and Δm^2_{21}) and hierarchy.

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha/2} & 0 & 0 \\ 0 & e^{i\beta/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric term
$\theta_{23} \approx 45^\circ \pm 5^\circ$
K2K, MINOS, NoVA

Cross mixing term
$\theta_{13} < 10^\circ$ (90% C.L.), δ_{CP} unknown
Chooz, Double Chooz, Daya Bay
K2K, MINOS, T2K, NoVA

Solar term
$\theta_{12} = 34^\circ \pm 3^\circ$
SNO, KamLand

Majorana term

Neutrinoless double beta decay

MINOS Experiment

- long-baseline neutrino oscillation experiment
- Two functionally identical detectors
- NuMI ν_μ beam as neutrino source
- L/E~500 km/GeV, $\nu_\mu \rightarrow \nu_\tau$ is the dominant oscillation mode.
- Physics Analyses strategy
  measurement at ND.
  Make FD prediction by extrapolating ND measurement to FD.
  Fit FD data to extract oscillation parameters/limits.

MINOS Physics Goals

- Measurement of $|\Delta m^2_{32}|$ and $\sin^2(2\theta_{23})$ via ν_μ disappearance.
- Measurement of $|\Delta \overline{m}^2_{32}|$ and $\sin^2(2\overline{\theta}_{23})$ via $\overline{\nu}_\mu$ disappearance.

  Zeynep Isvan's talk next session

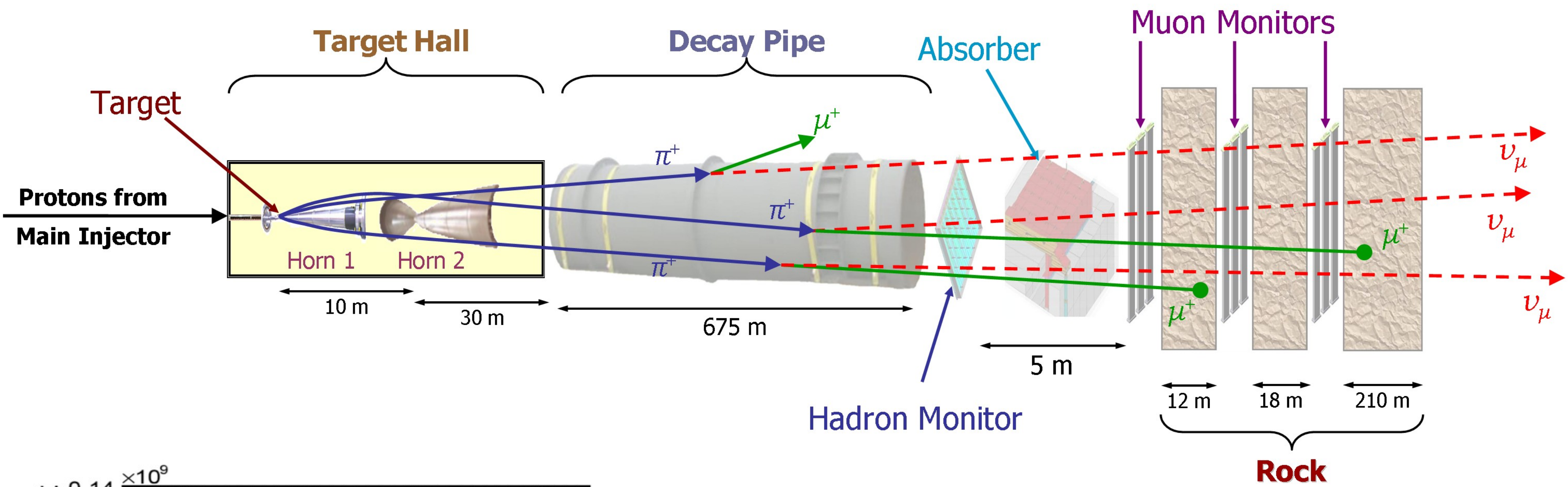
- Probe θ_{13} via ν_e appearance.

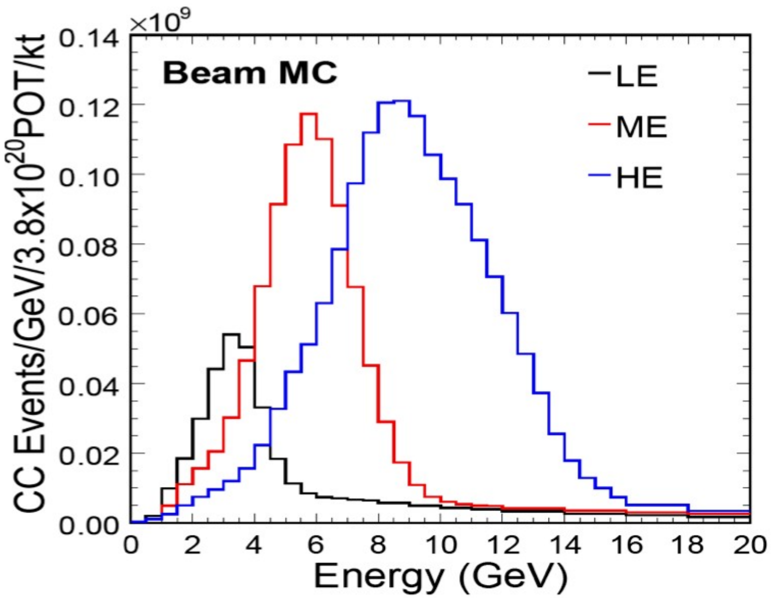
  Mhair & Adam talks in this session

- Search for sterile neutrinos.

- CPT and Lorentz violation search.
- Atmospheric neutrino and cosmic ray physics.
- Neutrino interactions and cross sections in ND.

NuMI Neutrino Beam

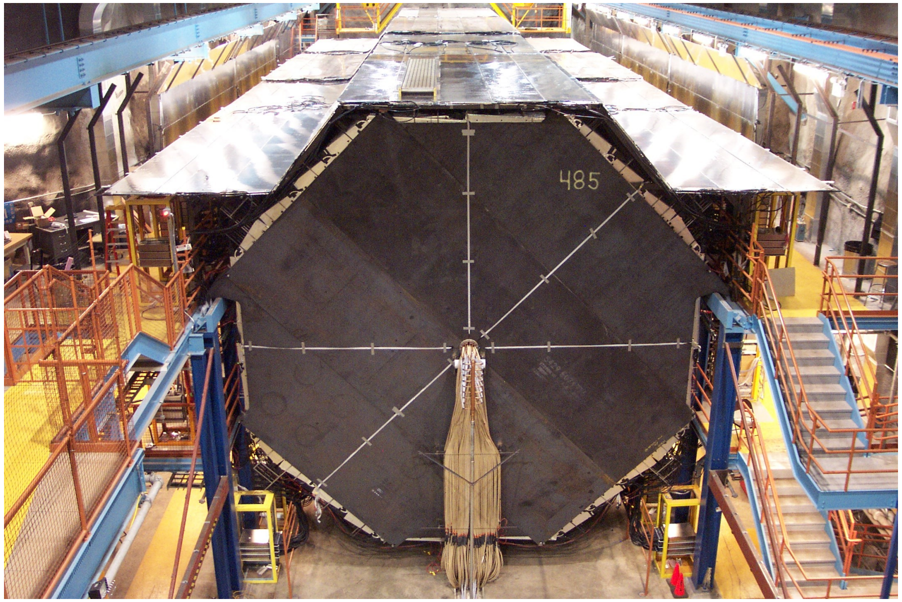




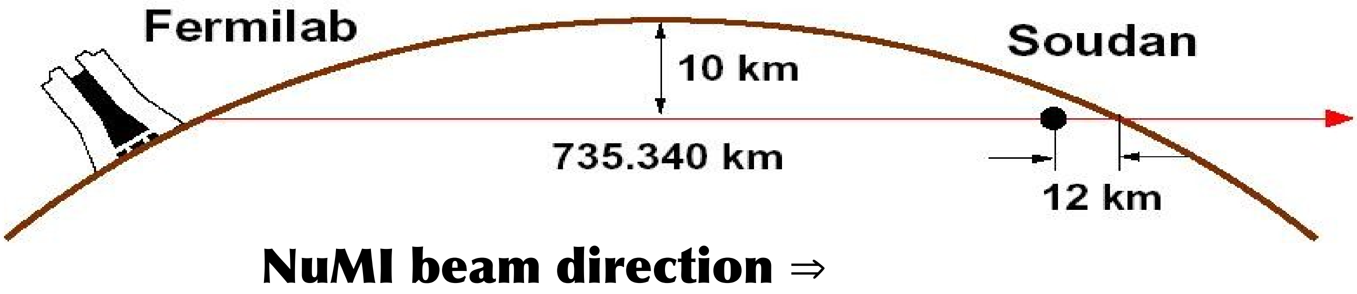
- 320 kw NuMI neutrino beam.
- 3 energy modes. MINOS runs at low energy mode.
- Switch between neutrino and antineutrino running by reversing the current of the focusing horn.

MINOS Detectors

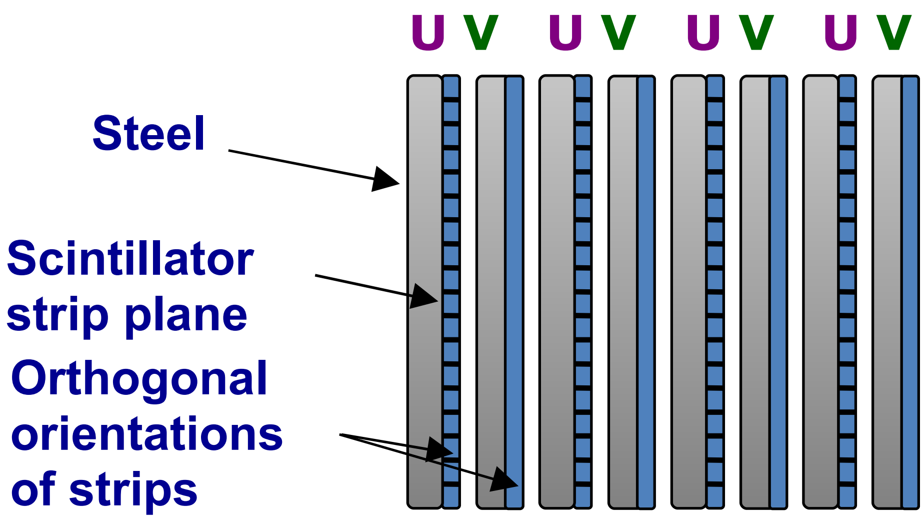
Near Detector (ND)
1 kT, 1 km downstream
100 m underground at Fermi lab



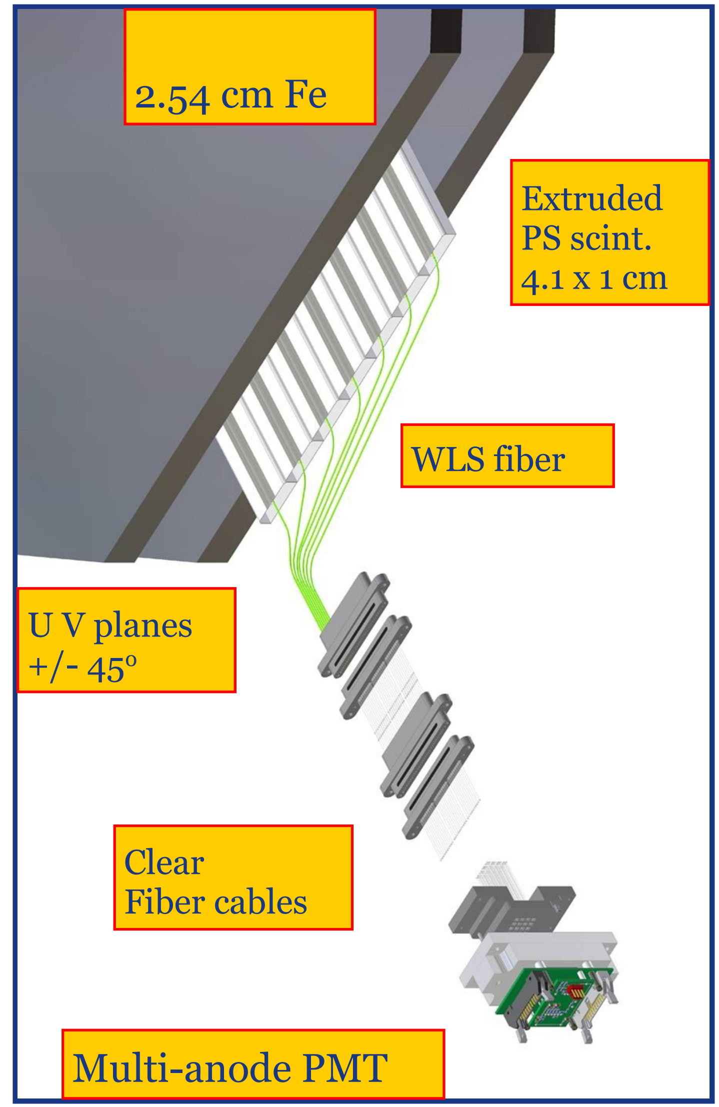
Far Detector (FD)
5.4 kT, 735 km downstream
714 m underground at Soudan mine



MINOS Detectors Read-out



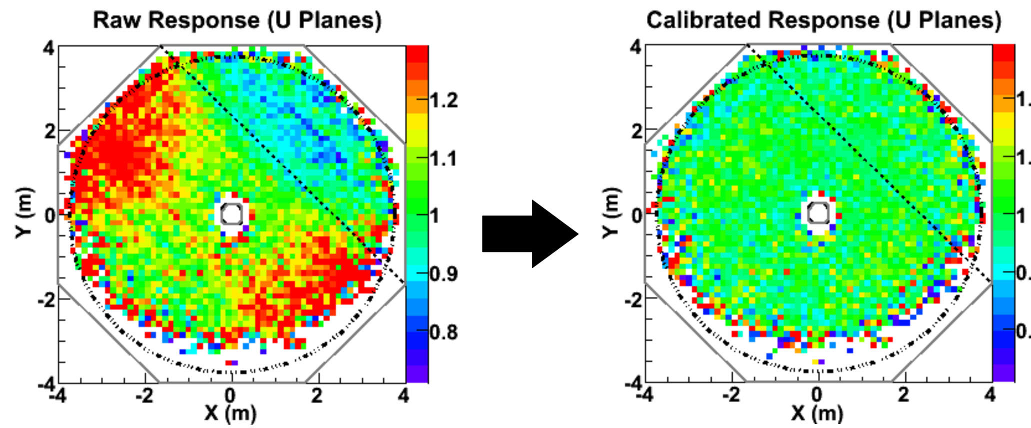
Side View of the MINOS Detector



- MINOS detectors are segmented tracking calorimeter
- Steel thickness: 2.54 cm (~1.4 X_0)
- Scintillator strips in adjacent planes are oriented orthogonally enabling 3D reconstruction
- Scintillator strip width: 4.1cm (~1.1 Moliere radii)
- Magnetized allows distinguish positive/negative muons
- Muon energy determined by range/curvature

Detector Calibration

Cosmic ray muons:
measure & remove **spatial variations**
(channel differences, attenuation)

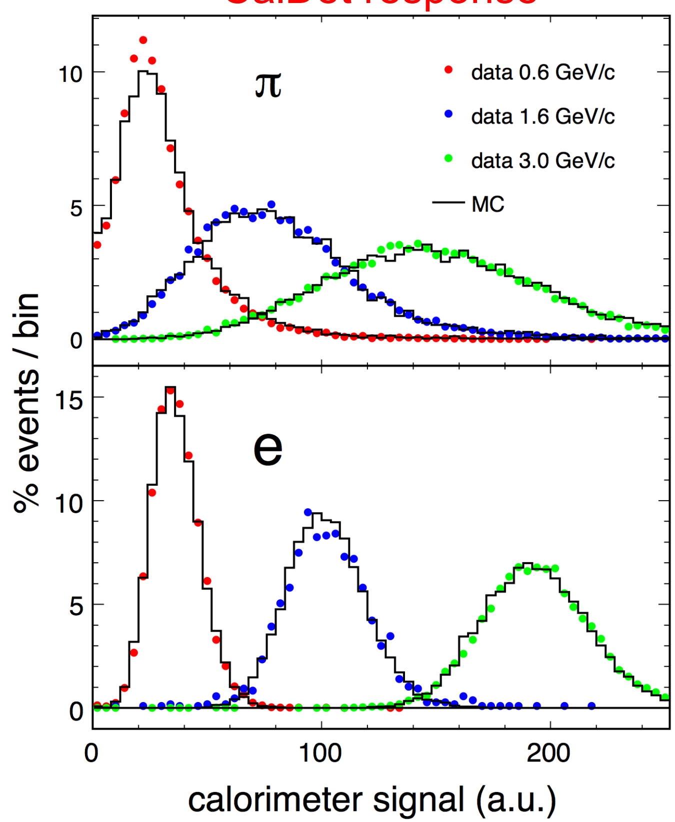


MINOS Calibration Detector (CalDet): *E* scale

- Exposed to **0.2–10 GeV** *p*, *e*, *μ*, *π* at CERN
- 60 planes, 1 m x 1 m

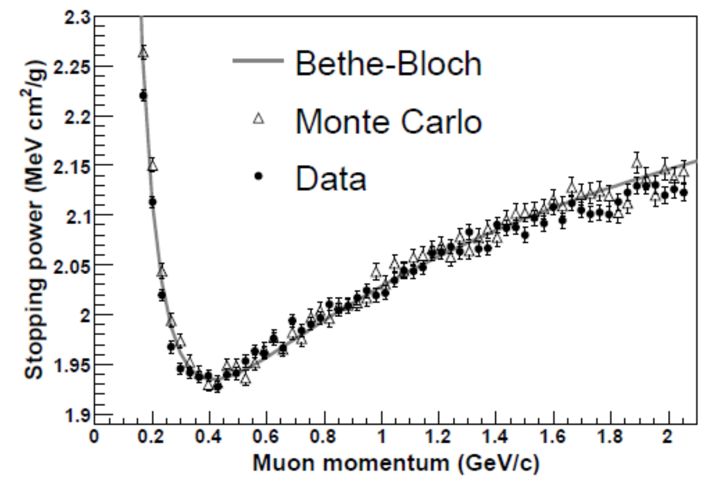
Ryan Patterson's slide, FNAL wine and cheese

CalDet response



Everything **tied together** with **stopping muons:**

Muons in Far Detector



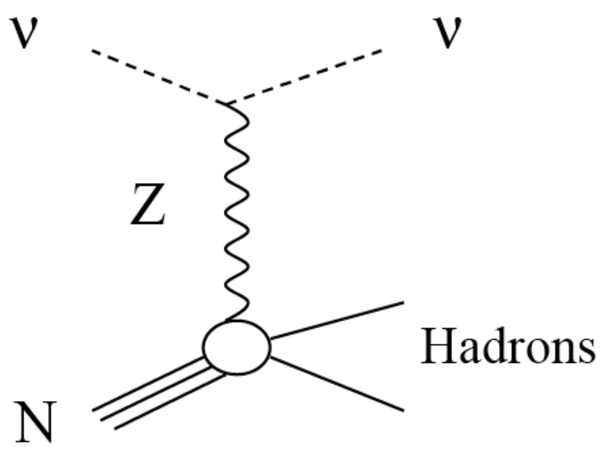
MINOS calorimetry good to:

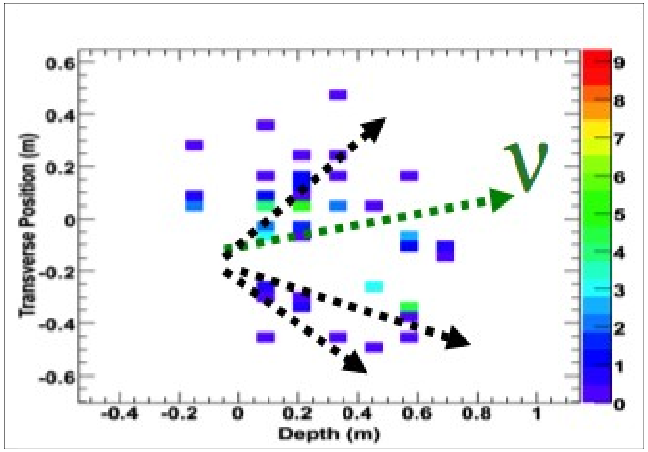
6% (absolute)
2% (relative near/far)

Events in the MINOS Detectors

NC events (MC)
Diffuse shower

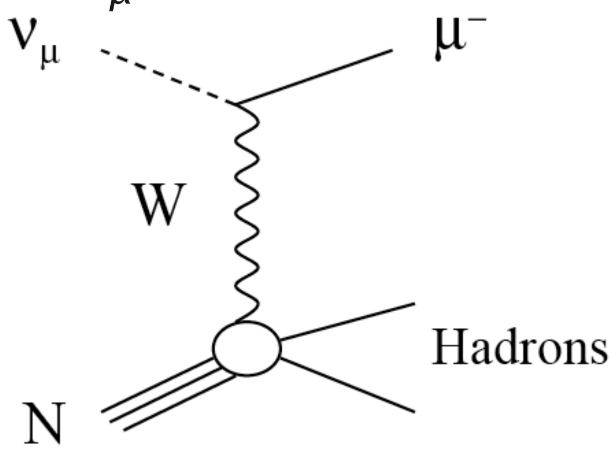
$$\nu\, N \rightarrow \nu\, X$$

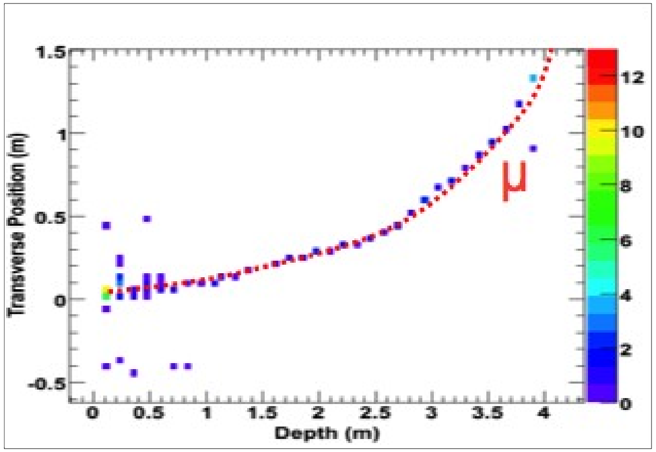




ν_μ CC events (MC)
long track

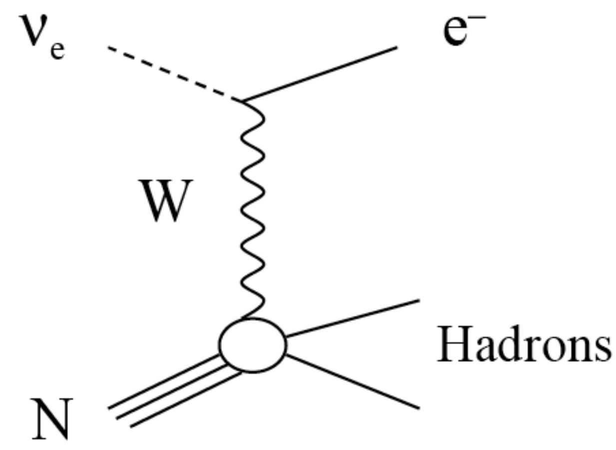
$$\nu_\mu N \rightarrow \mu^- X$$

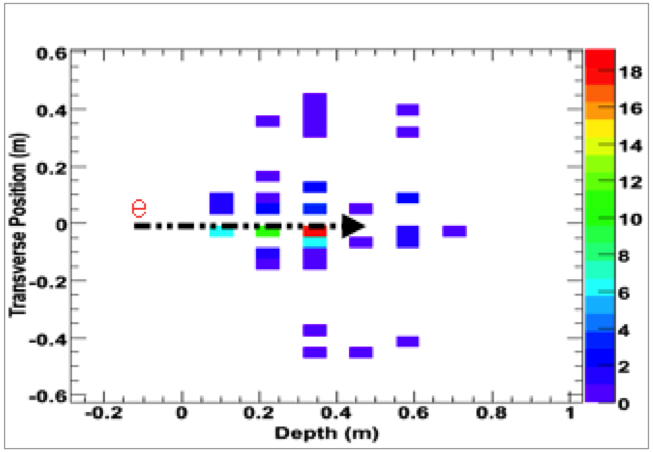




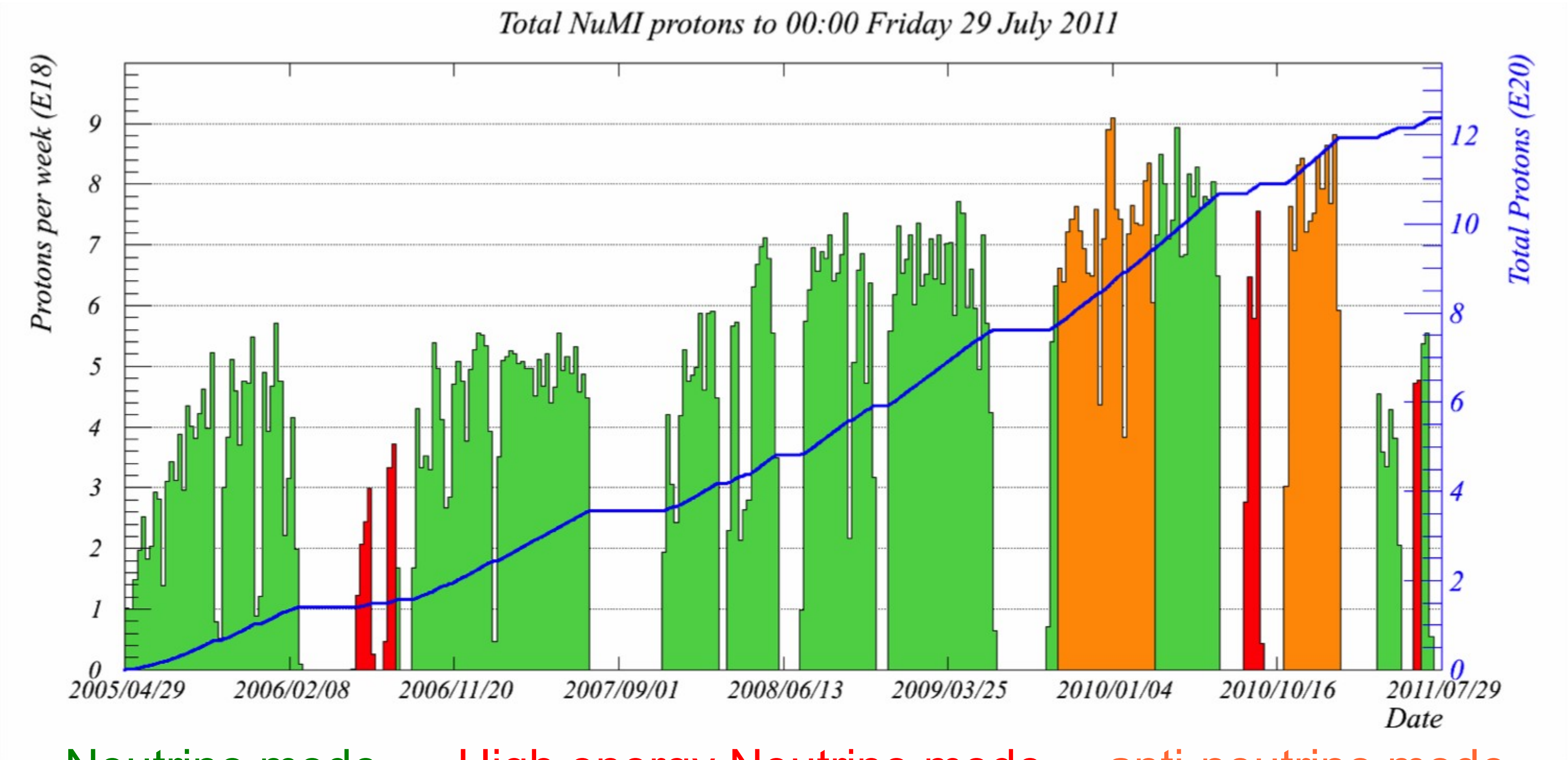
ν_e CC events (MC)
Compact EM shower

$$\nu_e N \rightarrow e^- X$$





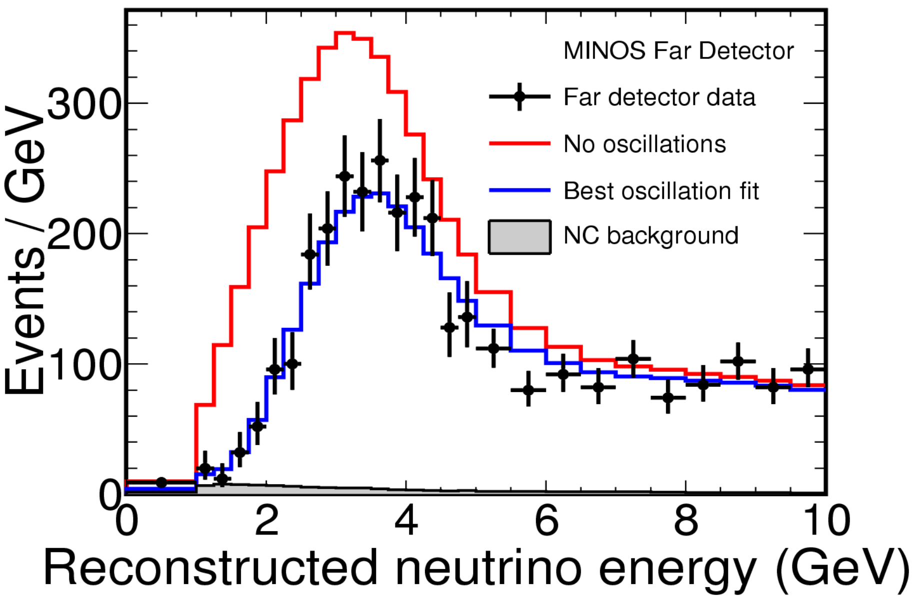
NuMI Beam Data

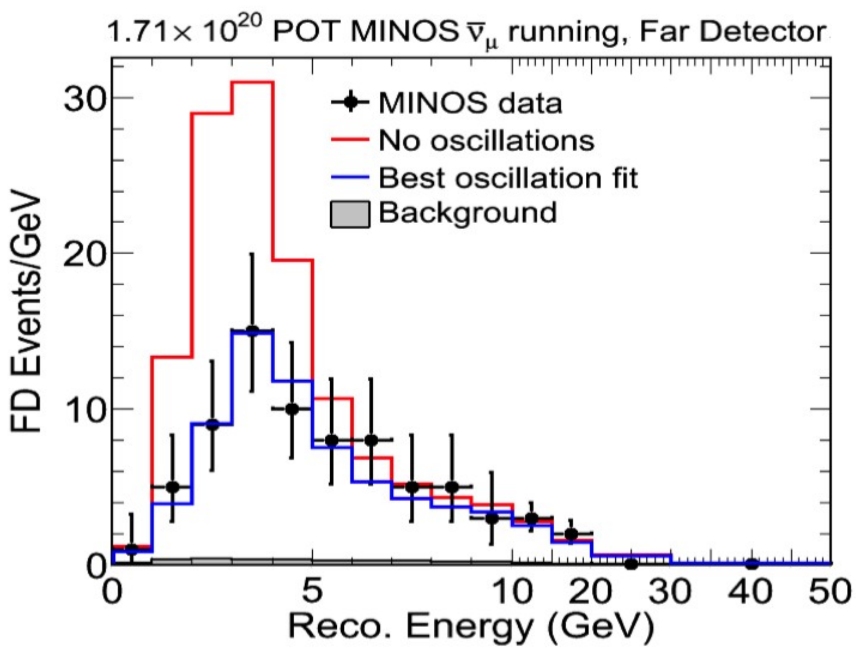


Neutrino mode High energy Neutrino mode anti-neutrino mode

MINOS started data-taking since 2005.
Data analyzed: 8.1×10^{20} POT ν_μ data and 1.7×10^{20} POT $\bar{\nu}_\mu$ data.

Disappearance Analyses





$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32} L/E)$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \approx 1 - \sin^2(2\bar{\theta}_{23})\sin^2(1.27\Delta \overline{m}^2_{32} L/E)$$

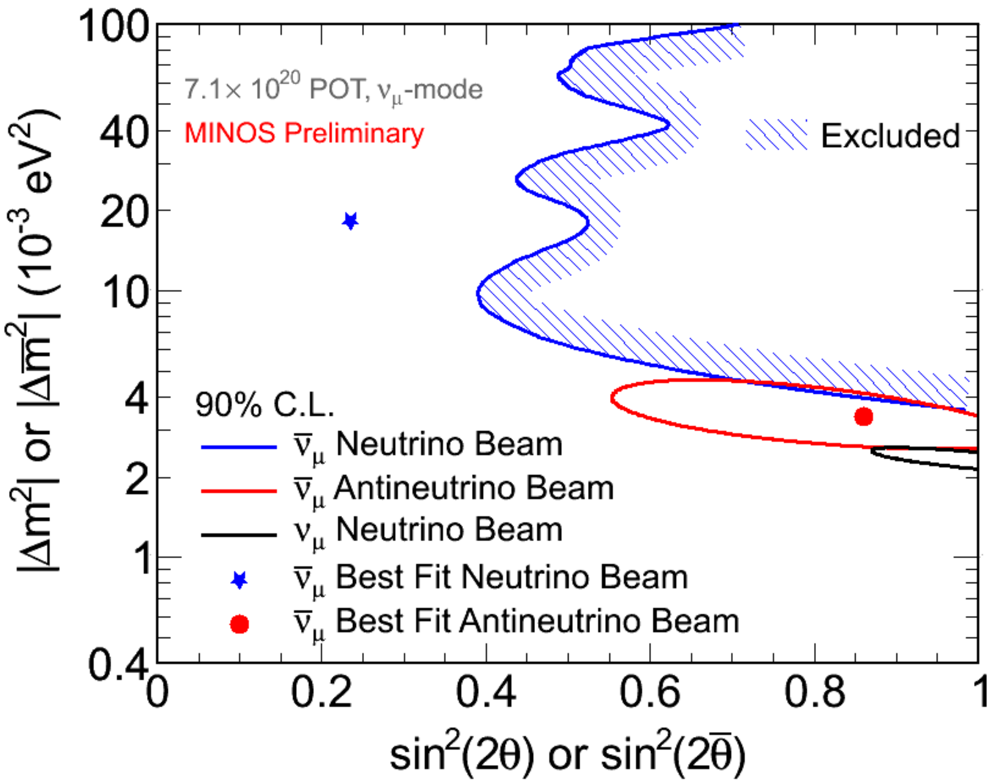
Event selection

- ν_μ CC events characterized by long muon track.
- Magnetic field allows separation of neutrino and antineutrino events.
- Further selections applied.

In both beam modes **the non-oscillation hypothesis is disfavored.**

Zeynep is going to give a more dedicated talk.

Disappearance Analyses



7.1×10^{20} POT muon neutrino

$$|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2,$$

$$\sin^2 2\theta_{23} > 0.90 (90\,\%\ \mathrm{C.L.})$$

Phys. Rev. Lett. 106, 181801 (2011)

1.7×10^{20} POT muon antineutrino

$$|\Delta \bar{m}^2_{32}| = 3.36^{+0.46}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2,$$

$$\sin^2 2\bar{\theta}_{23} = 0.86^{+0.11}_{-0.12}$$

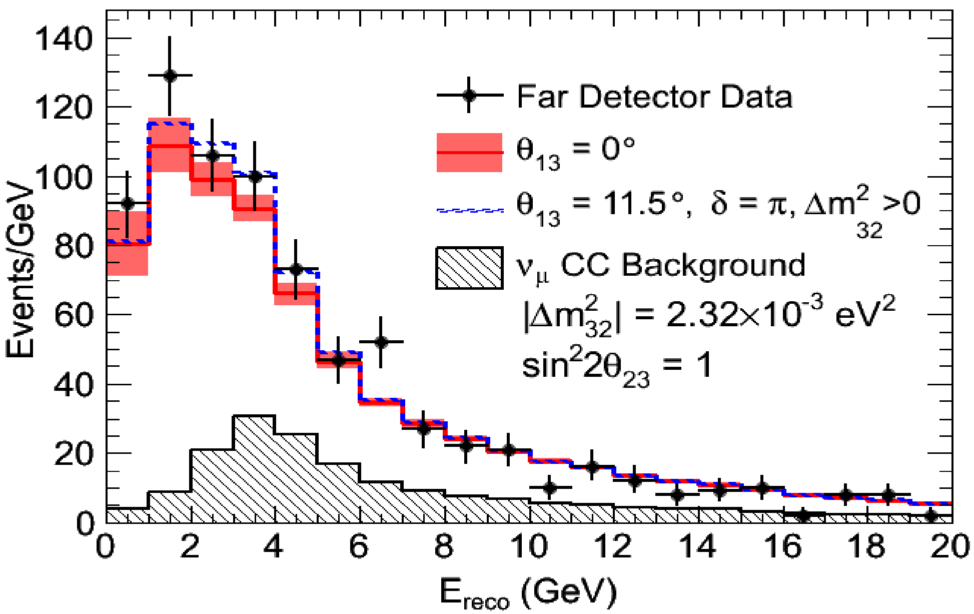
Phys. Rev. Lett. 107, 021801 (2011)

- Best $|\Delta m^2_{32}|$ measurement.
- Antineutrino anomaly. More antineutrino data are coming soon!

Antineutrino in neutrino beam mode ($3.42 < |\Delta \bar{m}^2| < 1000$) x 10^{-3} eV^2 excluded at 90% C.L. at maximal mixing

Sterile Neutrino Search

7.1×10[20] POT data



- Deficit of neutral current events could indicate transition to sterile neutrinos.
- Expected: 754 ± 28(stat.) ± 37(sys.) events.
- Observed: 802 events.
- Consistent with no oscillation into sterile neutrinos.

The fraction of active neutrino transition to sterile neutrinos, for $\theta_{13} = 0°$ (11.5°), is

$$f_s \equiv \frac{p_{\nu_\mu \to \nu_s}}{1 - p_{\nu_\mu \to \nu_\mu}} < 0.22\,(0.40) \quad \text{(at 90\% C.L.)}$$

Most stringent limit!

Phys. Rev. Lett. **107**, 011802(2011)

Electron-neutrino Appearance

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2(1.27\Delta m^2_{31} L/E)$

Also depends on δ_{cp} and matter effects.

MINOS is not optimized for θ_{13} measurement:

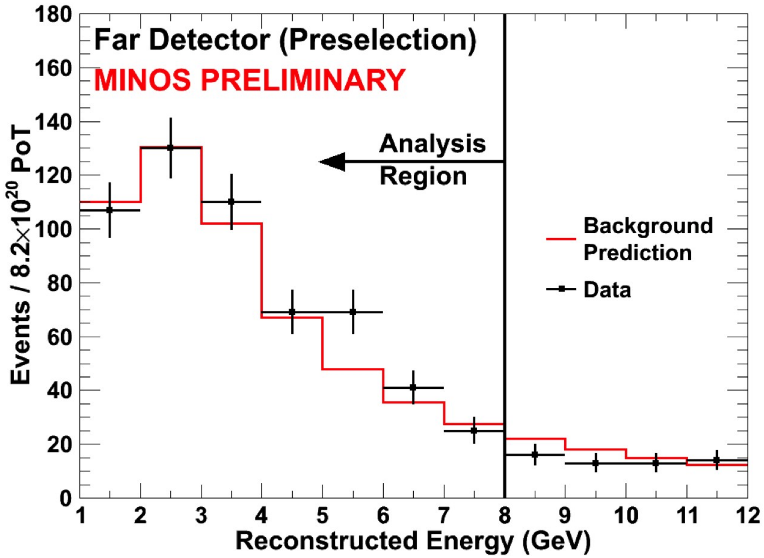
- L/E ~ 500 km/GeV, $\nu_\mu \rightarrow \nu_e$ is not dominant oscillation mode.
- Detectors have poor EM shower resolution.

Event selection

- Preselection cuts most of the ν_μ CC events.
- PID to determine ν_e CC events.
- Decompose near detector background
- Extrapolate components separately

Mhair is going to give a dedicated electron-neutrino appearance talk.

Electron-neutrino Appearance



- Expected Background:

  $49.6 \pm 7.0(\text{stat.}) \pm 2.7(\text{syst.})$ if $\theta_{13}=0$.

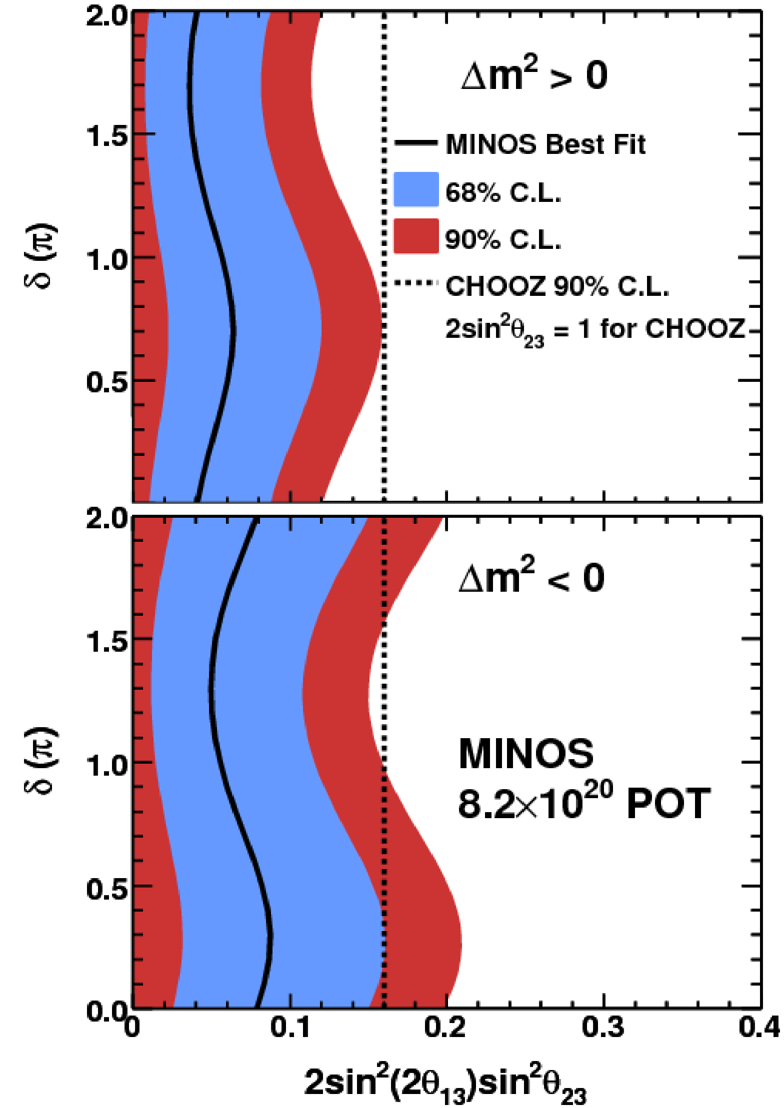
Observe 62 events. (1.7σ excess)

- At $\delta_{cp}=0$ and $\theta_{23}=\pi/4$ for normal (reverted) mass hierarchy,

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

  $\sin^2(2\theta_{13})=0.04$ (0.08) (best fit)

- $\sin^2(2\theta_{13})=0$ excluded at 89% C.L.



arXiv:1108.0015

Summary

The MINOS experiment provides us with exiting physics

- Best measurement of $|\Delta m^2_{32}|$ for neutrino.
- Anomaly with antineutrino disappearance.
- Best limit of fraction of transition to sterile neutrinos.
- Hint of non-zero θ_{13}.

MINOS+ is proposed to run MINOS at high energy mode.