Measuring Neutrino Oscillations with the MINOS Experiment

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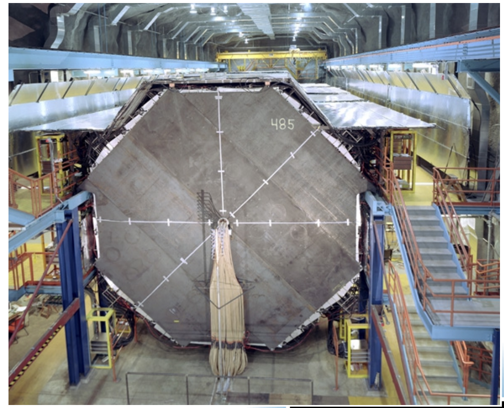
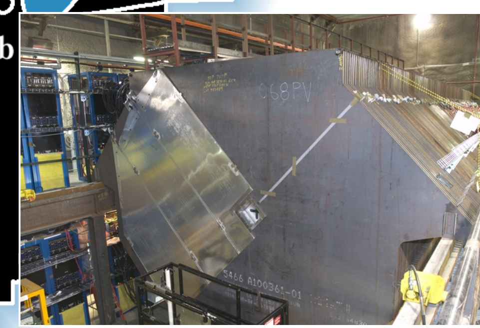
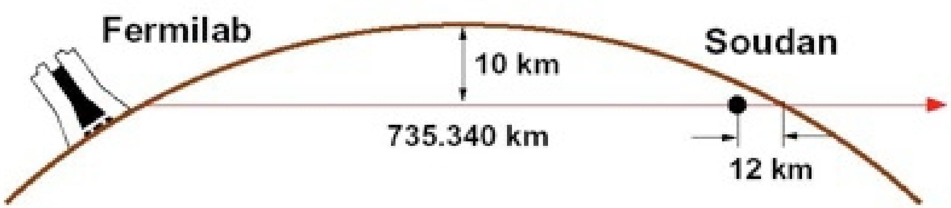
MINOS

- MINOS or Main Injector Neutrino Oscillation Search
- Uses Neutrinos from the NuMI beam line
- Has a peak L/E of ~250km/GeV
- Leading measure of $\left|\Delta m^2_{atm}\right|$







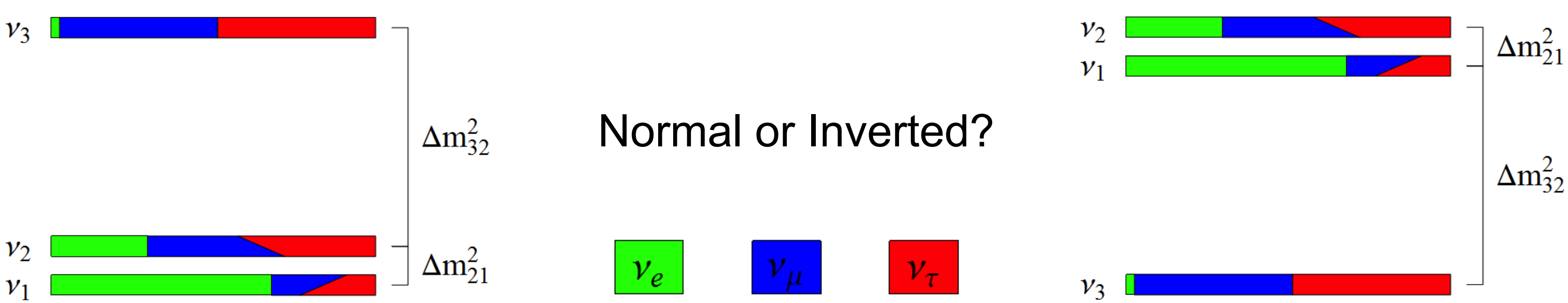
MINOS Physics Goals

NEW

- The measurement of **3ν** oscillations via the study of the NuMI and atmospheric neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U^* \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad P\left(\nu_\alpha \to \nu_\beta\right) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

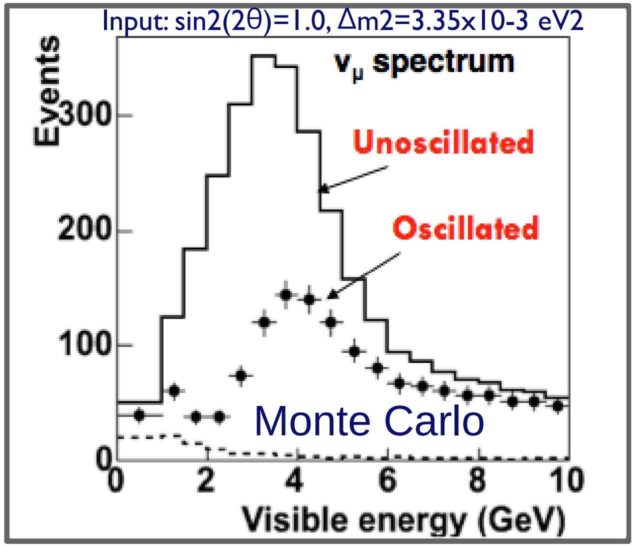
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

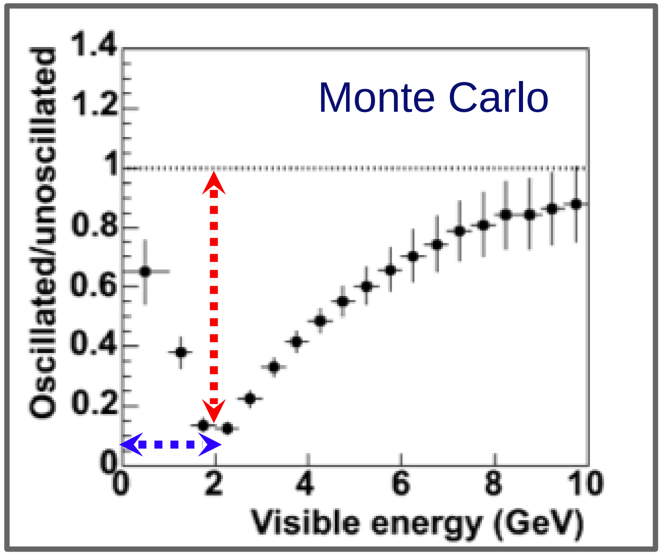


NuMI Neutrino Disappearance

- Precise measurement of muon neutrino disappearance
- Direct measurement of muon antineutrino disappearance
- Far detector prediction from near detector is compared to far detector measurement
- Neutrino oscillations deplete rate and distort the energy spectrum

$$P(\nu_\mu \rightarrow \nu_\mu) \approx$$
$$1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$





NuMI Neutrino Appearance

- Muons can also oscillate into electron neutrinos, giving us power to measure:
  - θ_{13}
  - δcp
  - θ_{23} octant
  - Mass hierarchy

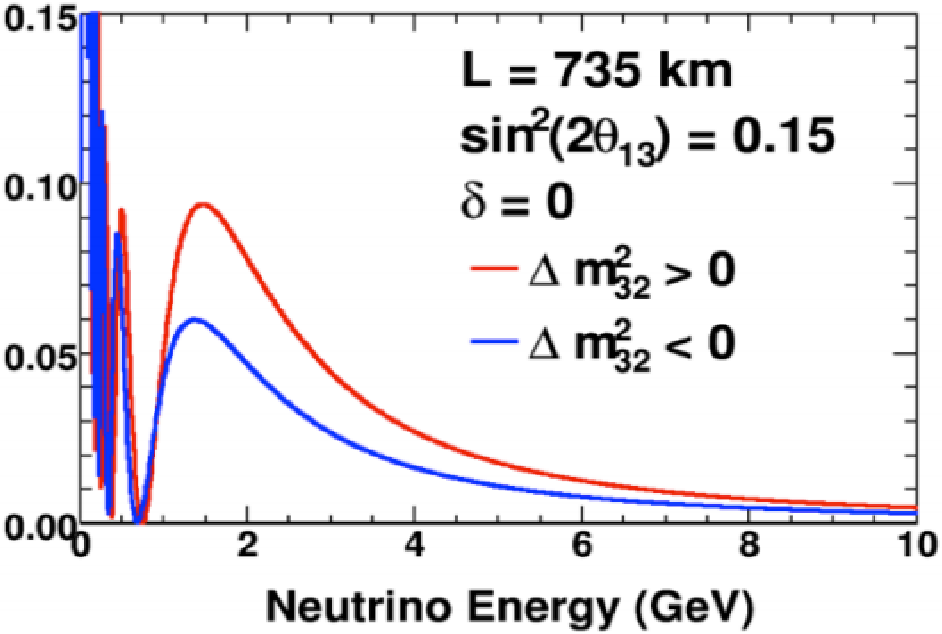
$$P(\nu_\mu \rightarrow \nu_e) \approx \left| \sqrt{P_{atm}} e^{-i\left(\frac{\Delta m^2_{32} L}{4E} + \delta_{cp}\right)} + \sqrt{P_{sol}} \right|^2$$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Solar term contributes <1% at MINOS L/E

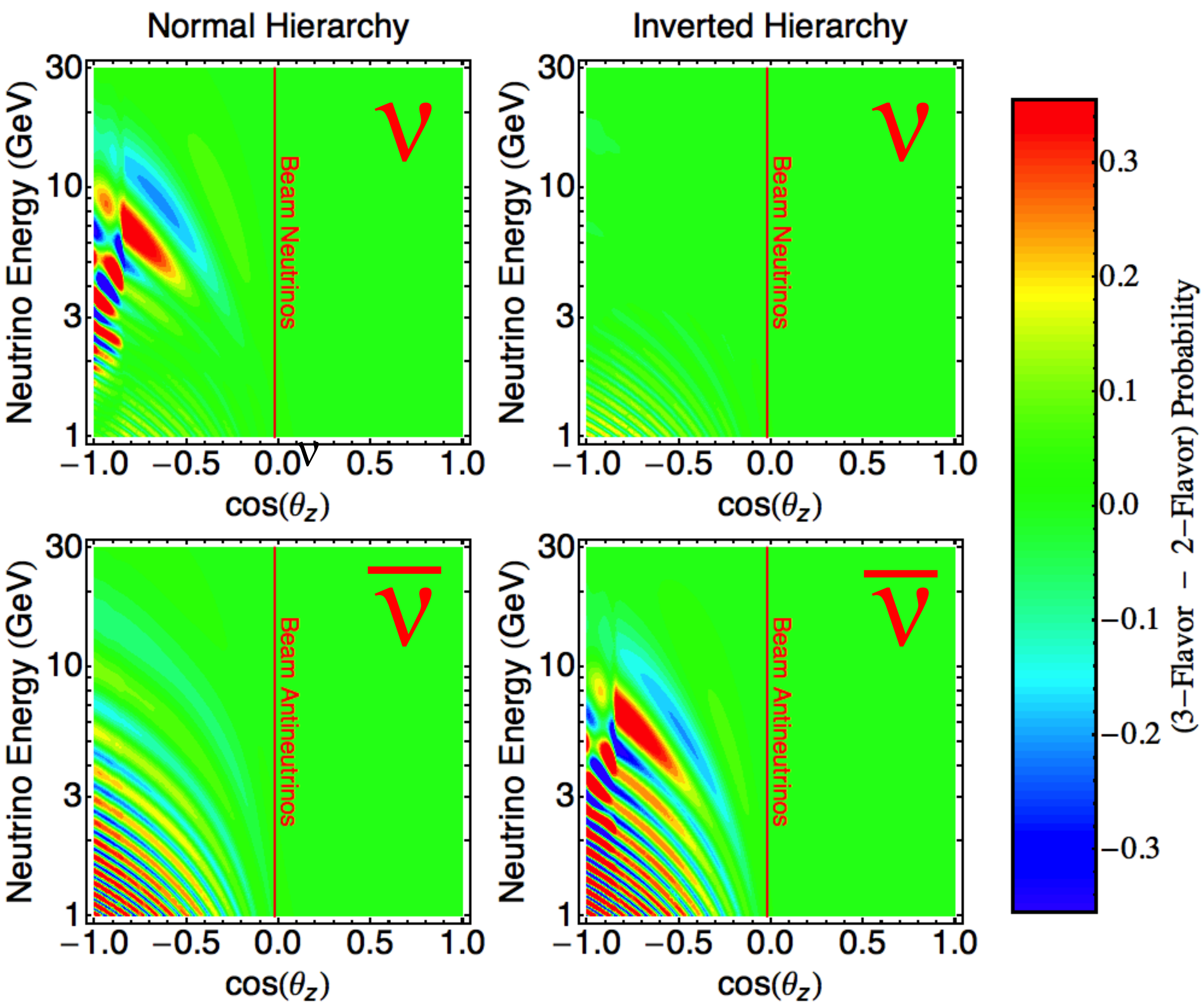
NuMI Neutrino Appearance

- Muons can also oscillate into electron neutrinos, giving us power to measure:
  - θ_{13}
  - δcp
  - θ_{23} octant
  - Mass hierarchy
- Electron neutrinos experience an extra CC interaction as they pass through matter, modifying oscillation probabilities



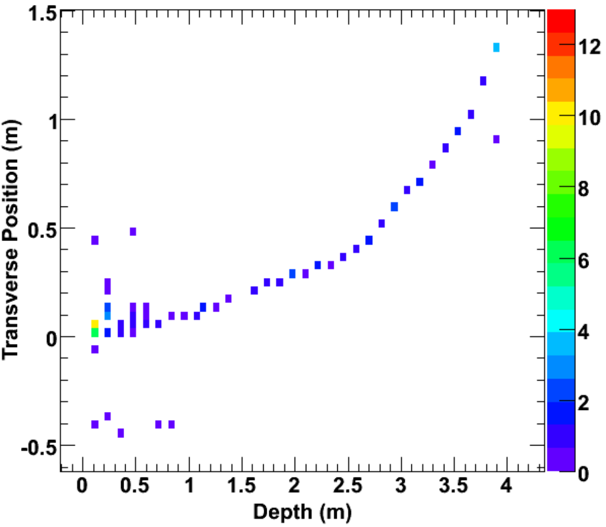
Atmospheric Neutrino Disappearance

- Very long baselines through matter compared to NuMI disappearance analysis
- Some sensitivity to θ_{23} octant, mass hierarchy and δ_{cp}

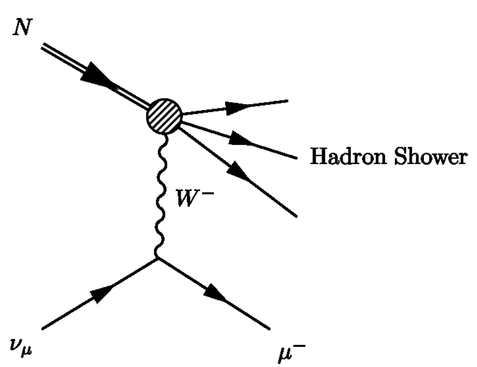


MC Event Topologies

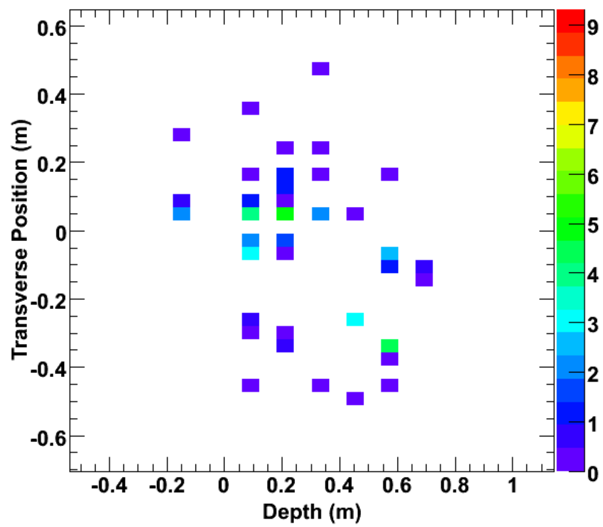
ν_μ Charged Current (CC)



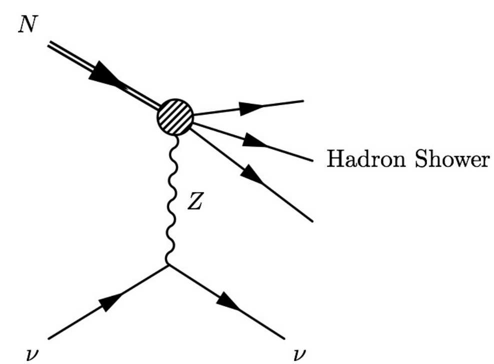
$$\nu_\mu + N \rightarrow \mu^- + X$$



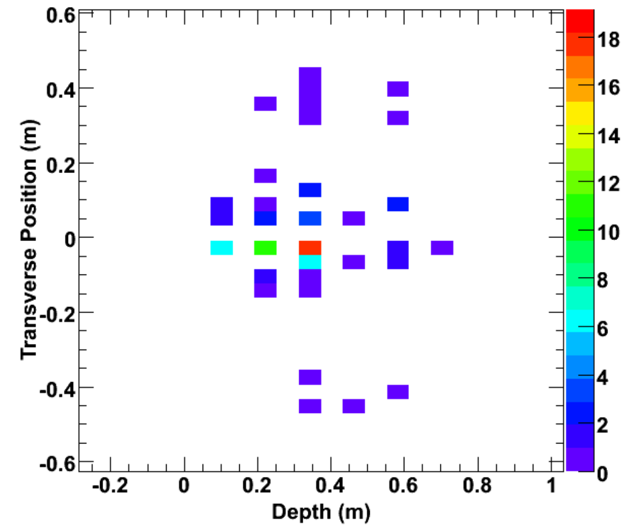
Neutral Current (NC)



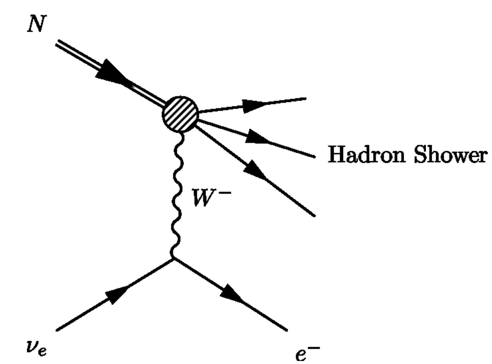
$$\nu + N \rightarrow \nu + X$$



ν_e CC



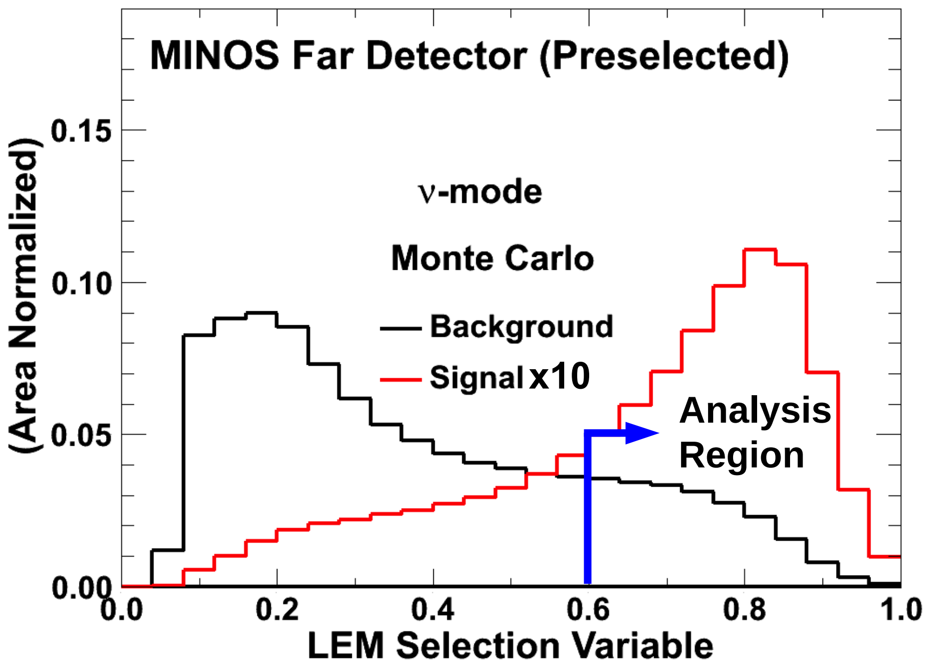
$$\nu_e + N \rightarrow e^- + X$$

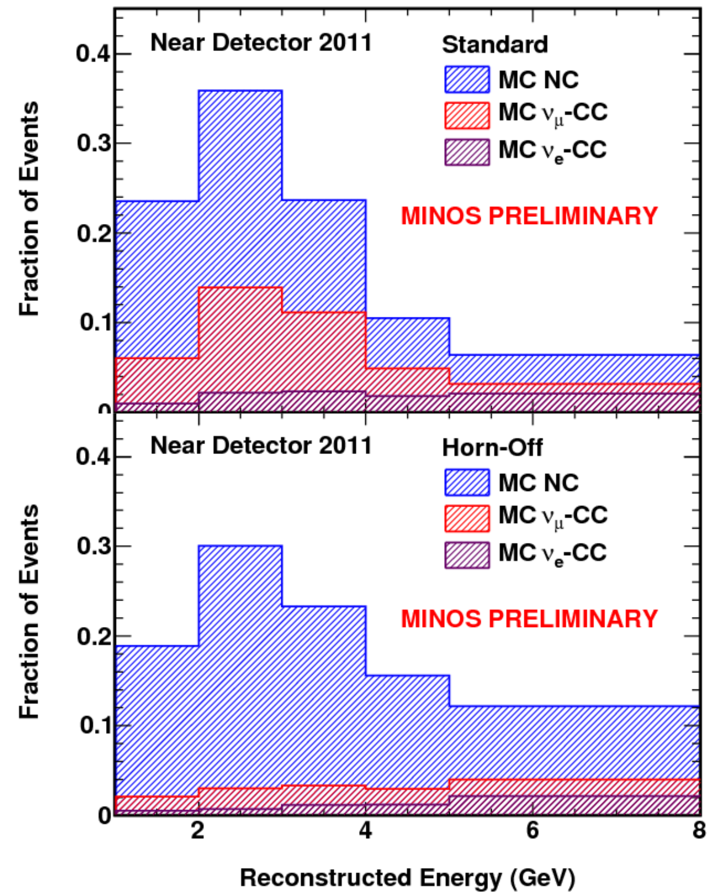


Electron Neutrino Appearance

Electron Neutrino Appearance

- MINOS detector granularity makes ν_e CC identification challenging
- Background estimation based on Near Detector data
- Compare candidate events to a library of MC using "Library Event Matching" (LEM)





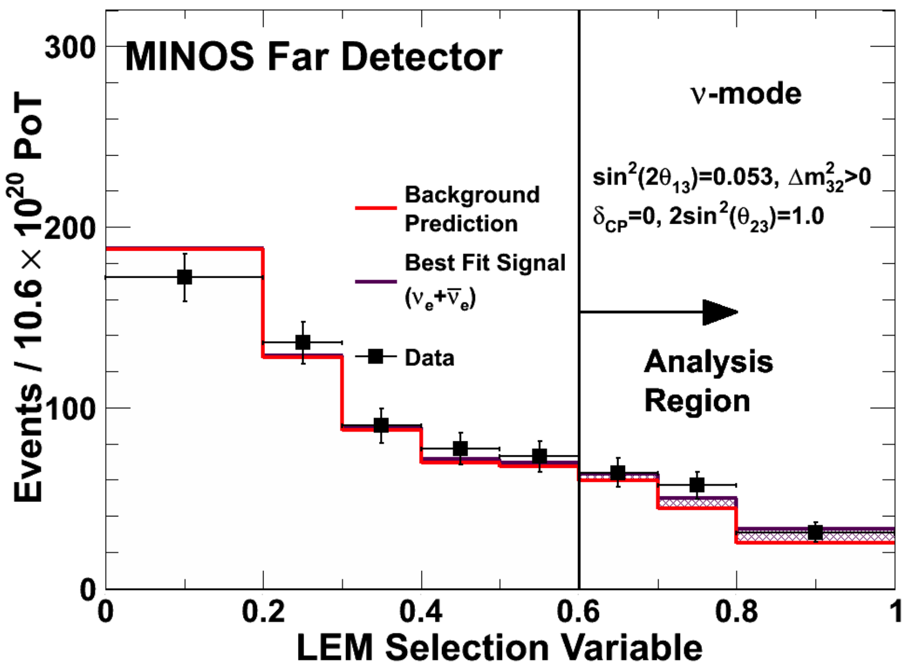
Electron Neutrino Appearance

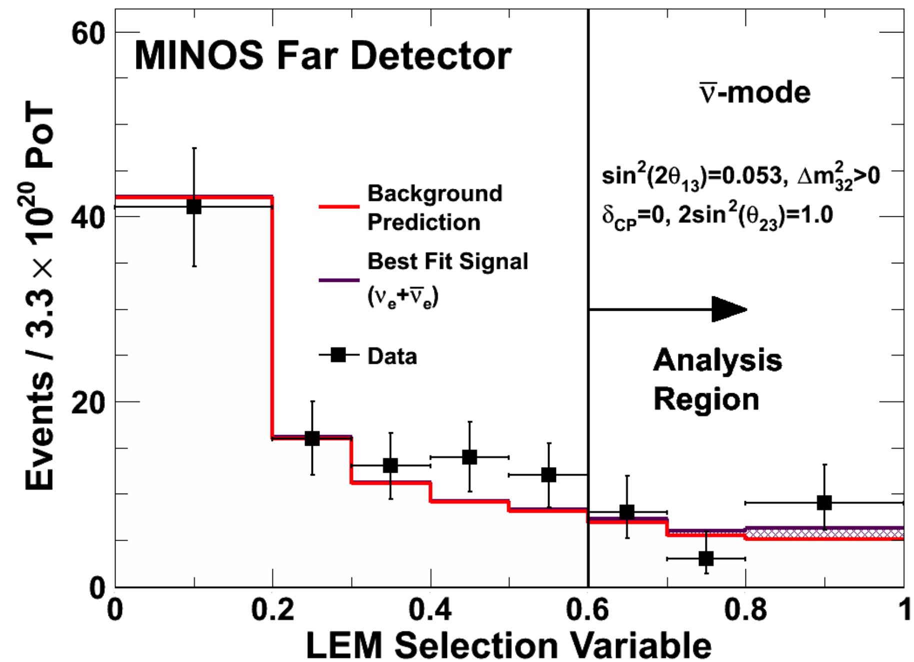
With the *neutrino-enhanced* beam in Signal Enhanced Region:

- If $\theta_{13} = 0$: 128.6 BG Events
- If $\sin^2(2\theta_{13}) = 0.1$: +32.5 Events
- Total Prediction: 161 Events
- Observed: 152 Events

With the *antineutrino-enhanced* beam in Signal Enhanced Region:

- If $\theta_{13} = 0$: 17.5 BG Events
- If $\sin^2(2\theta_{13}) = 0.1$: +3.7 Events
- Total Prediction: 21.2 Events
- Observed: 20 Events





Combined Electron Neutrino Appearance

Cannot distinguish between ν_e and anti-ν_e events, so we perform a combined analysis:

$$\text{At } \delta_{CP} = 0 \text{ and } \theta_{23} < \pi/4,$$

- Assuming normal hierarchy:

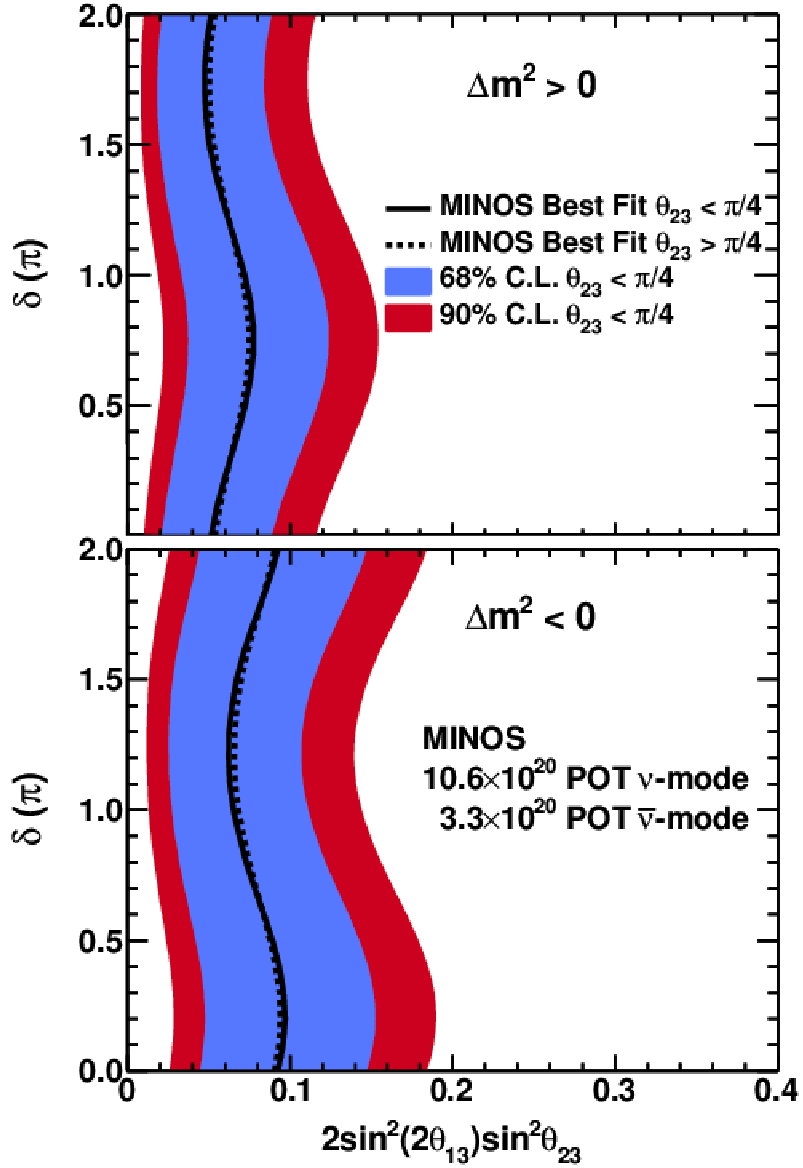
$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$$

$$0.01 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.12 \text{ (90\% C.L.)}$$

- Assuming inverted hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$

$$0.03 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.18 \text{ (90\% C.L.)}$$



Muon Neutrino Disappearance

Neutrino Disappearance

- Five distinct data sets are used to study muon neutrino disappearance:
  - 10.7x10^{20} POT in "neutrino-enhanced" NuMI beam
    - Muon neutrino charged current interactions
    - Anti muon neutrino charged current interactions
  - 3.4x10^{20} POT in "antineutrino-enhanced" NuMI beam
    - Anti-muon neutrino charged current interactions
  - 37.9 kton-years of atmospheric neutrinos
    - Muon neutrino charged current interactions
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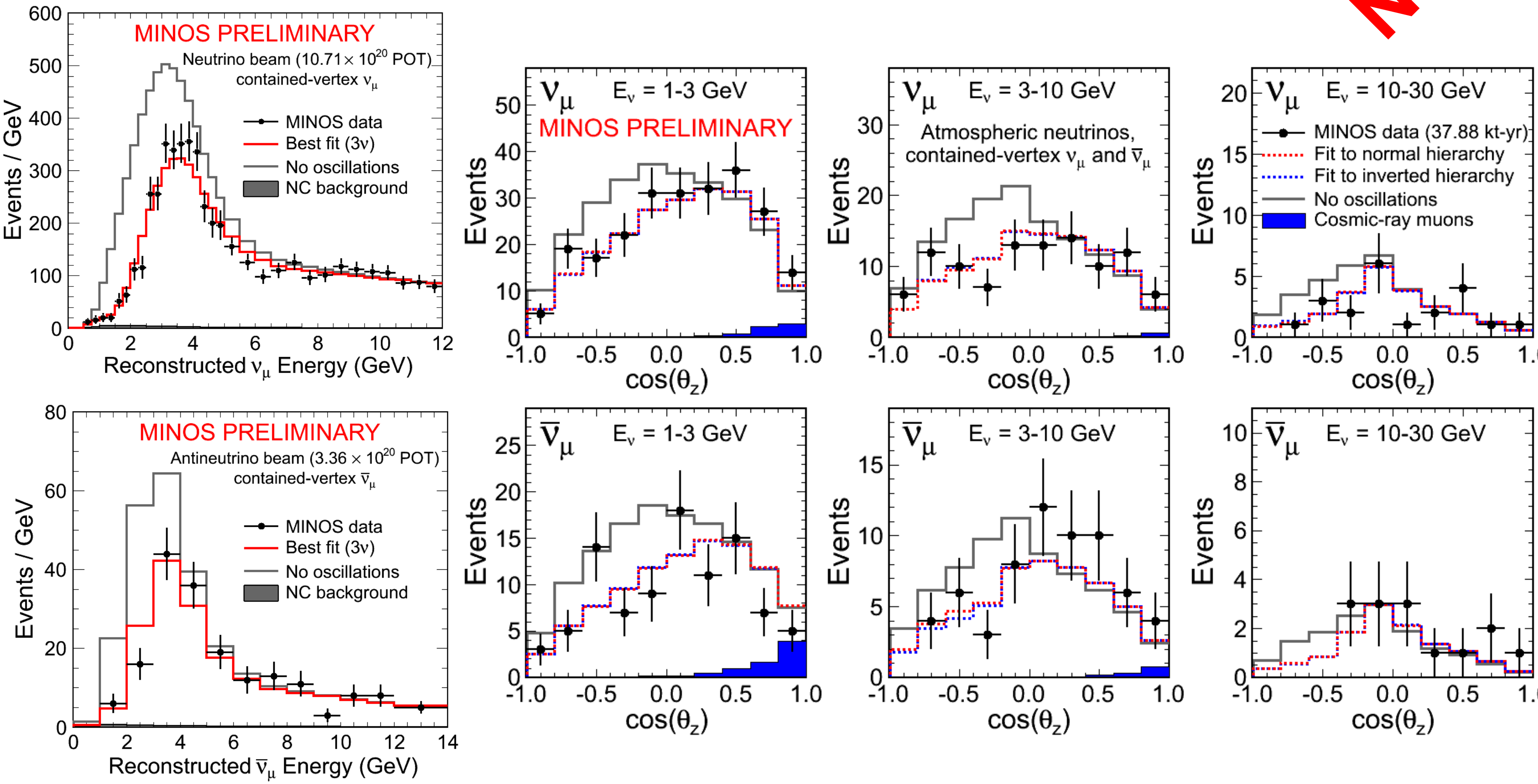
Neutrino Disappearance

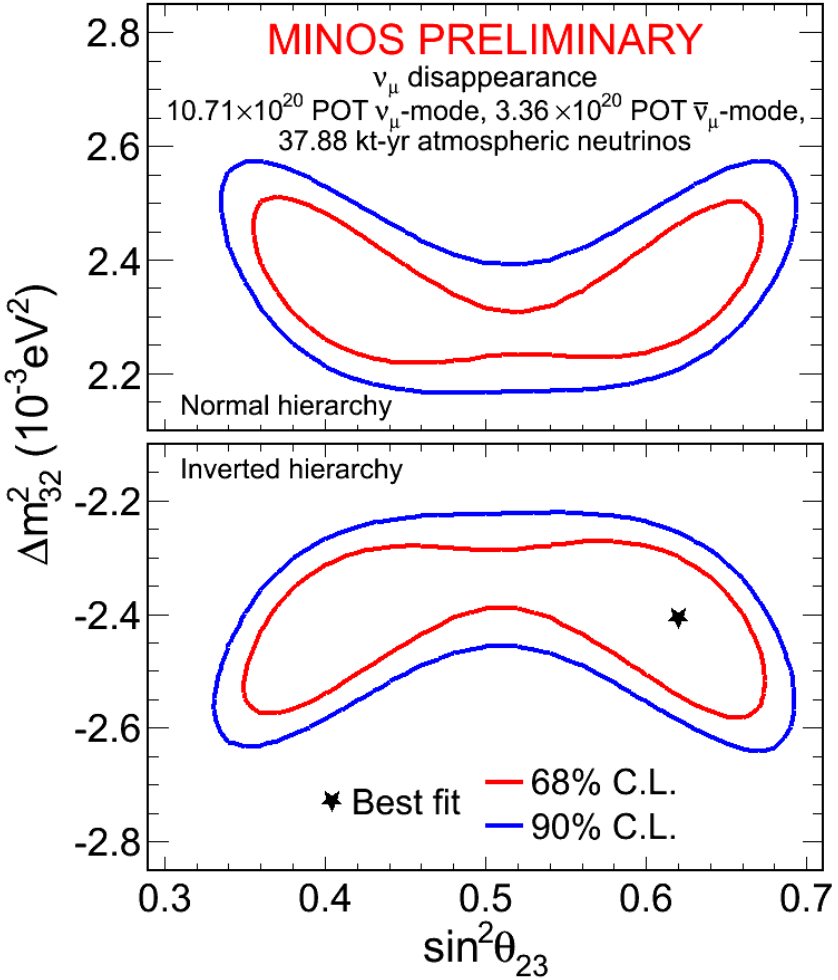
NEW



Combined Beam and Atmospheric Neutrino Disappearance Best Fit

NEW

- Assumes identical neutrino and antineutrino mixing parameters
- Gaussian constraint based on world knowledge of θ_{13}
- δ_{cp} allowed to freely float in [0,2π] range
- Other mixing parameters set at worlds best knowledge
- 15 systematics included as nuisance parameters



Combined Muon Disappearance and Electron Neutrino Appearance

Combined Neutrino Appearance and Disappearance Best Fit

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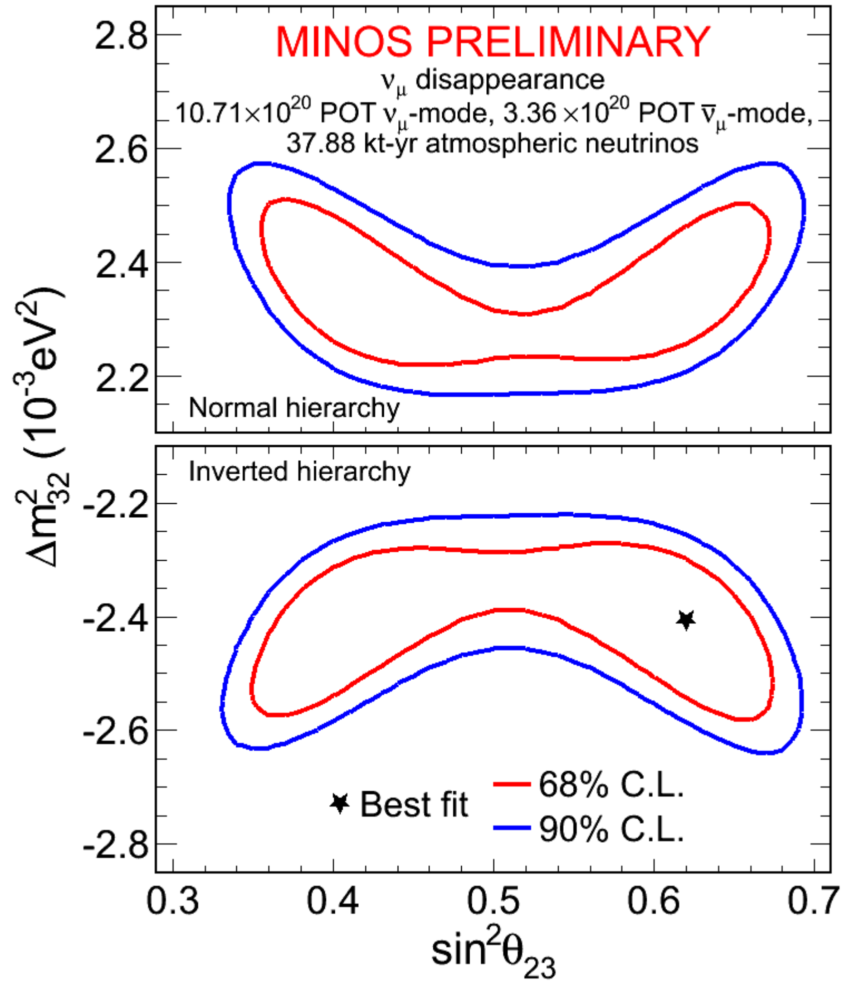
- Appearance systematics included, assumes no correlation with disappearance



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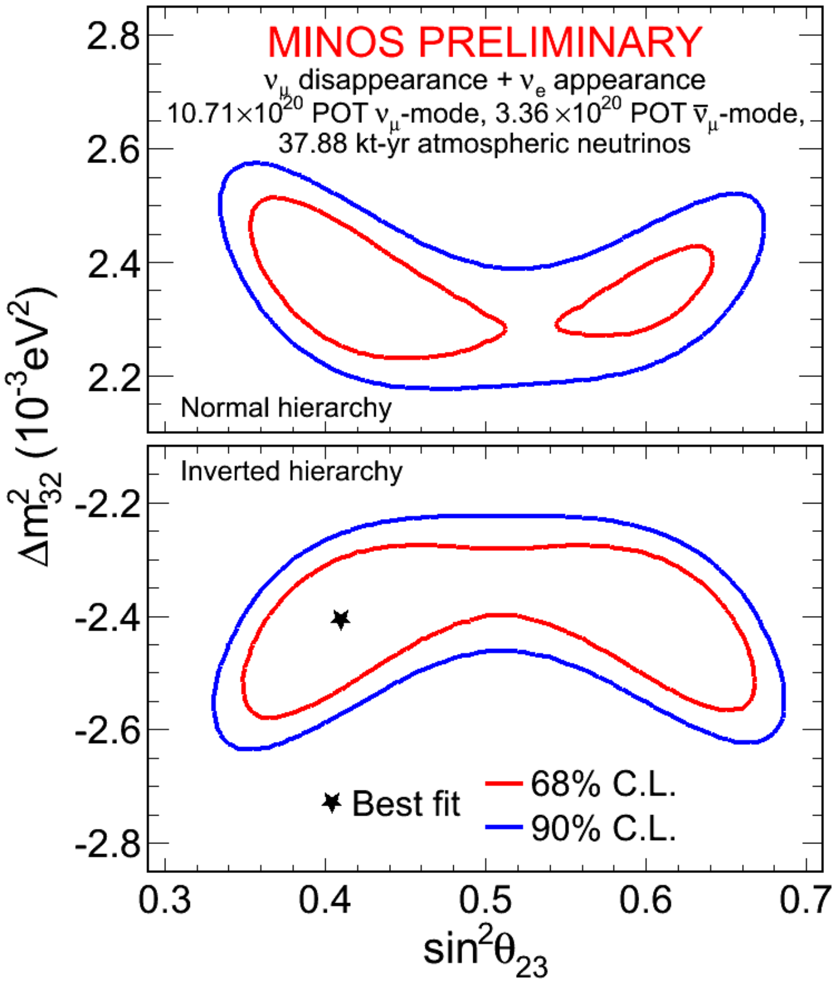

Combined Neutrino Appearance and Disappearance Best Fit

- We can also marginalize over δ_{cp}
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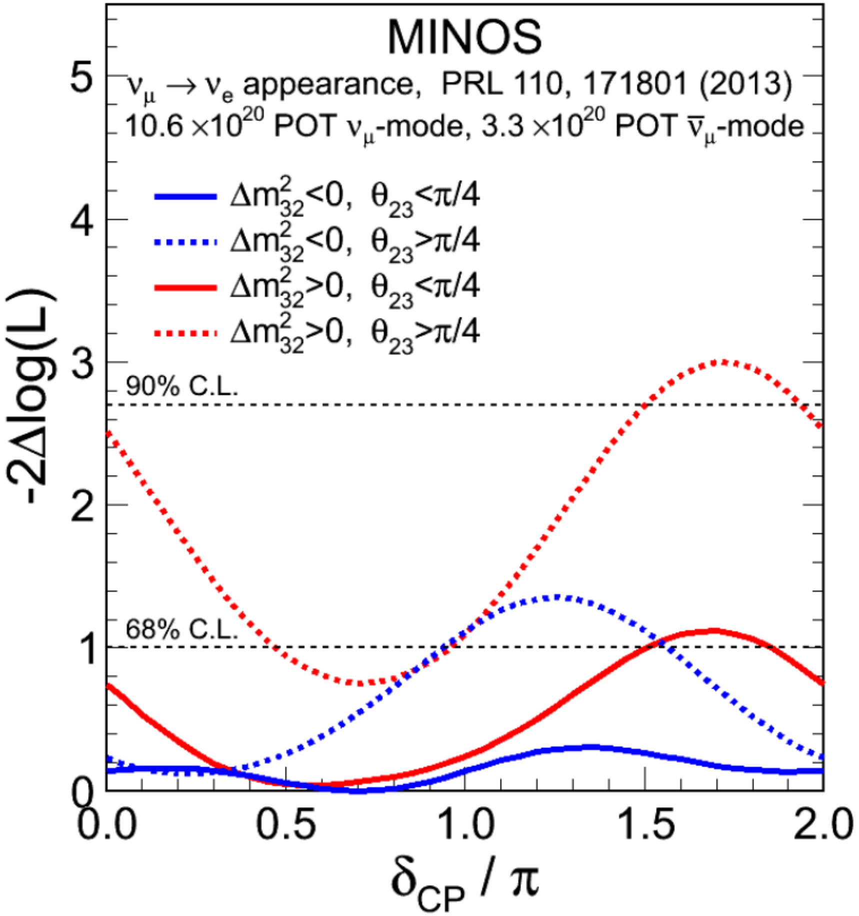

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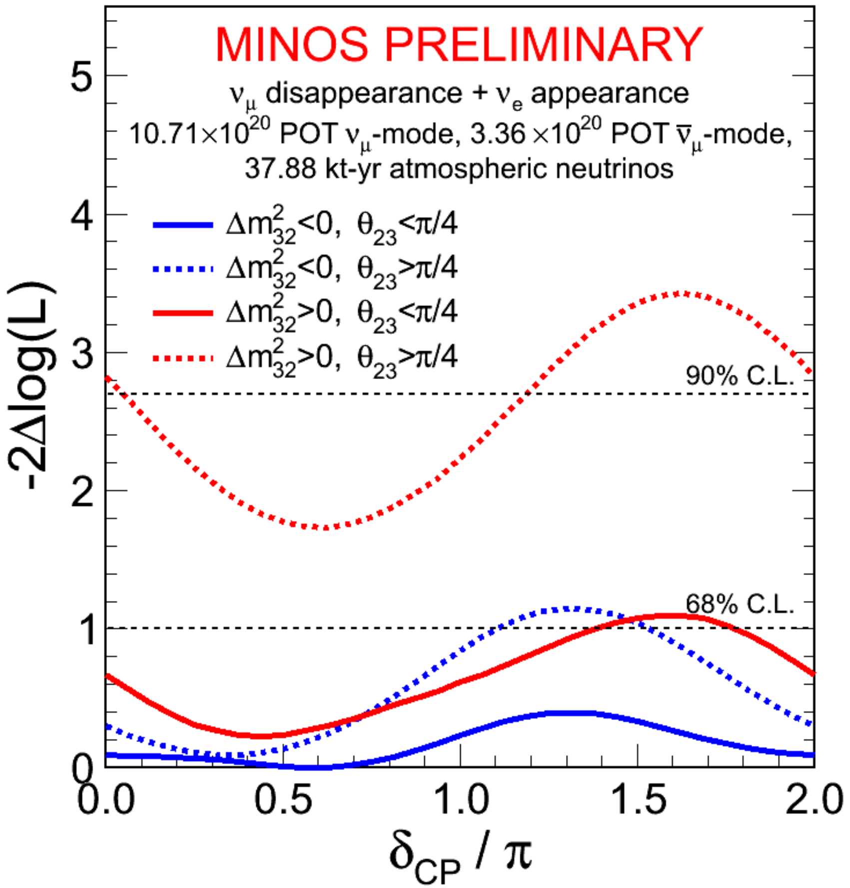

Combined Neutrino Appearance and Disappearance Best Fit

NEW

Hierarchy, Octant	Best fit oscillation parameters				
	Δm^2_{32} / 10^{-3}eV^2	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	δ_{CP}/π	$-2\Delta\log(L)$
Normal, Lower	$+2.37$	0.41	0.0242	0.44	0.23
Normal, Higher	$+2.35$	0.61	0.0238	0.62	1.74
Inverted, Lower	-2.41	0.41	0.0243	0.62	–
Inverted, Higher	-2.41	0.61	0.0241	0.37	0.09

	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}$eV^2	2.37	$2.28-2.46$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35-0.65$ (90% C.L.)
Inverted hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}$eV^2	2.41	$2.32-2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.34-0.67$ (90% C.L.)

Preference for inverted hierarchy: $-2\Delta\log L = 0.23$

Preference for lower octant: $-2\Delta\log L = 0.09$

Exclusion of maximal mixing: $-2\Delta\log L = 1.54$ ($\Rightarrow$ 79% C.L.)

Summary

MINOS has completed a combined analysis of:

- 10.7×10^{20} POT to measure muon neutrino disappearance
- 3.4×10^{20} POT to measure muon antineutrino disappearance
- 37.9 kton-years of atmospheric data

MINOS has completed a combined analysis of:

- 10.6×10^{20} POT to measure electron neutrino appearance
- 3.3×10^{20} POT to measure electron antineutrino appearance

- And now a full combination of our neutrino appearance and disappearance fits, allowing us to make our strongest comments yet on the octant degeneracy, δ_{cp}, and the mass hierarchy

Q&A

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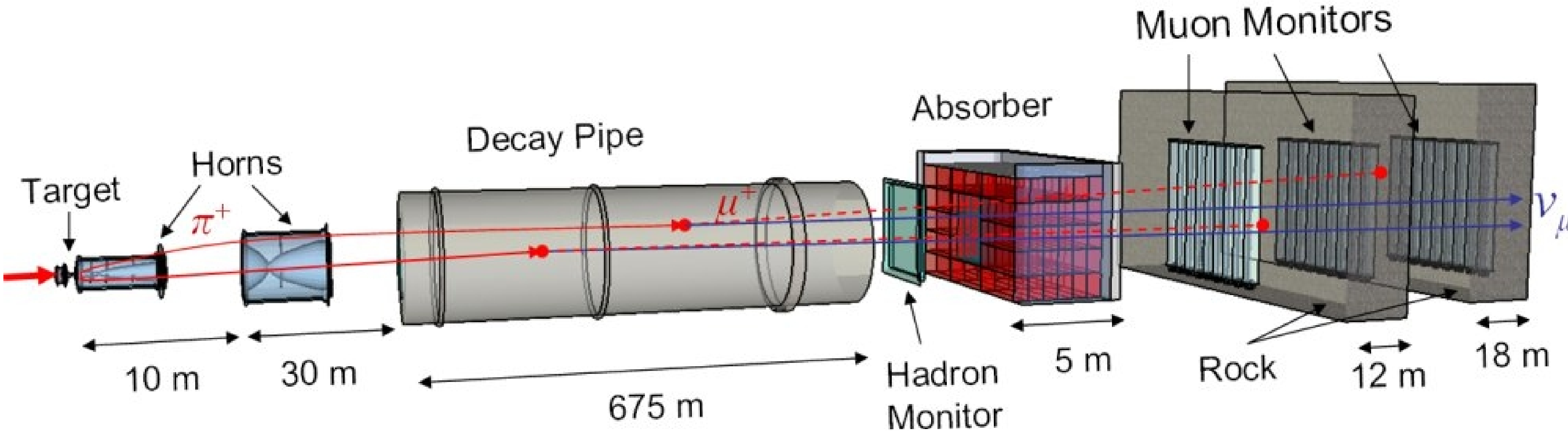
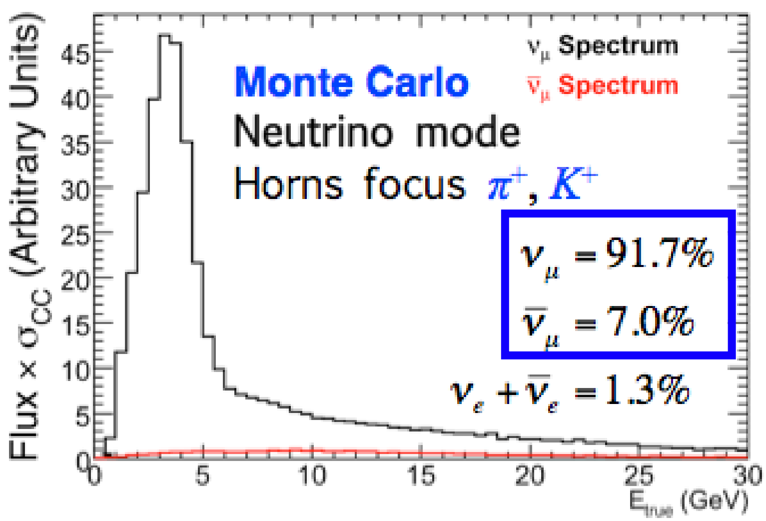
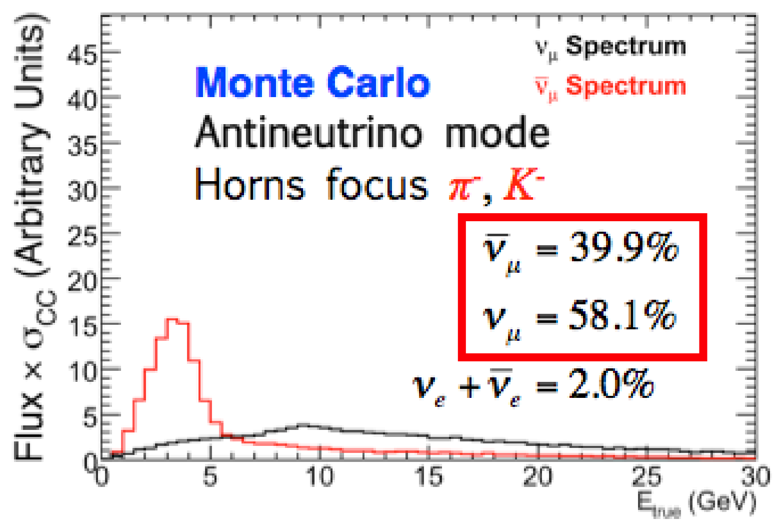
NuMI Neutrino Beam

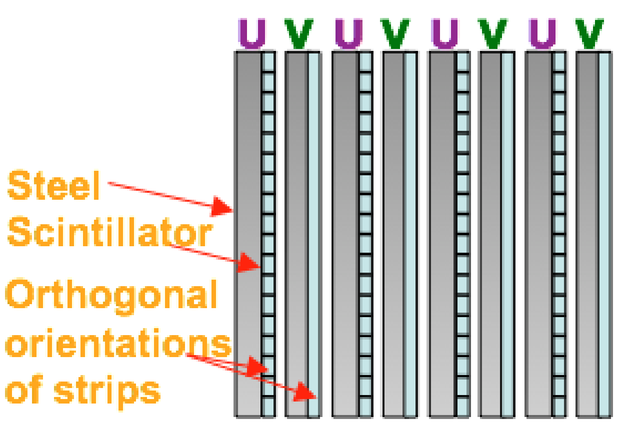


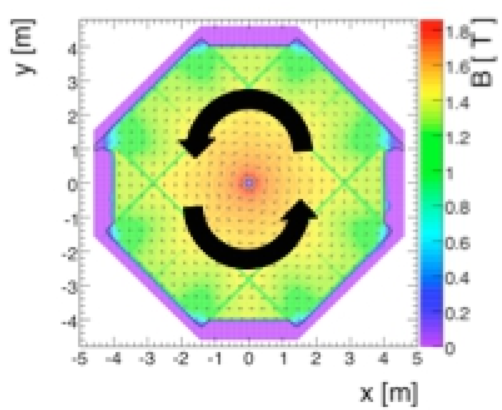


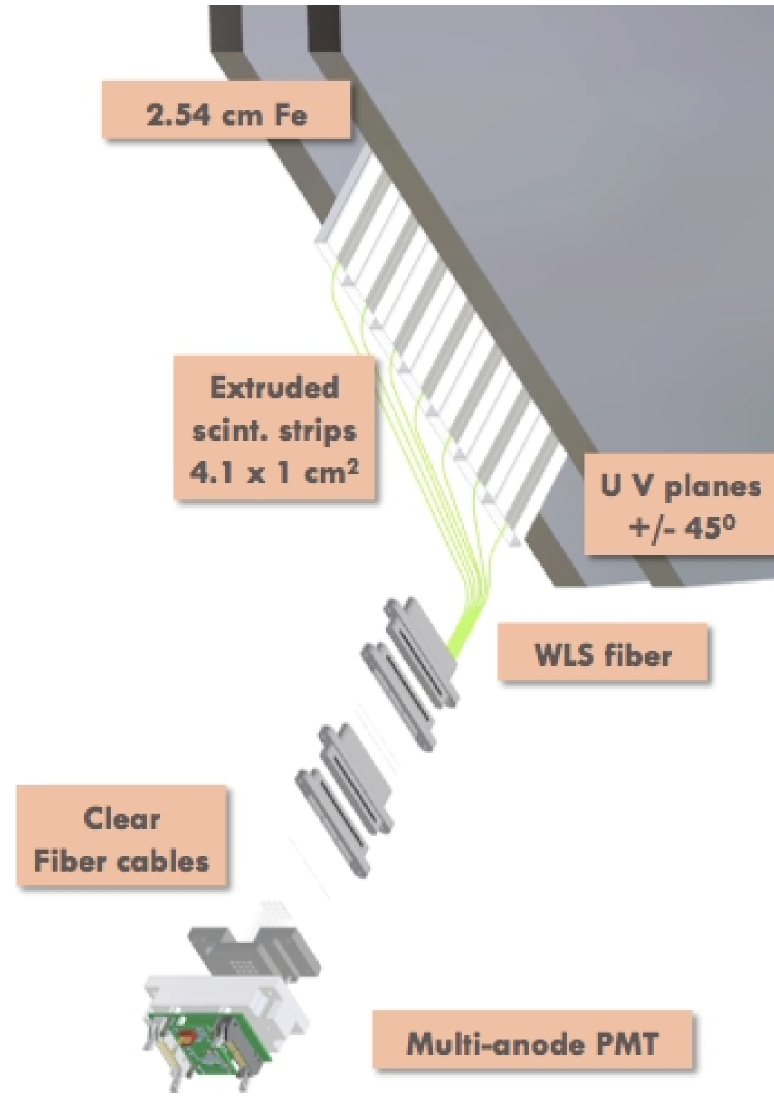


MINOS Detector

- Steel/Scintillator Tracking Calorimeter
  - 2.54 cm-thick steel plates
  - 1 cm-thick, 4.1 cm-wide extruded polystyrene scintillator strips
- Magnetized at <B> ~1.3T
  - Able to distinguish between μ^- and μ^+







Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- 2 parameter fit assumes identical neutrino and antineutrino mixing parameters
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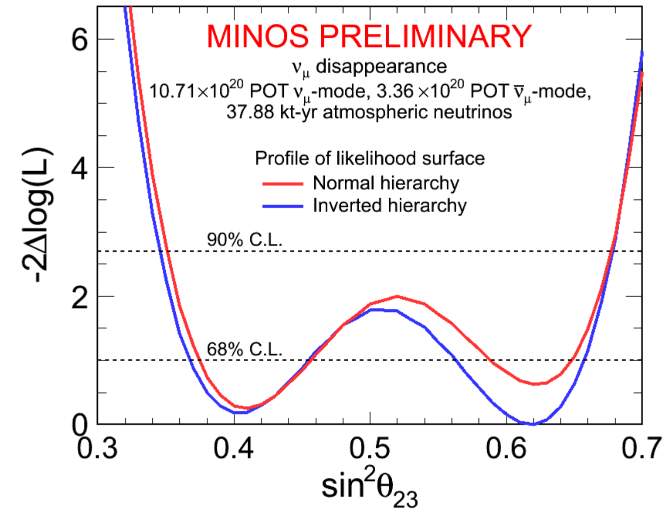
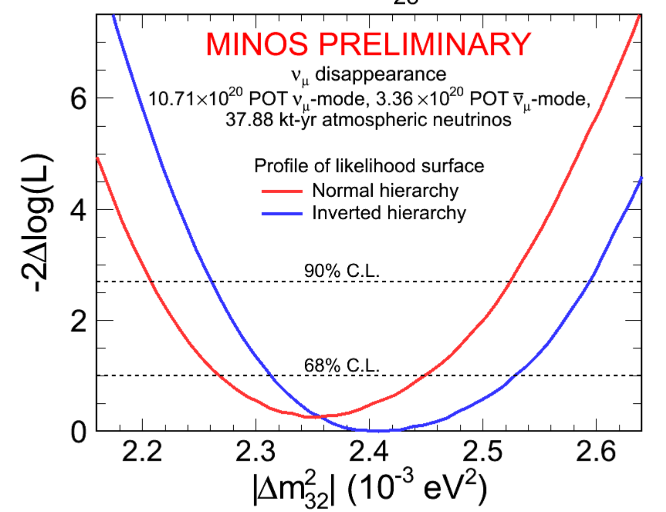
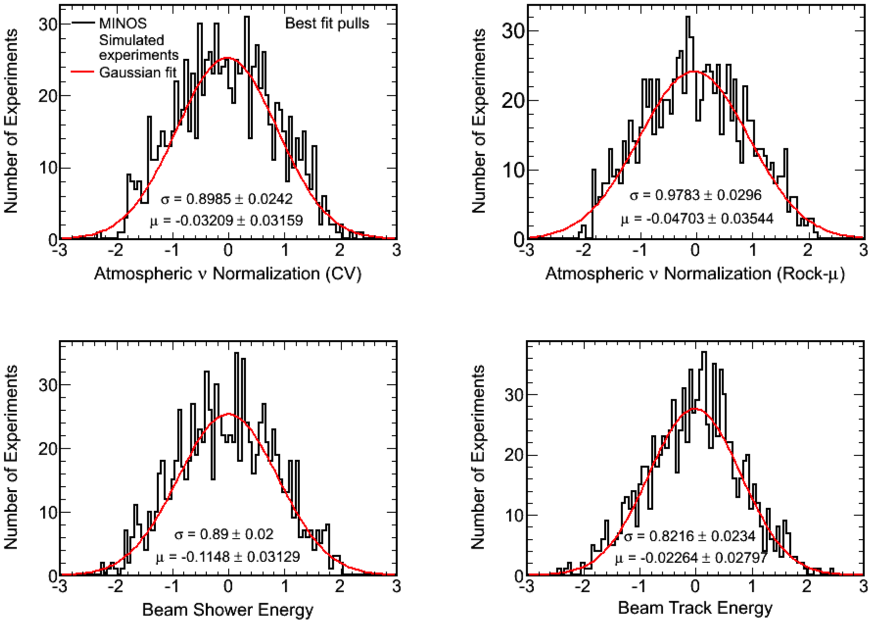




Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- 15 largest systematics included as nuisance parameters
- Best fit systematics all have a mean value near zero and width close to unity
- Well described by gaussian distributions
- No apparent bias or pathology



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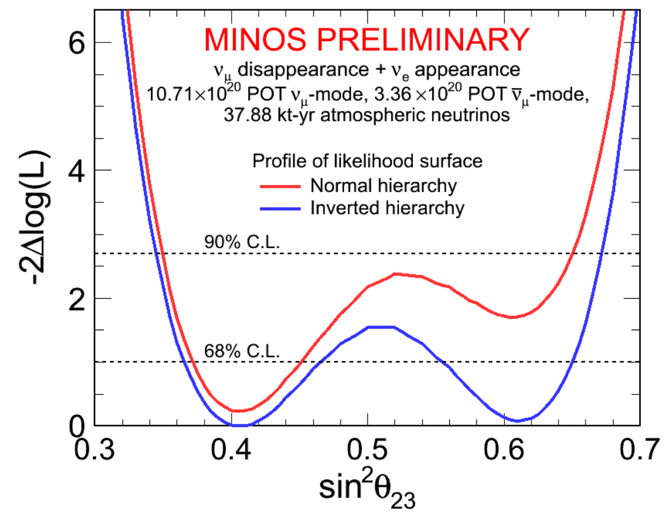

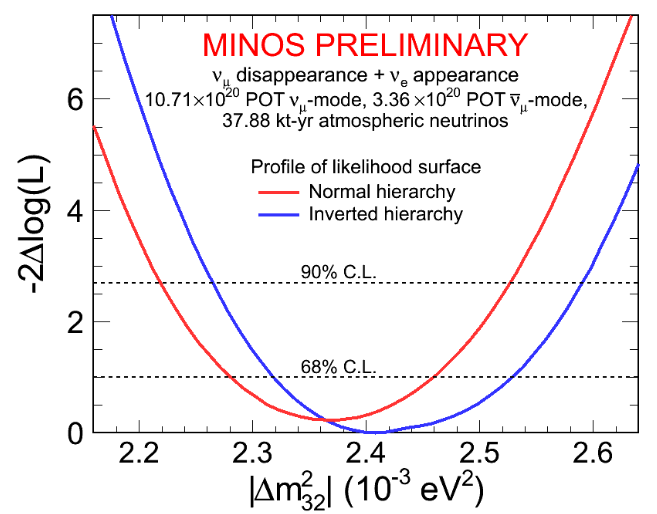

Combined Neutrino Appearance and Disappearance Best Fit Inputs

- θ_{23} , $|\Delta m^2_{32}|$ and δ_{cp} allowed to freely float
- Gaussian constraint based on world knowledge of θ_{13}, $\sin^2\theta_{13}=0.0242 \pm 0.0025$. Based on a weighted average of published results from the Daya Bay, RENO and Double-Chooz reactor neutrino experiments
- The solar parameters are set to fixed values of $\Delta m^2_{21} = 7.54 \times 10^{-5}\ \text{eV}^2$ and $\sin^2(\theta_{12}) = 0.307$, from the Fogli global analysis*

* "Global analysis of neutrino masses, mixings and phases: entering the era of leptonic CP violation searches", Fogli, G. L. et al, Phys. Rev. D, 86,1,2012

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Cannot distinguish between ν_e and anti-ν_e events, so we perform a combined analysis:

At $\delta_{CP} = 0$ and $\theta_{23} < \pi/4$,

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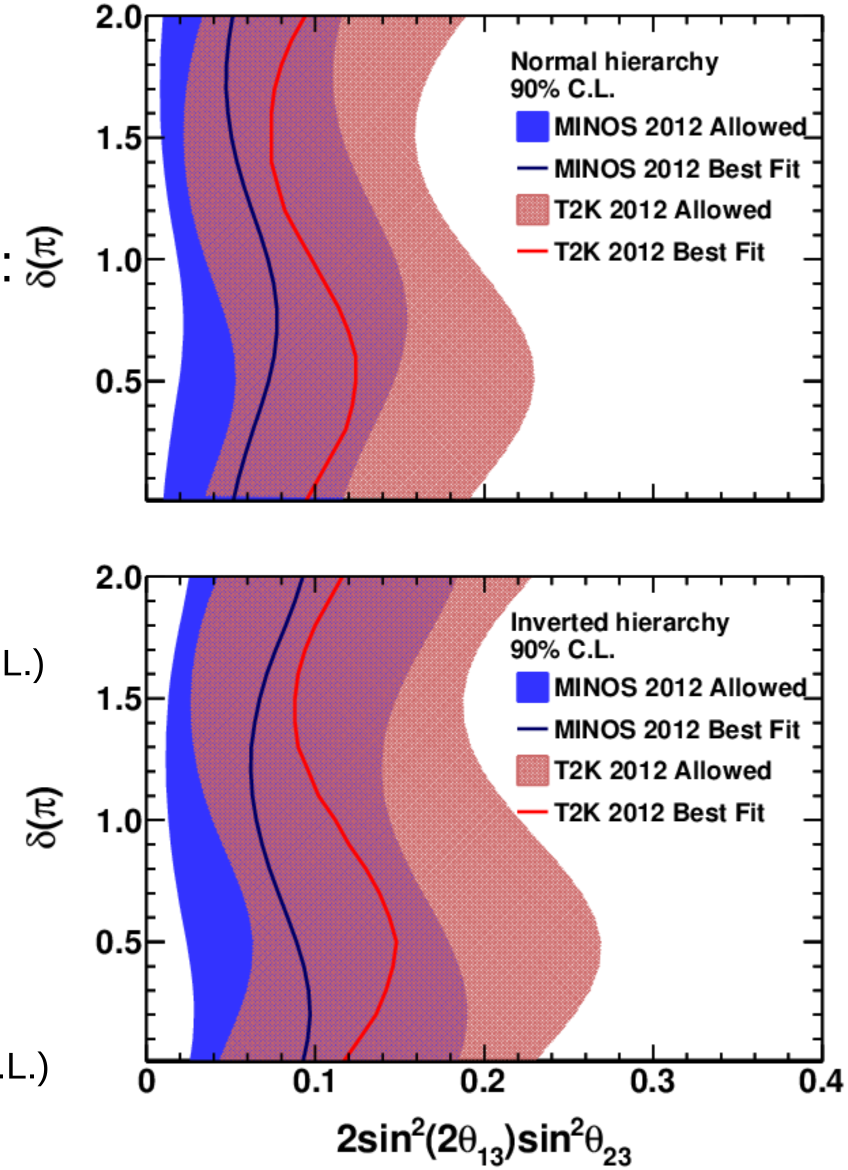
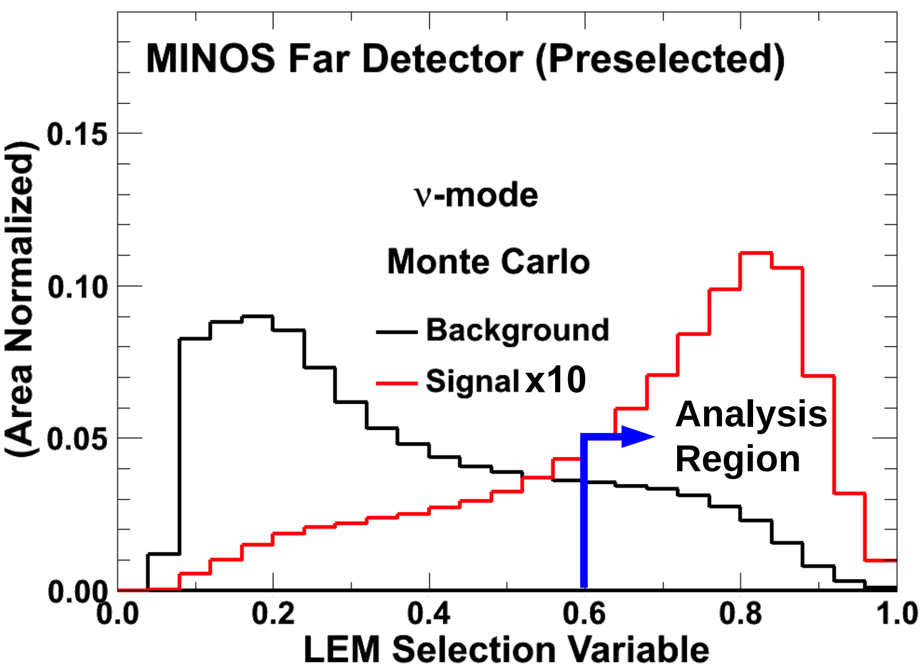
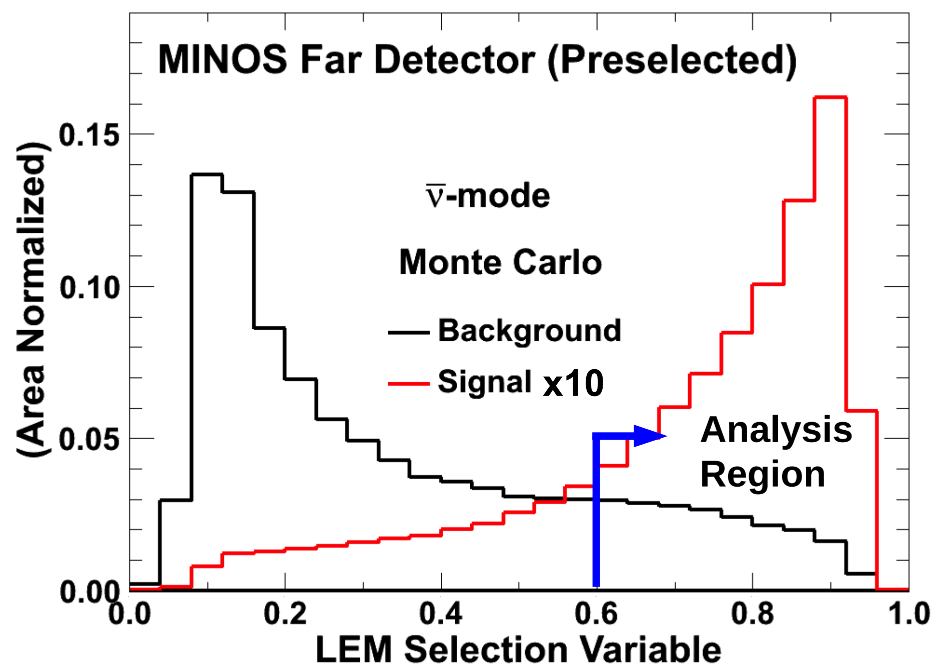


Electron Neutrino Appearance

- MINOS detector granularity makes ν_e CC identification challenging
- Compare candidate events to a library of MC using "Library Event Matching" (LEM)
- Compute discriminating variables based on truth information from library events that best match the candidate





Combined Beam and Atmospheric Neutrino Disappearance Best Fit

	Parameter	Best fit	Confidence limits
Normal hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.35	$2.27 - 2.45$ (68% C.L.)
	$\sin^2\theta_{23}$	0.41	$0.35 - 0.68$ (90% C.L.)
Inverted hierarchy	$\lvert\Delta m^2_{32}\rvert/10^{-3}\text{eV}^2$	2.41	$2.31 - 2.53$ (68% C.L.)
	$\sin^2\theta_{23}$	0.62	$0.34 - 0.68$ (90% C.L.)

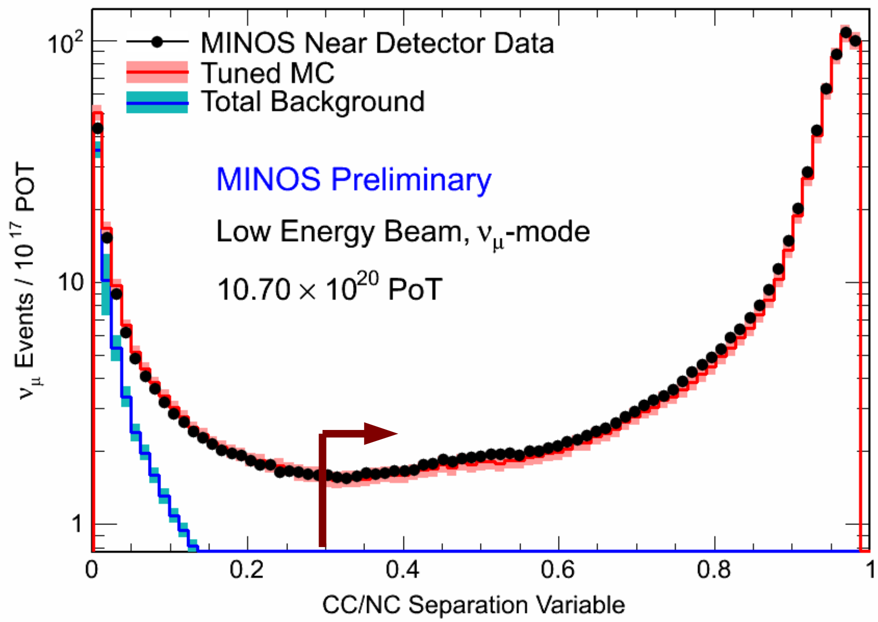
Preference for inverted hierarchy: $-2\Delta\log L = 0.25$

Preference for higher octant: $-2\Delta\log L = 0.20$

Exclusion of maximal mixing: $-2\Delta\log L = 1.79$ ($\Rightarrow$ 82% C.L.)

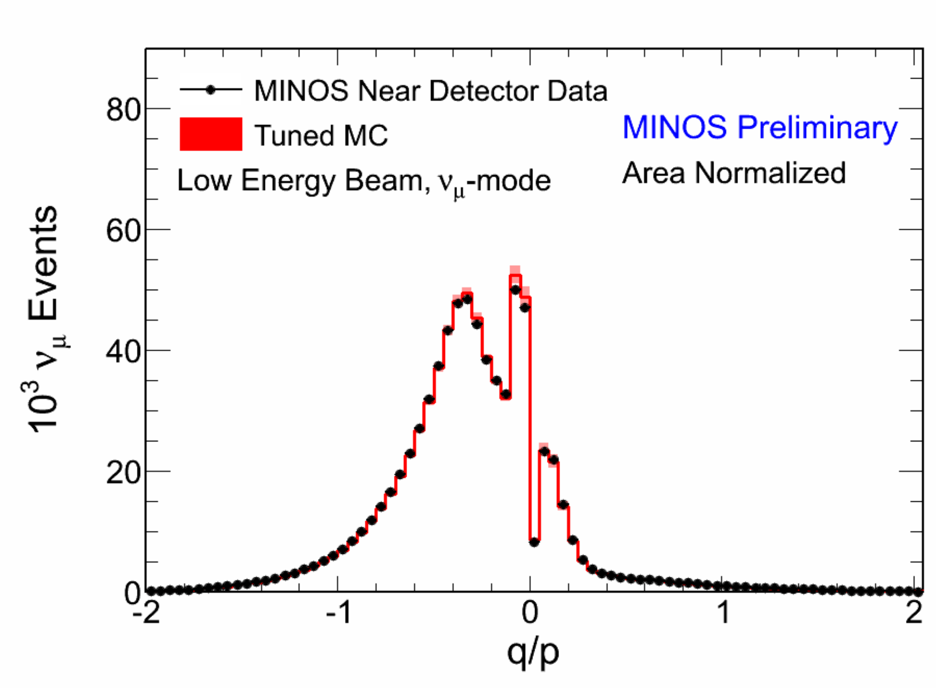
MINOS: Selection I

- The actual analysis selection can be broken down into two main parts.
- The first is the selection of muon like events by using a kNN (k nearest neighbour) algorithm. This takes advantage of the way muon tracks deposit energy, specifically:
  - Track Length.
  - Mean signal in track planes.
  - Transverse track profile.
  - Signal fluctuation in the track.

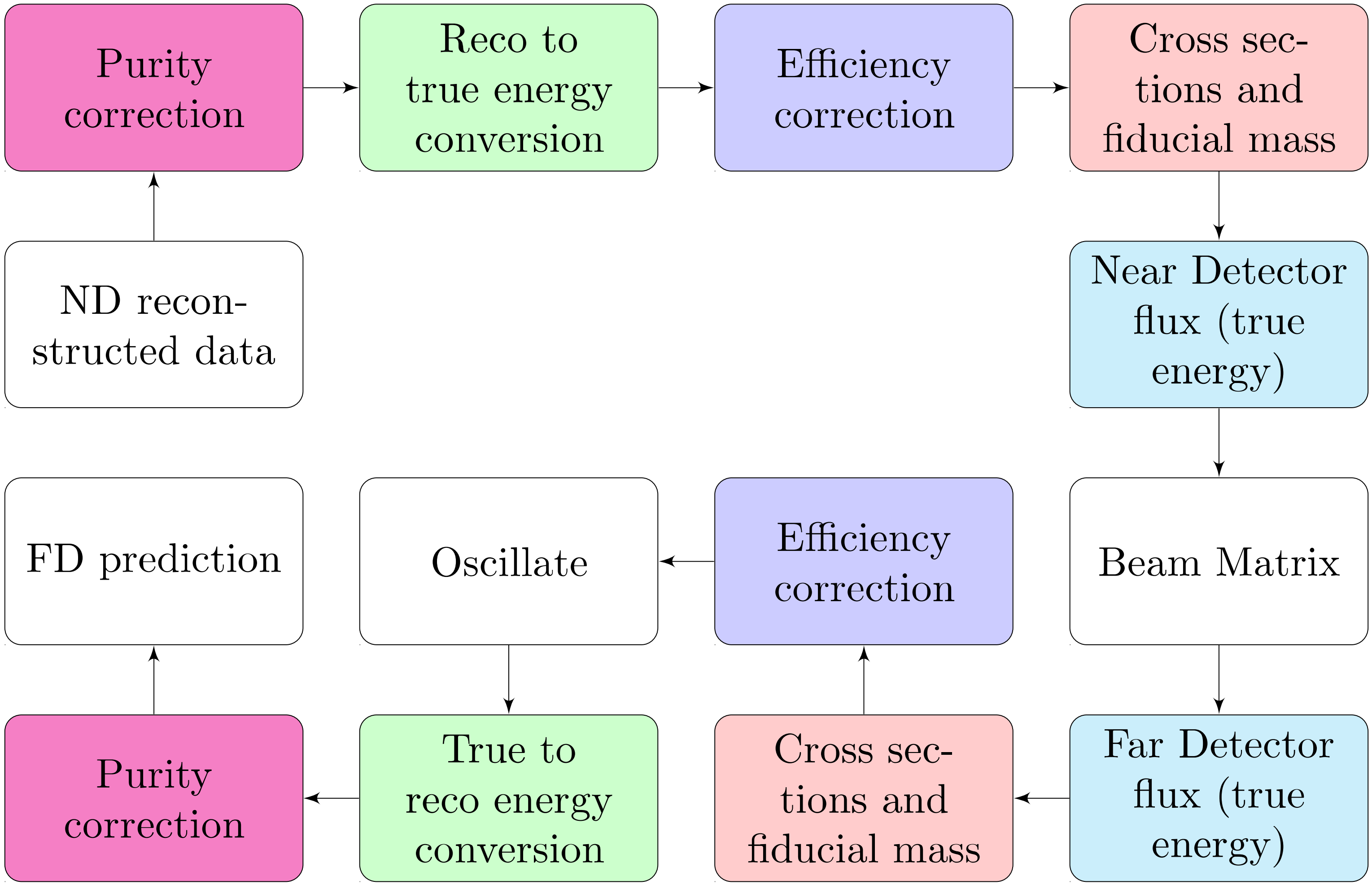


MINOS: Selection II

- The next is charge sign selection, judged by looking at the q/p of the track.
- Particularly important in the anti-neutrino analysis which aims to perform its fit with only anti-neutrinos.
- Less important for the 2 parameter analysis which includes positive sign CC events in its sample.

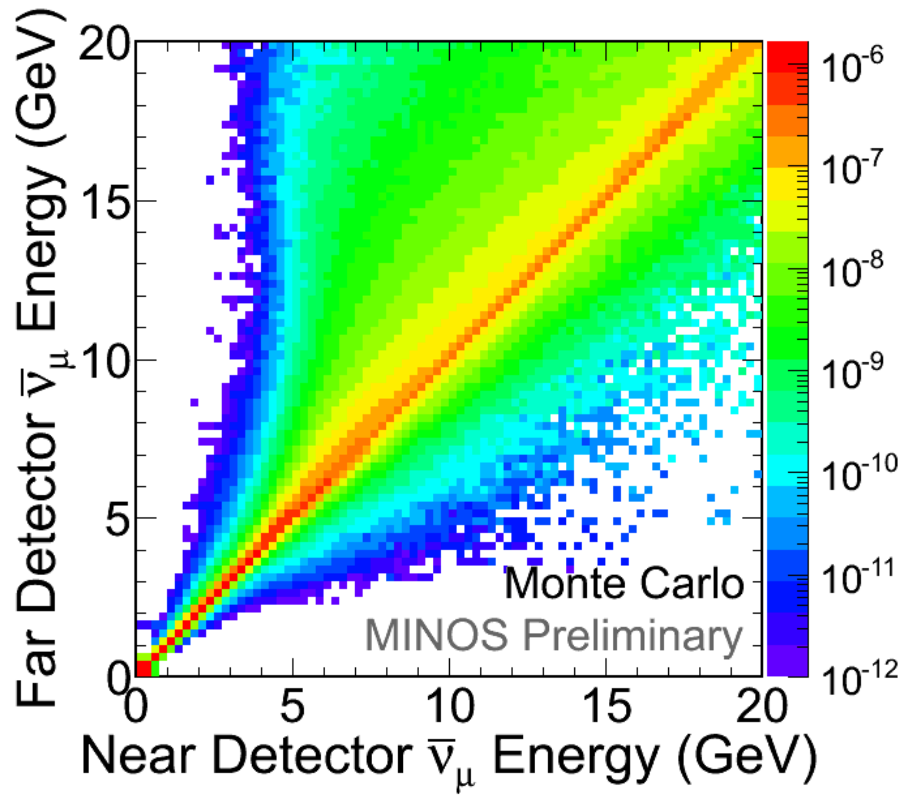


Near to Far Extrapolation



Beam Matrix

- To achieve this we use the a beam matrix
- This matrix describes the energy dependant differences in the neutrino flux seen at the near and far detector.
- π/K/μ producing events of a given energy in the near detector produce a range of energies in the far detector, yielding the energy smearing seen.



Selected Disappearance Events

Data Set	Simulation No osc.	Simulation With osc.	Events Observed
ν_μ from ν_μ beam	3201	2543	2579
$\overline{\nu}_\mu$ from ν_μ beam	363	324	312
Non-fiducial μ from ν_μ beam	3197	2862	2911
$\overline{\nu}_\mu$ from $\overline{\nu}_\mu$ beam	313	227	226
Atm. contained-vertex $\nu_\mu + \overline{\nu}_\mu$	1100	881	905
Atm. non-fiducial $\mu^- + \mu^+$	570	467	466
Atm. showers	727	724	701

Library Event Matching (LEM)

Find best matches from a library of MC Events

Judge how signal-like an event is based on those best matches.

Matching is done using only strip info (location and charge)

No dependence on high level reconstructed quantities