A Study of the Neutrino Mass Hierarchy with MINOS Far Detector Atmospheric Neutrinos

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Neutrino Oscillation and Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric, accelerator — mixed terms — solar, reactor

$\theta_{23} \approx 45°$	Super-Kamiokande + MINOS
$\theta_{12} \approx 34°$	SNO solar data + KamLAND
$\theta_{13} < 11°$	CHOOZ reactor + MINOS
$\lvert m_3^2 - m_1^2 \rvert \approx 2.32 \times 10^{-3} eV^2$	MINOS + Super-Kamiokande
$m_2^2 - m_1^2 \approx 7.59 \times 10^{-5} eV^2$	KamLAND + all the SNO solar data
$\delta_{CP} = ?$	CP violating phase, value currently unknown

neutrino mass ordering (spectrum)

$m_3^2 \gg m_2^2 > m_1^2$ normal hierarchy (NH)

or

$m_2^2 > m_1^2 \gg m_3^2$ inverted hierarchy (IH)

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Two of the next frontiers of neutrino physics

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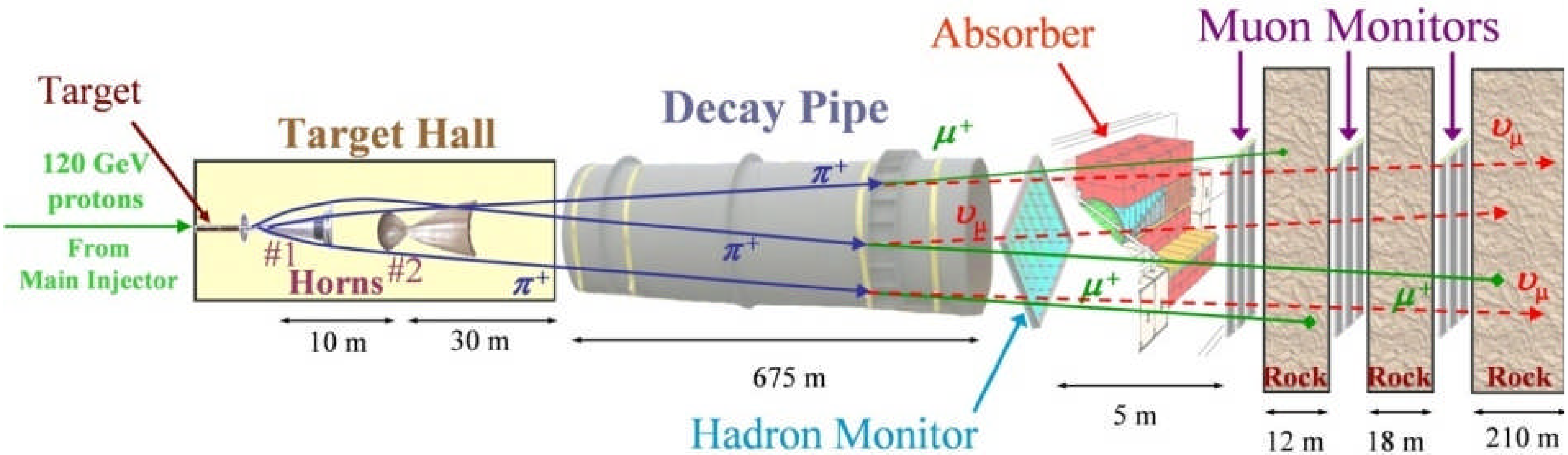
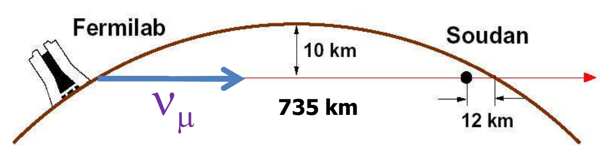
important for understanding the origin of neutrino masses and mixing

The MINOS experiment

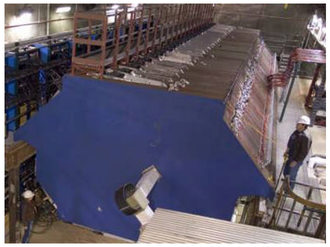


- MINOS - Main Injector Neutrino Oscillation Search
- High intensity high purity ν_μ beam from Fermilab
- Long baseline accelerator neutrino experiment

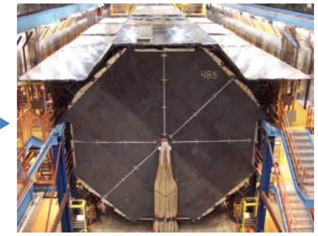


The MINOS Detectors

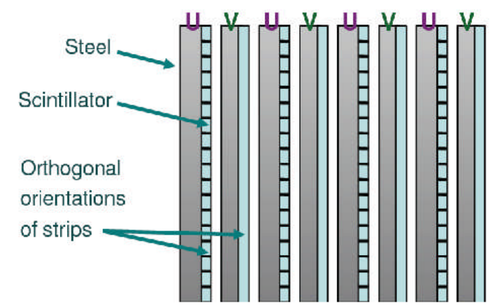
98.7% ν_μ
1.3% ν_e



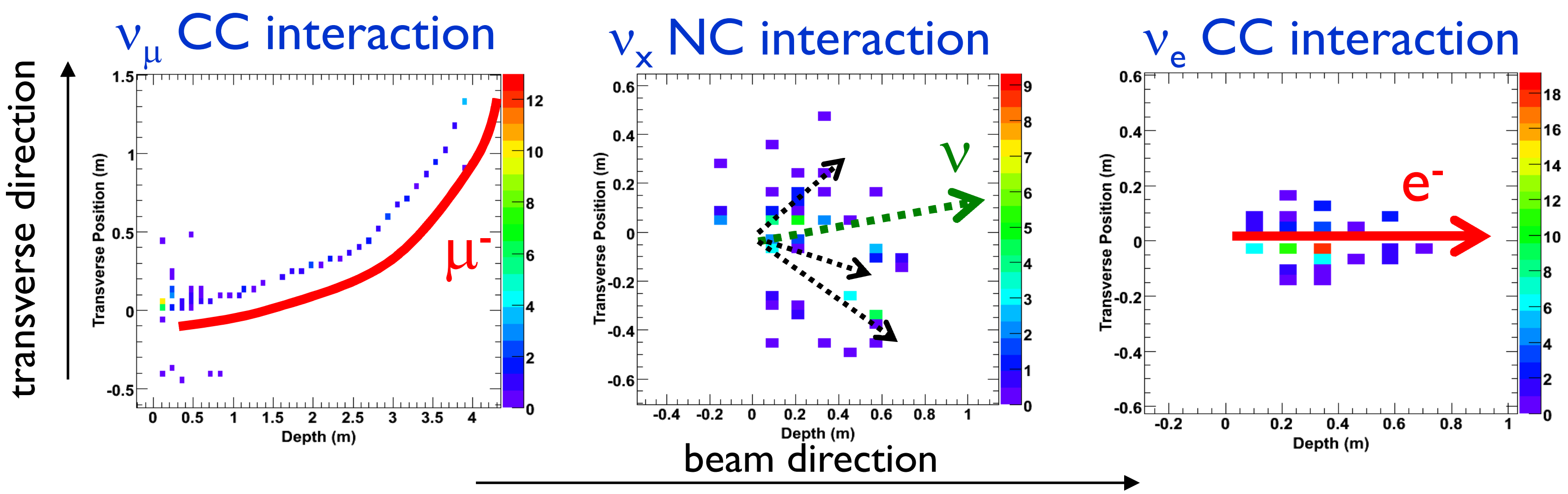
L = 735 km



- Two functionally identical detectors
  - Near Detector (0.029 kton fiducial mass) at Fermilab, IL to measure beam composition and energy spectrum
  - Far Detector (4 kton fiducial mass) at Soudan mine, MN to search for oscillation signals
  - Largely reduced systematics due to similarity of two detectors
- Steel/scintillator alternating magnetized tracking calorimeter
  - octagonal planes of steel - 2.54 cm thick
  - scintillator strips - 1.0 cm thick, 4.1 cm wide
- Designed for beam ν_μ disappearance oscillation study
- Capable of atmospheric ν appearance search



Neutrino Interactions in Detectors



Color scale represents energy deposition

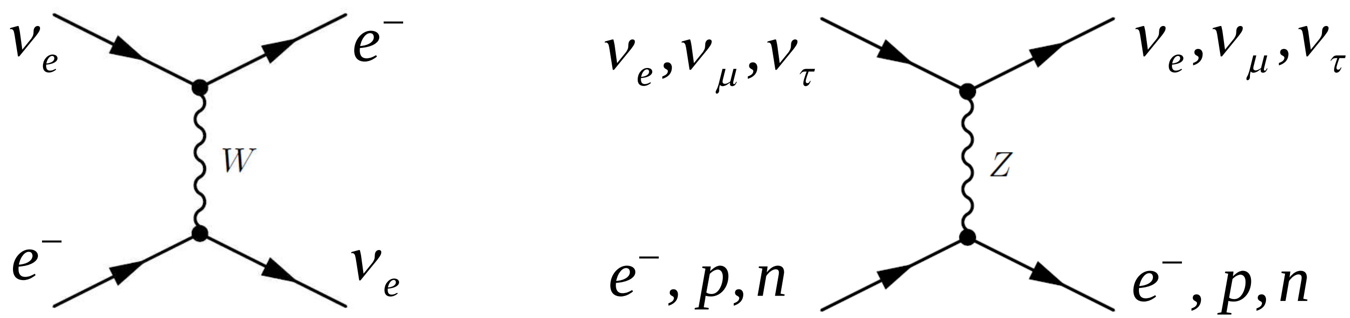
long muon track

short with diffuse shower
wider transverse energy distribution

short with compact shower

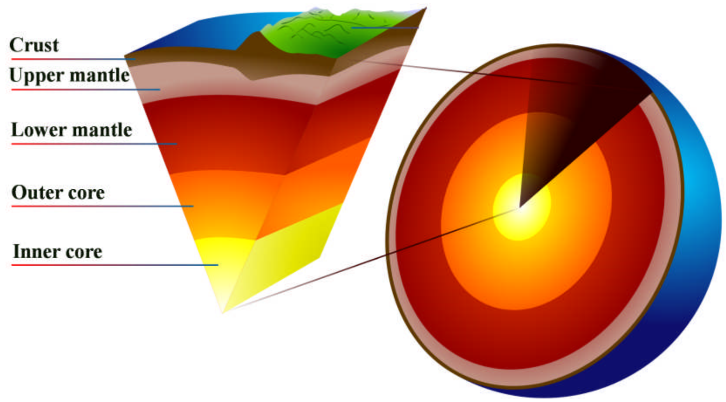
MINOS Approach to Determine Mass Hierarchy

- Widely discussed method for hierarchy determination: sizable matter effects at long baselines (e.g. diameter of the Earth)
- Matter effect (MSW effect) from the Earth

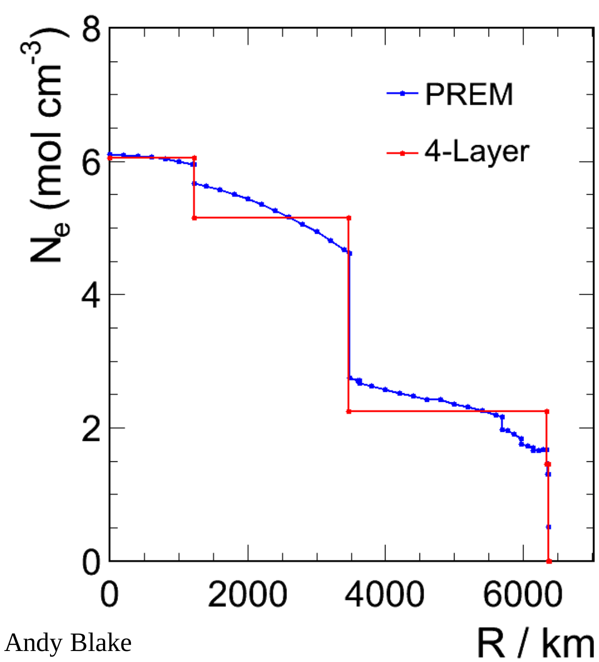


- Benefit of atmospheric neutrinos as the source
  - Wide ranges in energy (E) and baseline (L)
  - Possible to observe large resonant matter effects
- Uniqueness of MINOS detector
  - Magnetized tracking calorimeter
  - Muon charge identification to distinguish between ν_μ and $\bar{\nu}_\mu$ induced events
  - 7 years of data-taking collects hundreds of atmospheric ν_μ and $\bar{\nu}_\mu$ events

Earth Model



Credit: Jeremy Kemp, *et. al.*



Credit: Andy Blake

Earth's radial electron density distribution according to PREM and in MINOS

- ✓ Spherically symmetric density distribution in Earth models
- ✓ Median electron density in each region of preliminary reference Earth model (PREM)
- ✓ Piecewise constant radial matter density
- ✓ The oscillation probability is calculated with the product of the transition amplitudes of each layer a neutrino travels together with the amplitude crossing the Earth's atmosphere

Layer	inner core	outer core	mantel	crust
Mean e$^-$ number densities (mol cm^{-3})	6.050	5.205	2.215	1.470
Radius (km)	1220	3470	6336	6371
Zenith angle (deg)	169	147	96.0	~90

Cosmic Ray and Atmospheric Neutrinos

- Neutrino production in the atmosphere

Proton Nucleus Collision

$$p + N \rightarrow \pi^+ + \pi^- + N'$$

Pion Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Muon Decay

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

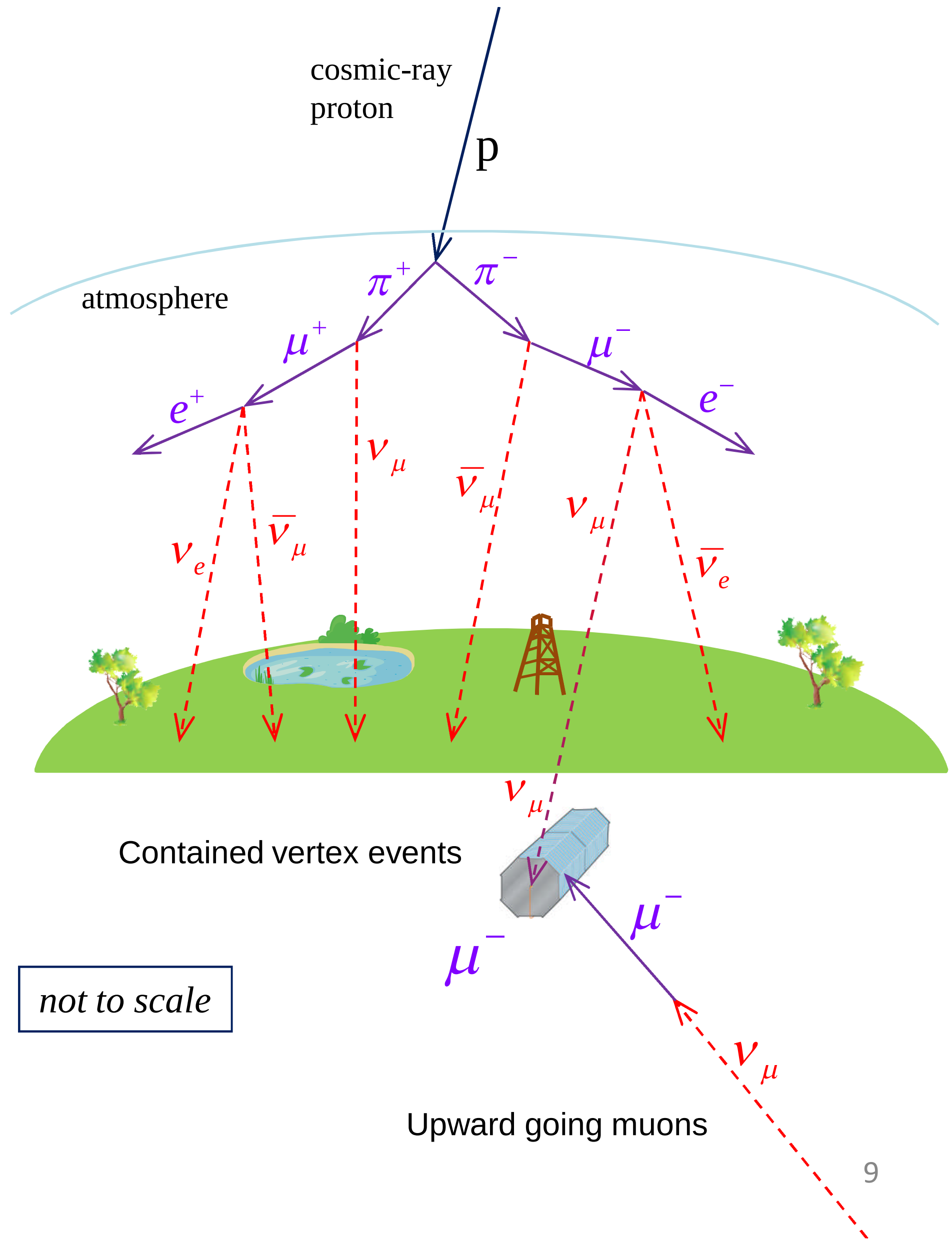
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

- Neutrino Interaction in the Earth and in the detector

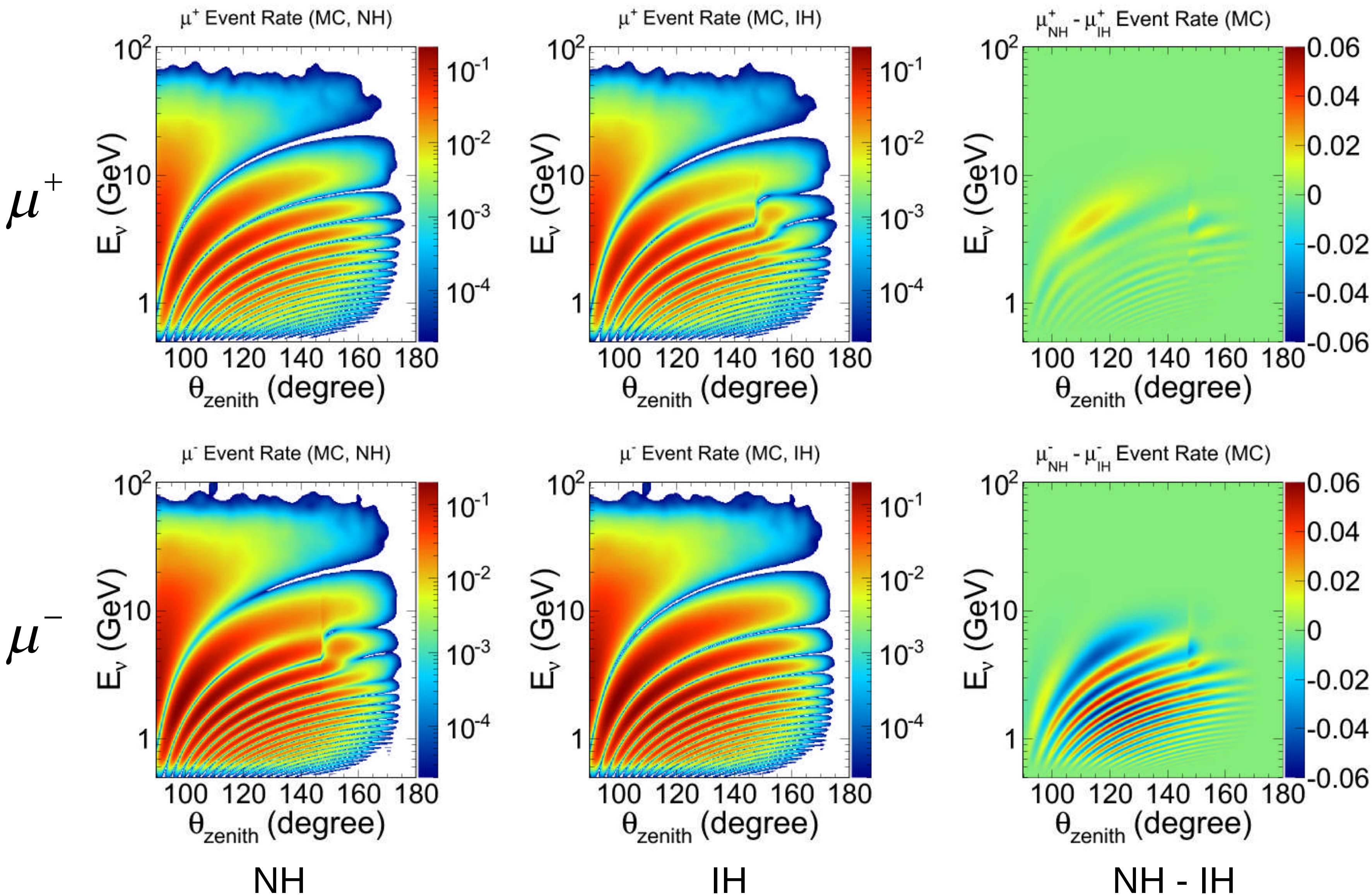
Neutrino-Nucleus Collision

$$\nu_\mu + N \rightarrow \mu^- + N'$$

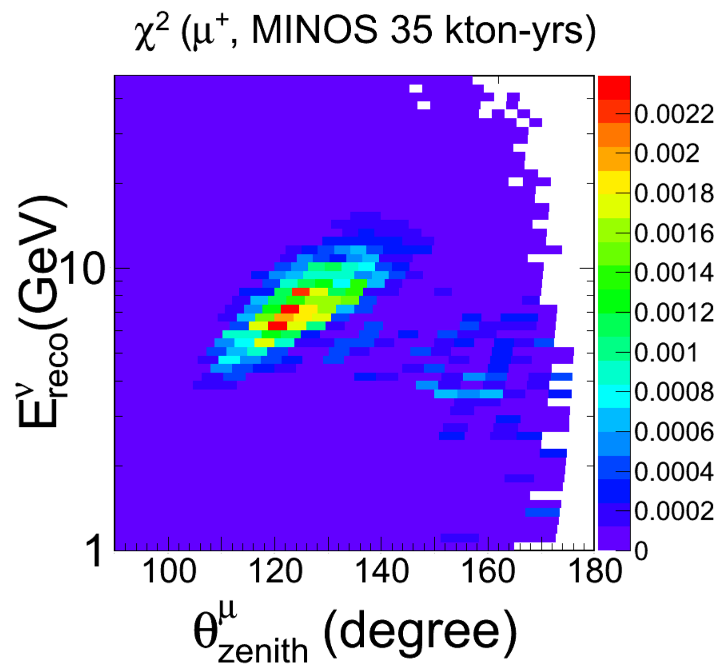
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + N'$$

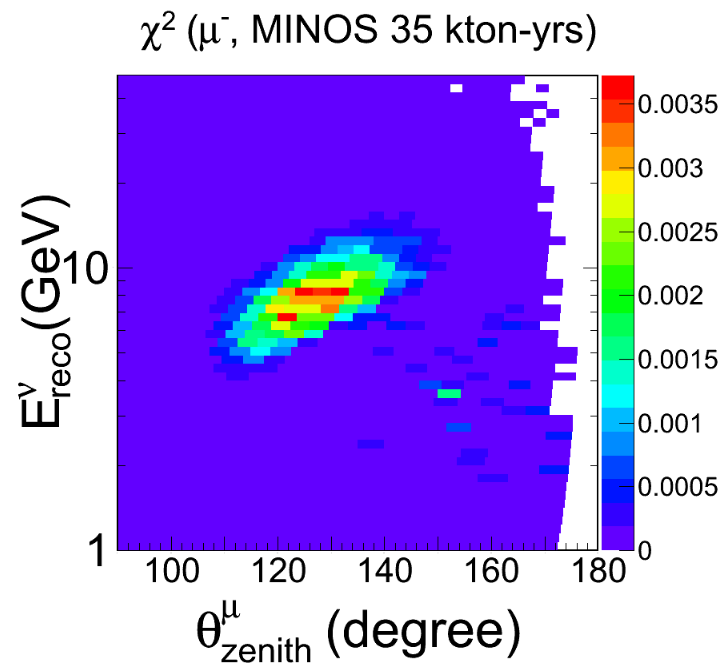


MINOS MC with Neutrino Oscillation Applied



χ^2 Analysis





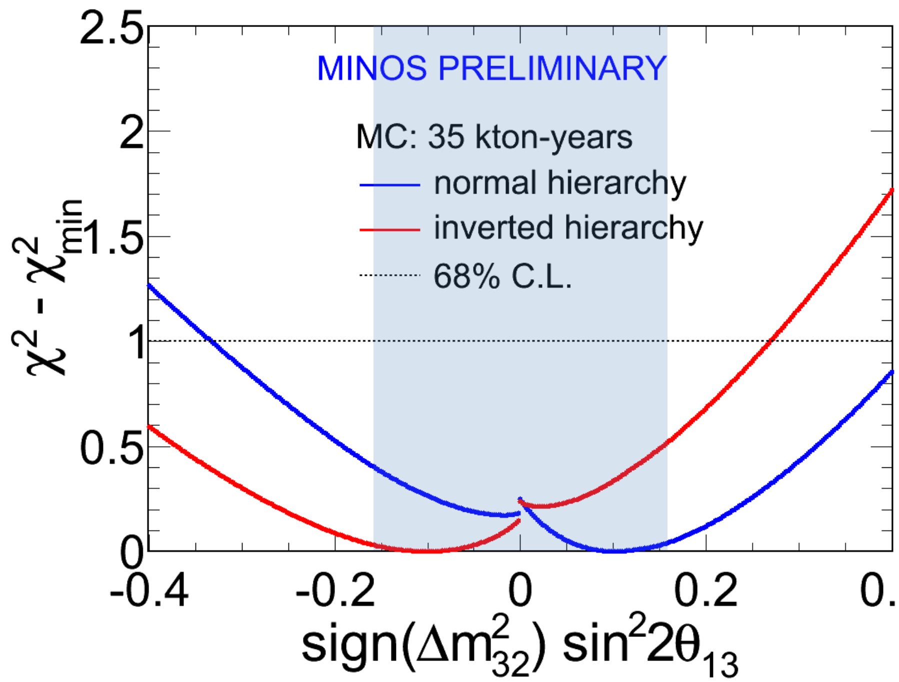
χ^2 function is defined as

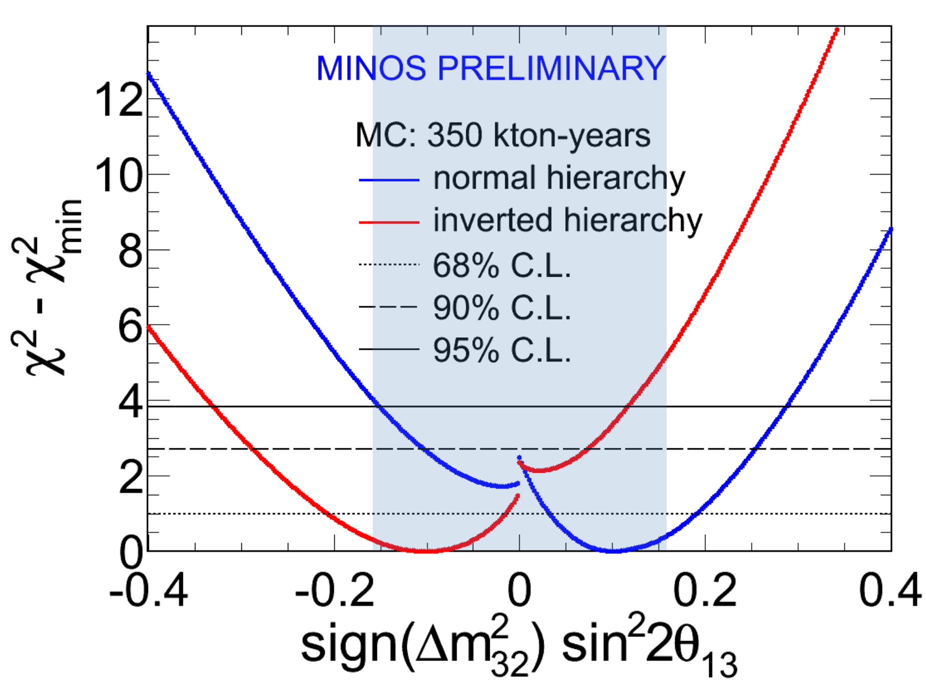
$$\chi^2 = 2\sum_{i=1}^{N}[\nu_i - n_i + n_i \ln(n_i / \nu_i)]$$

Where n_i is the number of data events in the i^{th} bin of the E - θ_{zenith} histogram, vi is the number of expected number of events in the i^{th} bin (from MC).

The total χ^2 runs over all the bins in each histograms, and over both μ^+ and μ^-.

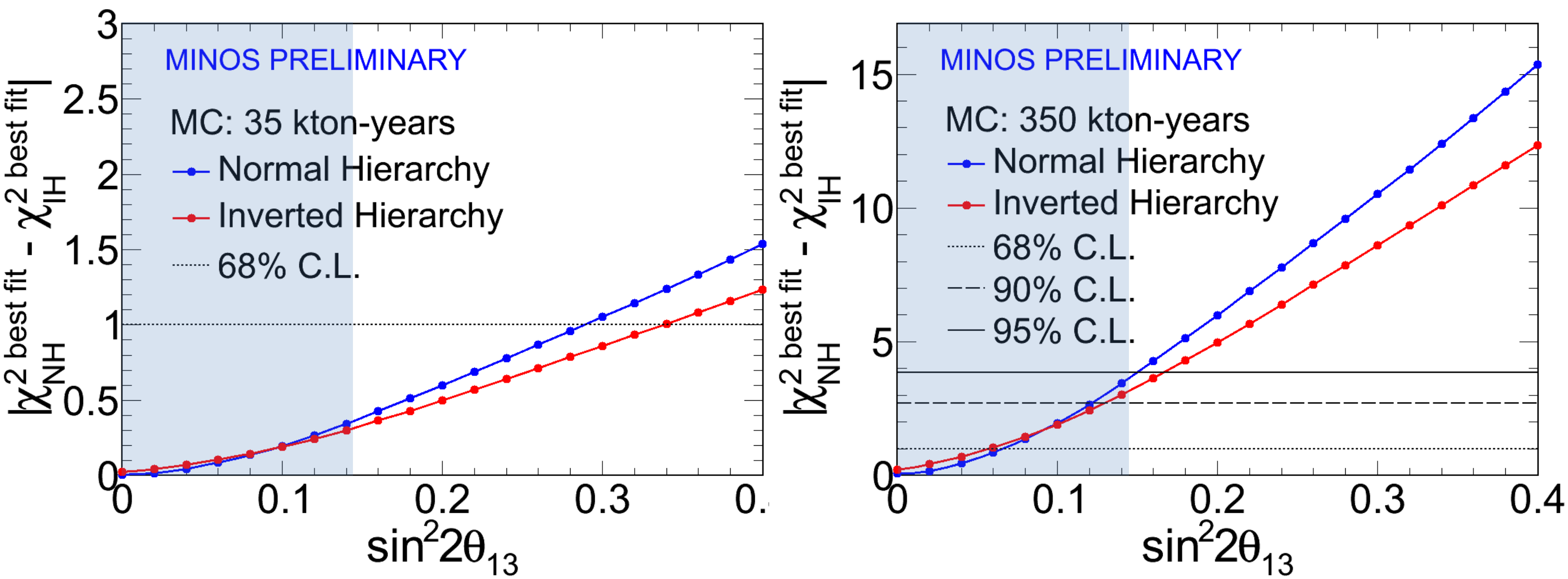
Determine Neutrino Mass Hierarchy from *$sign(\Delta m^2)sin^2 2\theta_{13}$*





χ^2 obtained from distributions with different θ_{13} compared to the one with $\sin^2 2\theta_{13} = 0.1$

Neutrino Mass Hierarchy Sensitivity



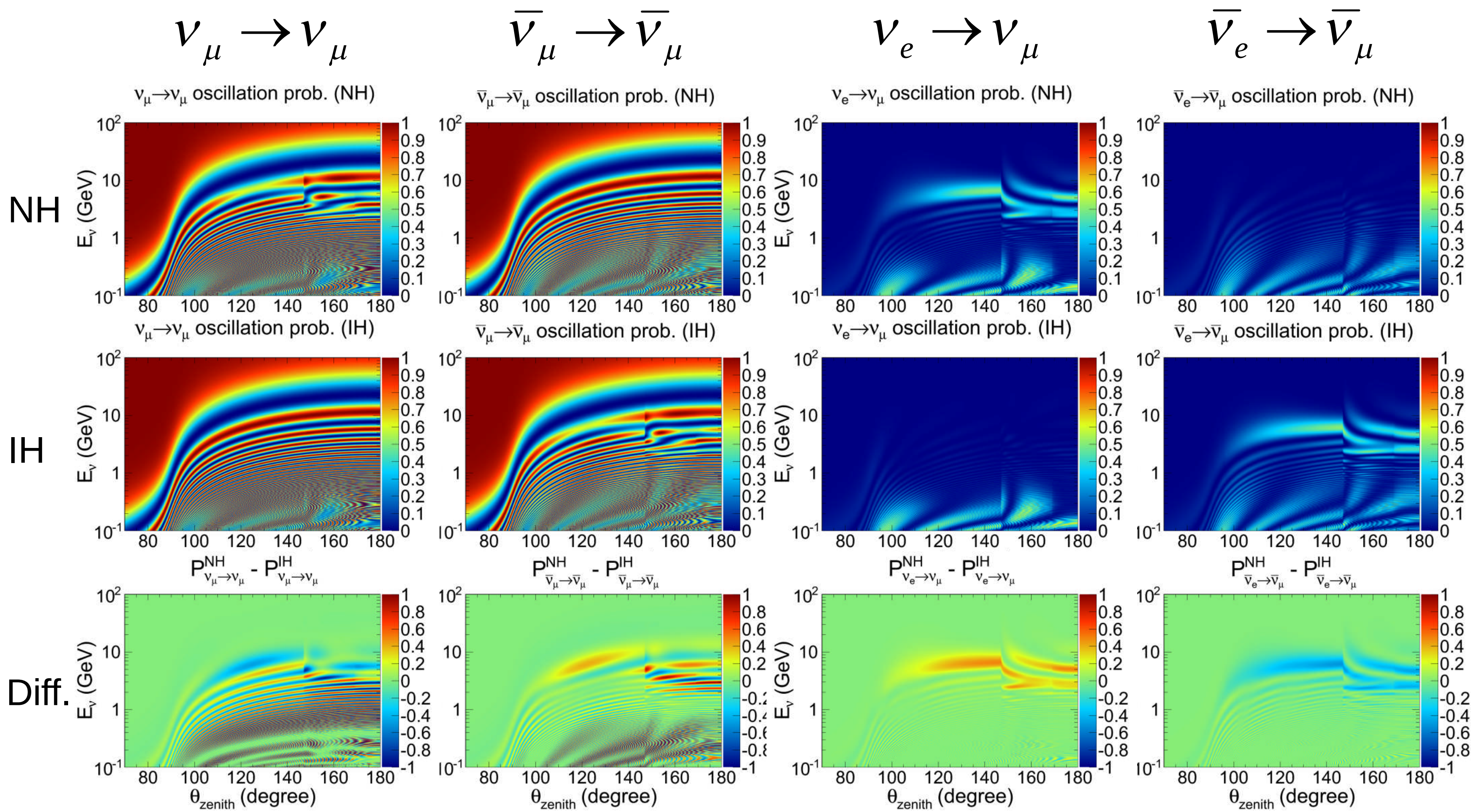
- ✓ Repeat steps in previous slide for different input values of $\sin^2 2\theta_{13}$
- ✓ Not much sensitivity to mass hierarchy with current MINOS exposure (35 kton-yrs)

Summary

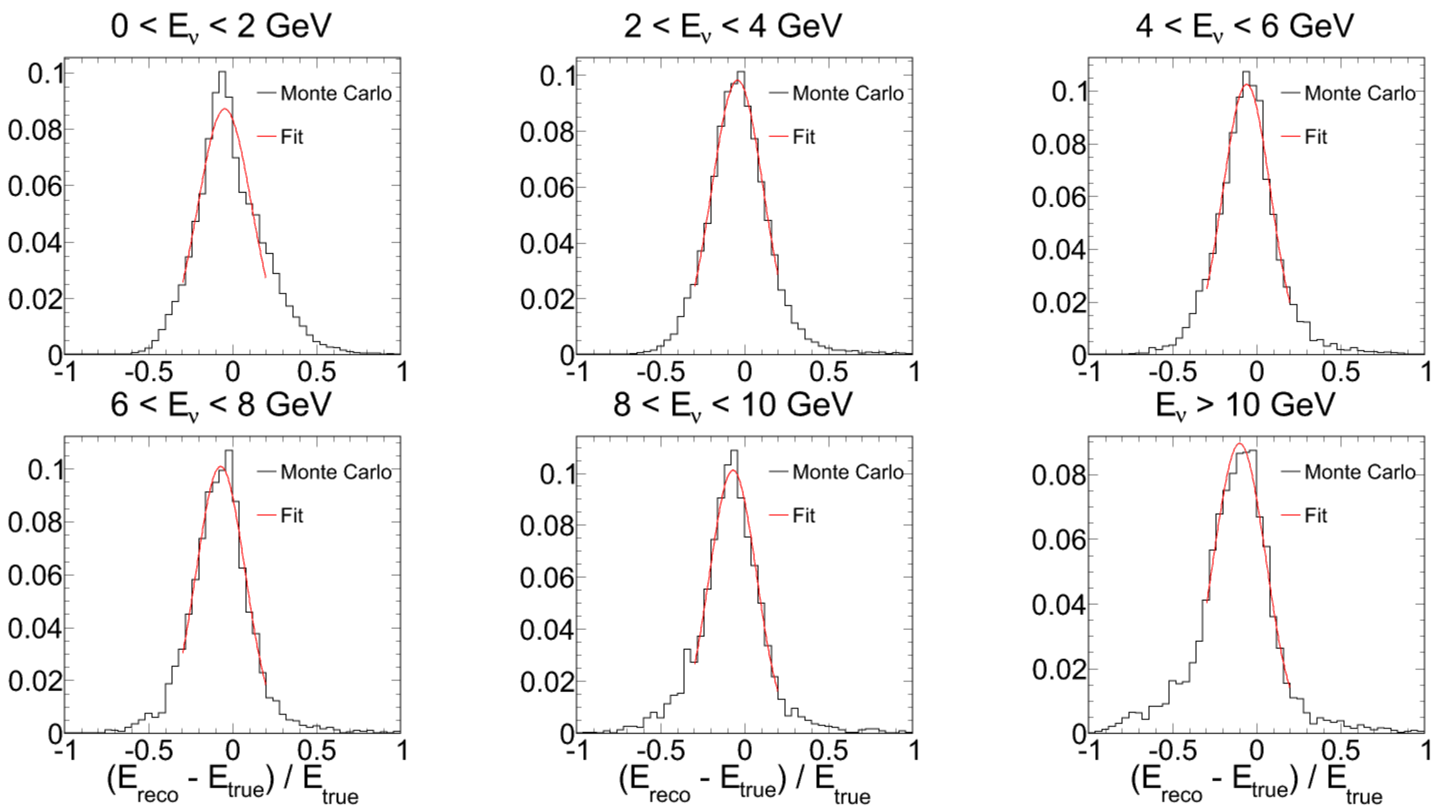
- MINOS Monte Carlo contained vertex events are used to estimate the sensitivity to determine neutrino mass hierarchy
- Current MINOS exposure doesn't have much sensitivity to determine neutrino mass hierarchy. The analysis gives us some guidance on the future neutrino detector with similar technique
- Work in progress
  - Roughly double the statistics once upward going muon events are included
  - Fold systematic errors into the analysis

Backup Slides

Atmospheric Neutrino Oscillations



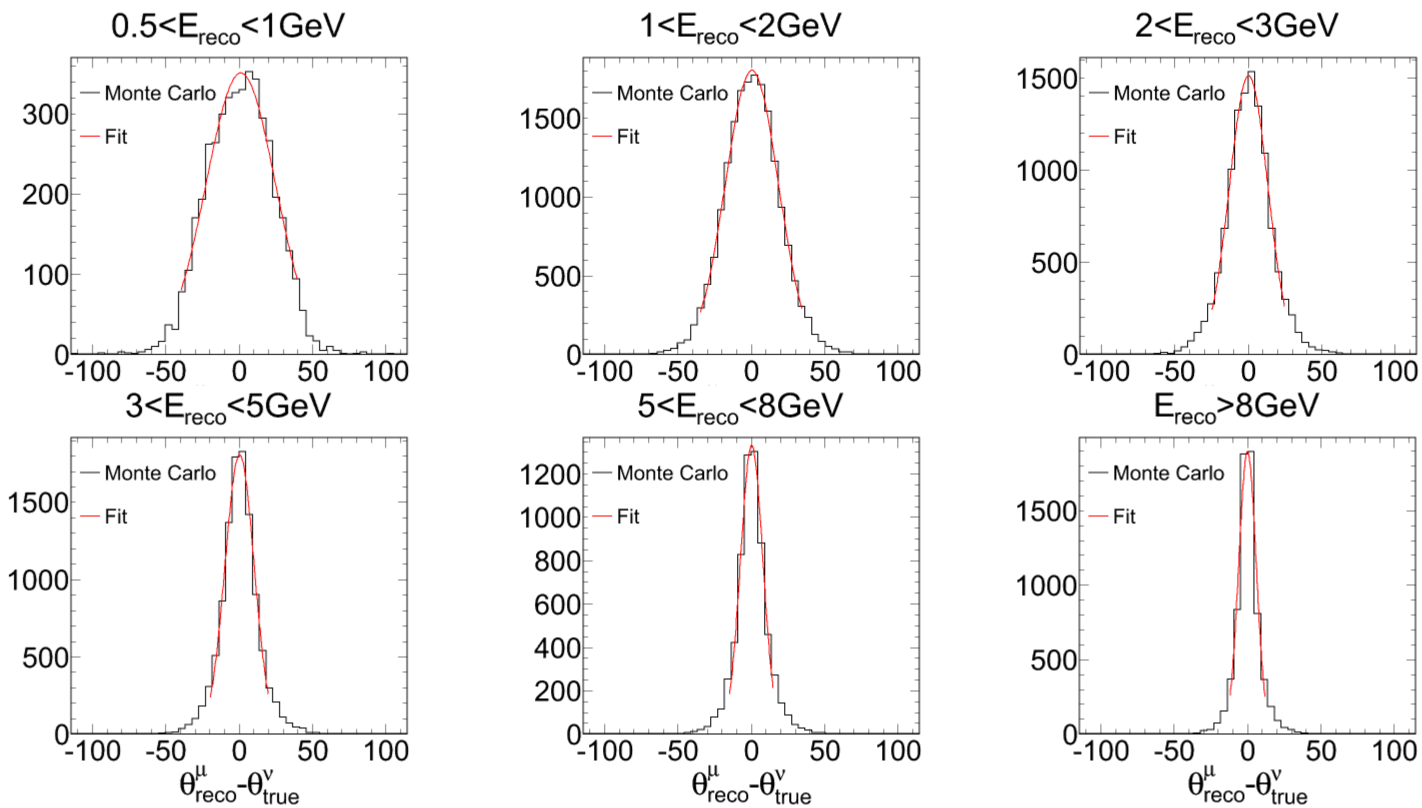
MINOS Energy Resolutions



Reconstructed Neutrino Energy Resolution:

Bins	0-2 GeV	2-4 GeV	4-6 GeV	6-8 GeV	8-10 GeV	>10 GeV
δE/E	0.16	0.15	0.14	0.15	0.14	0.16

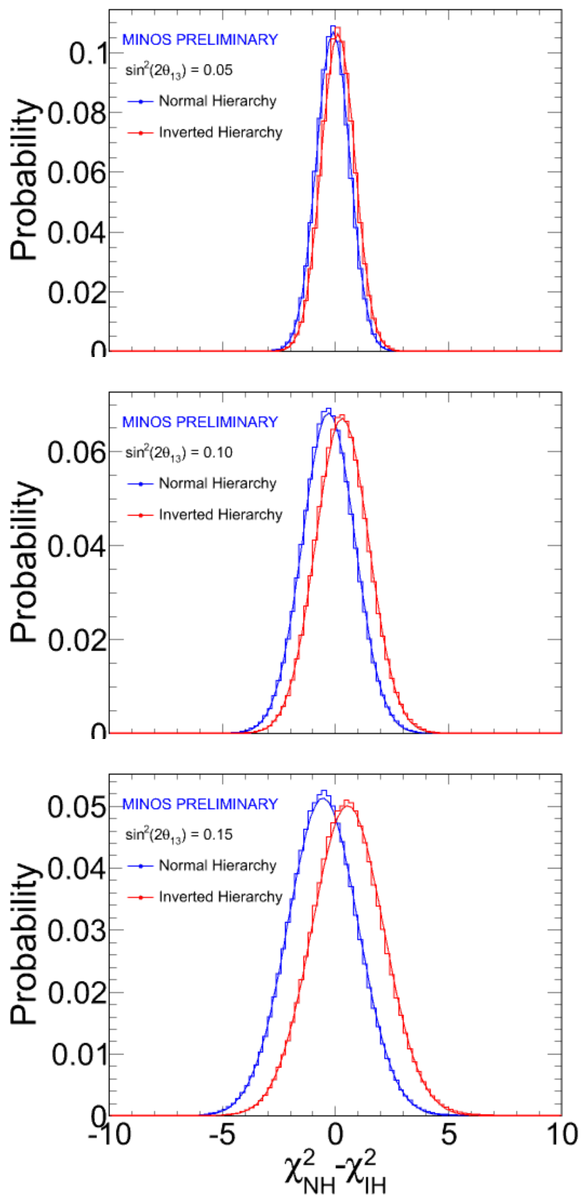
MINOS Angular Resolutions



Reconstructed Muon Track Angular Resolution:

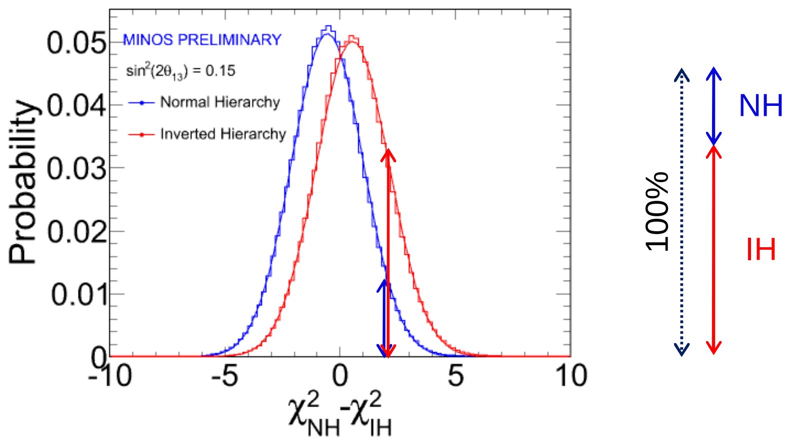
Bins	0.5 -1 GeV	1-2 GeV	2-3 GeV	3-5 GeV	5-8 GeV	> 8 GeV
θ_{reco}-θ_{true} (degree)	23.7	18.0	13.0	9.9	7.6	5.9

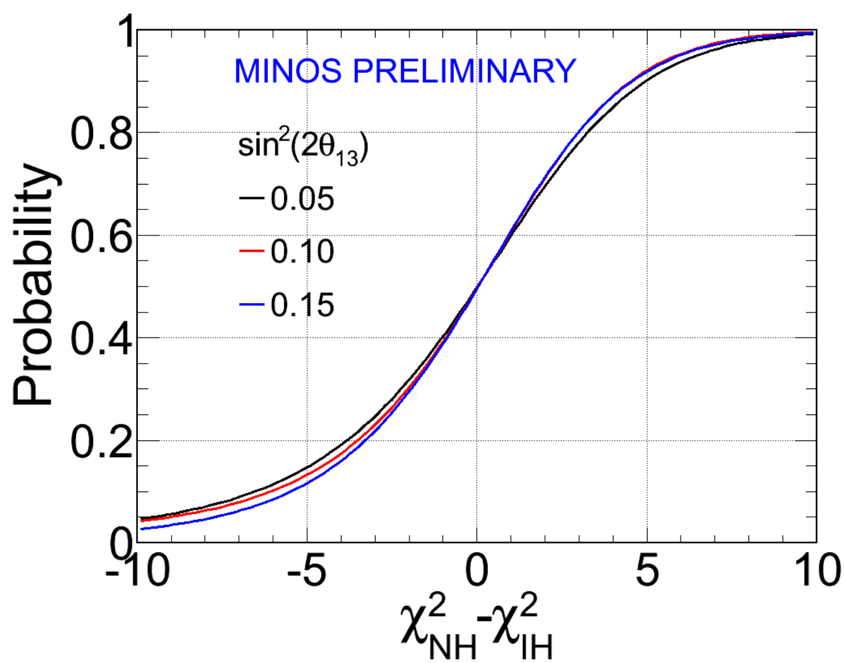
χ^2 Analysis with Pseudo Experiments



- ✓ χ^2_{NH} - χ^2_{IH} distribution obtained from pseudo-experiments for NH and IH assumption for three different input values of $\sin^2 2\theta_{13}$ = 0.05, 0.10, 0.15.
- ✓ 1,000,000 pseudo-experiments with 35 kton-years exposure are generated on a half of MINOS MC for a given value of θ_{13}, and for NH and IH
- ✓ Poisson fluctuation of the number of events in each bin.
- ✓ Each pseudo-experiment calculates the χ^2 value against NH (χ^2_{NH}) and IH (χ^2_{IH})
- ✓ The other mixing parameter are $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$, $\Delta m^2_{21} = 7.59 \times 10^{-5}$ eV^2, $\sin^2 2\theta_{12} = 0.87$, $\delta_{CP} = 0$

The Probability to be Inverted Mass Hierarchy





- ✓ From the probability density function of the normal mass hierarchy and inverted mass hierarchy $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH}$ histogram, the probability to have a measured $\Delta\chi^2$ value to be inverted mass hierarchy as a function of $\Delta\chi^2$ can be calculated
- ✓ The probability to have a measured $\Delta\chi^2$ value to be normal mass hierarchy is complementary
- ✓ Once a measurement of $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH}$ is done on a experiment from data, we may make a statement of the probability of normal mass hierarchy or inverted mass hierarchy
- ✓ The probability is 50% when $\Delta\chi^2 = 0$ for both NH and IH, meaning no discrimination between two hierarchies

Acknowledgments

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