# THE MINOS EXPERIMENT

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# The MINOS Experiment


- Long-baseline neutrino oscillation experiment
  - Neutrinos from NuMI beam line
    - L/E ~ 250 km/GeV
      - atmospheric $\Delta m^2$


**Brand New! 3 flavor Combination**

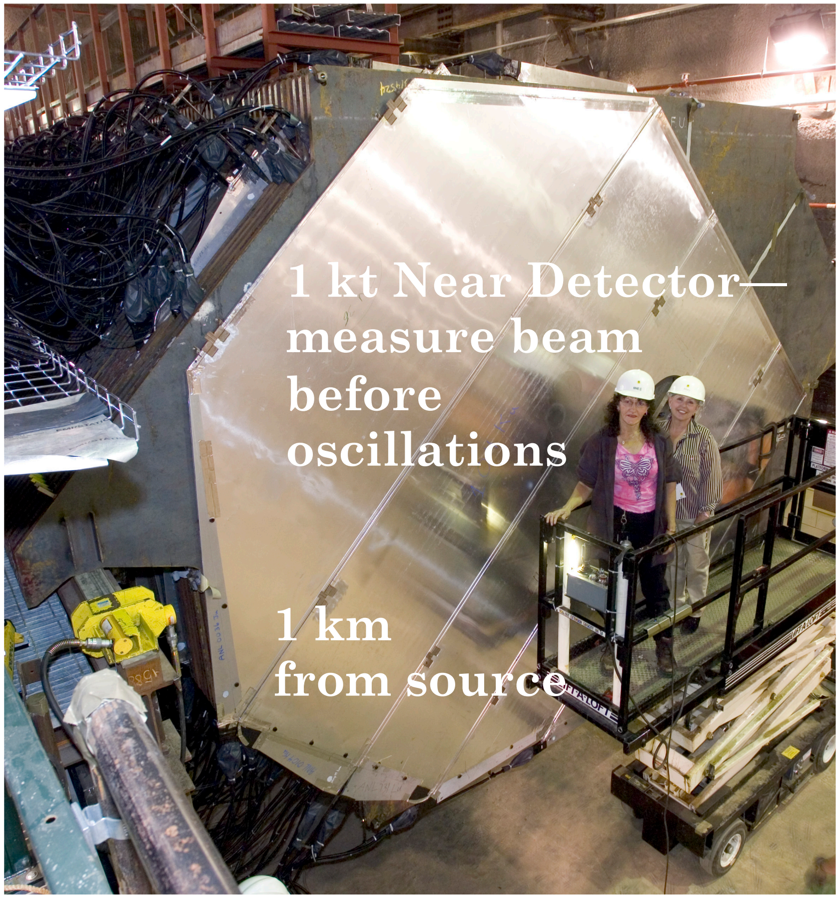
- Physics goals:
  - Measure $\nu_\mu$ disappearance as a function of energy
  - Study $\nu_\mu \rightarrow \nu_e$ mixing
  - Measure rate of Neutral Current interactions

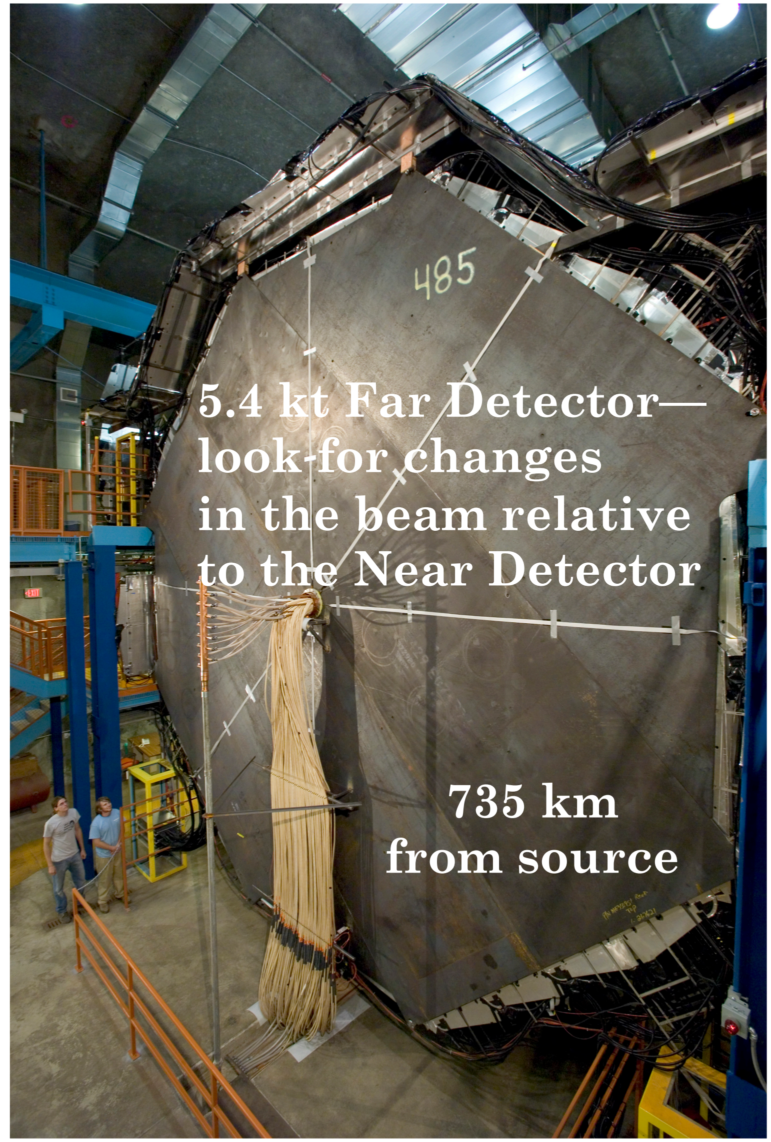
Update, more stats!

# THE DETECTORS

FD running since 2003

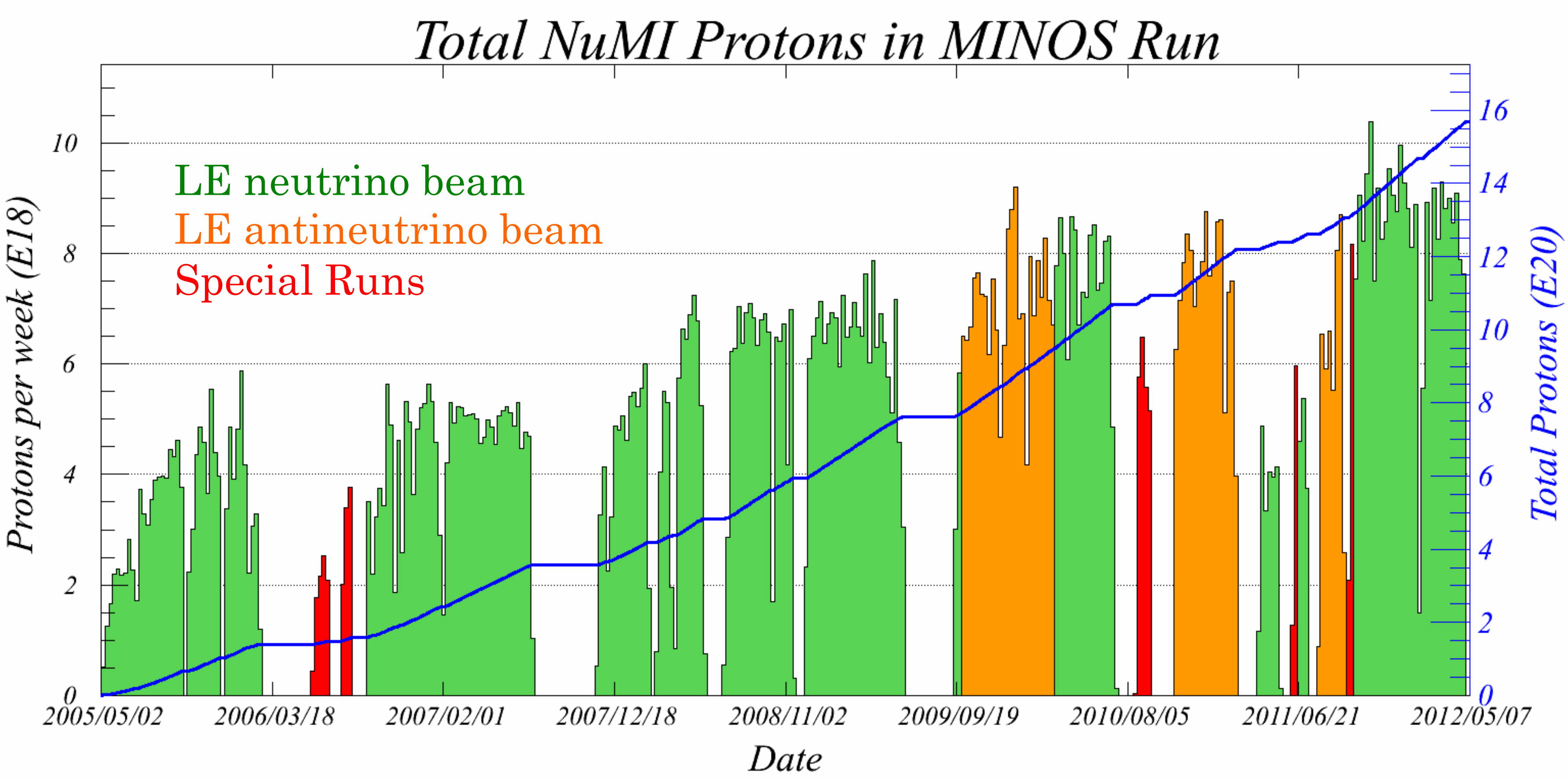
ND running since 2005




- Magnetized Steel-Scintillator Tracking sampling calorimeters

# The data sets



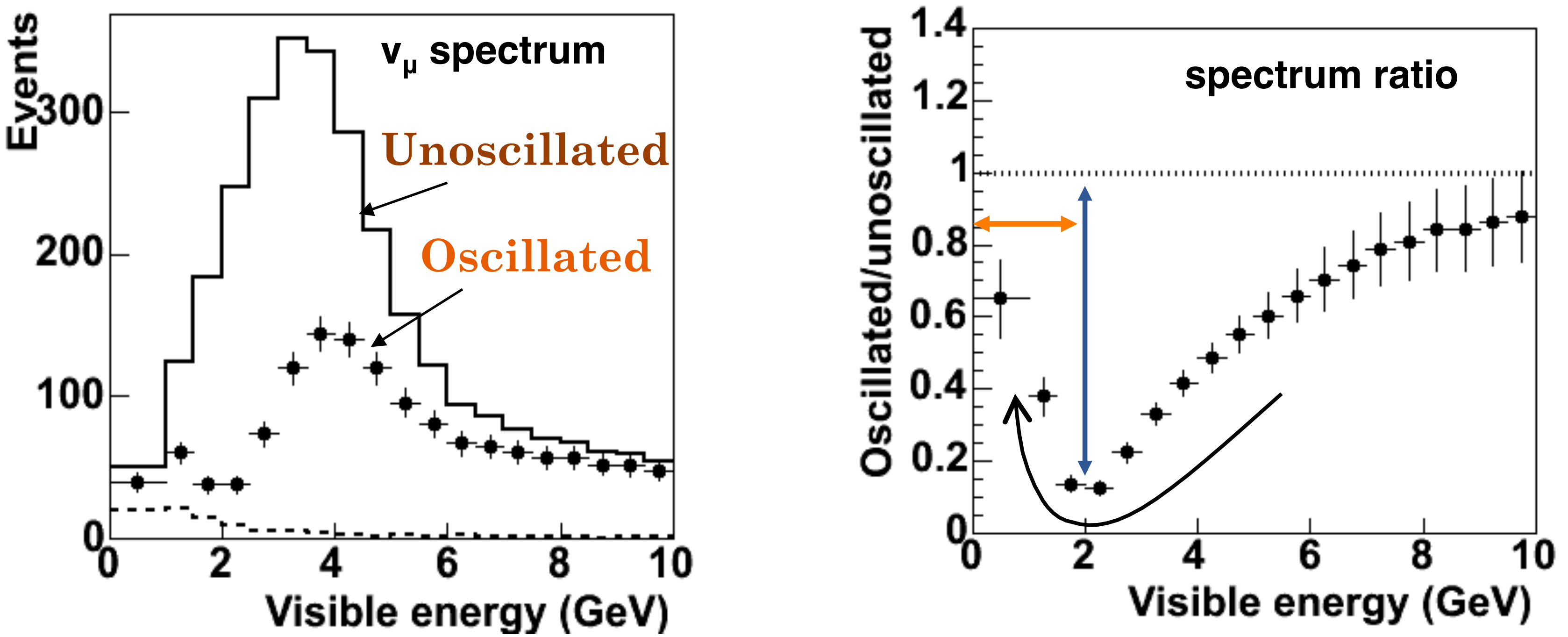

- Results from entire beam run
  - 10.7 x $10^{20}$ POT in (LE) neutrino running
  - 3.36 x $10^{20}$ POT in antineutrino running
- 37.8 kton years of atmospheric neutrinos in FD

# 2 Flavor Muon Neutrino Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

**Monte Carlo**

(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ $eV^2$ )






PRL 110:251801 (2013)

# Extending to 3 Flavors

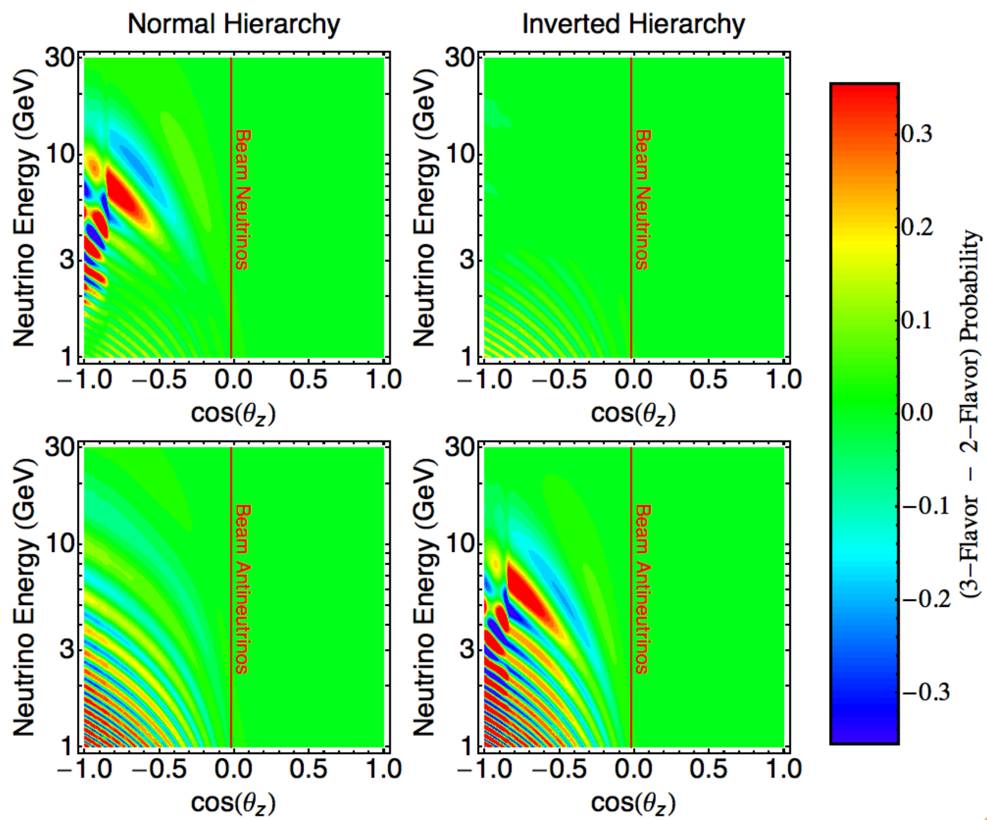
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2(1.27\Delta m^2_{\mu\mu} L/E) + \mathcal{O}\left(\Delta m^2_\odot \frac{L}{E}\right)^2$$

$$\sin^2(\theta_{\mu\mu}) = \sin^2\theta_{23}\cos^2\theta_{13} \qquad \Delta m^2_{\mu\mu} = \Delta m^2_{32} + \frac{|U_{\mu 1}|^2}{1-|U_{\mu 3}|^2}\Delta m^2_{21}$$

depends on $\theta_{13}$, $\theta_{23}$ octant, mass hierarchy, $\delta_{CP}$

(and solar mixing parameters)

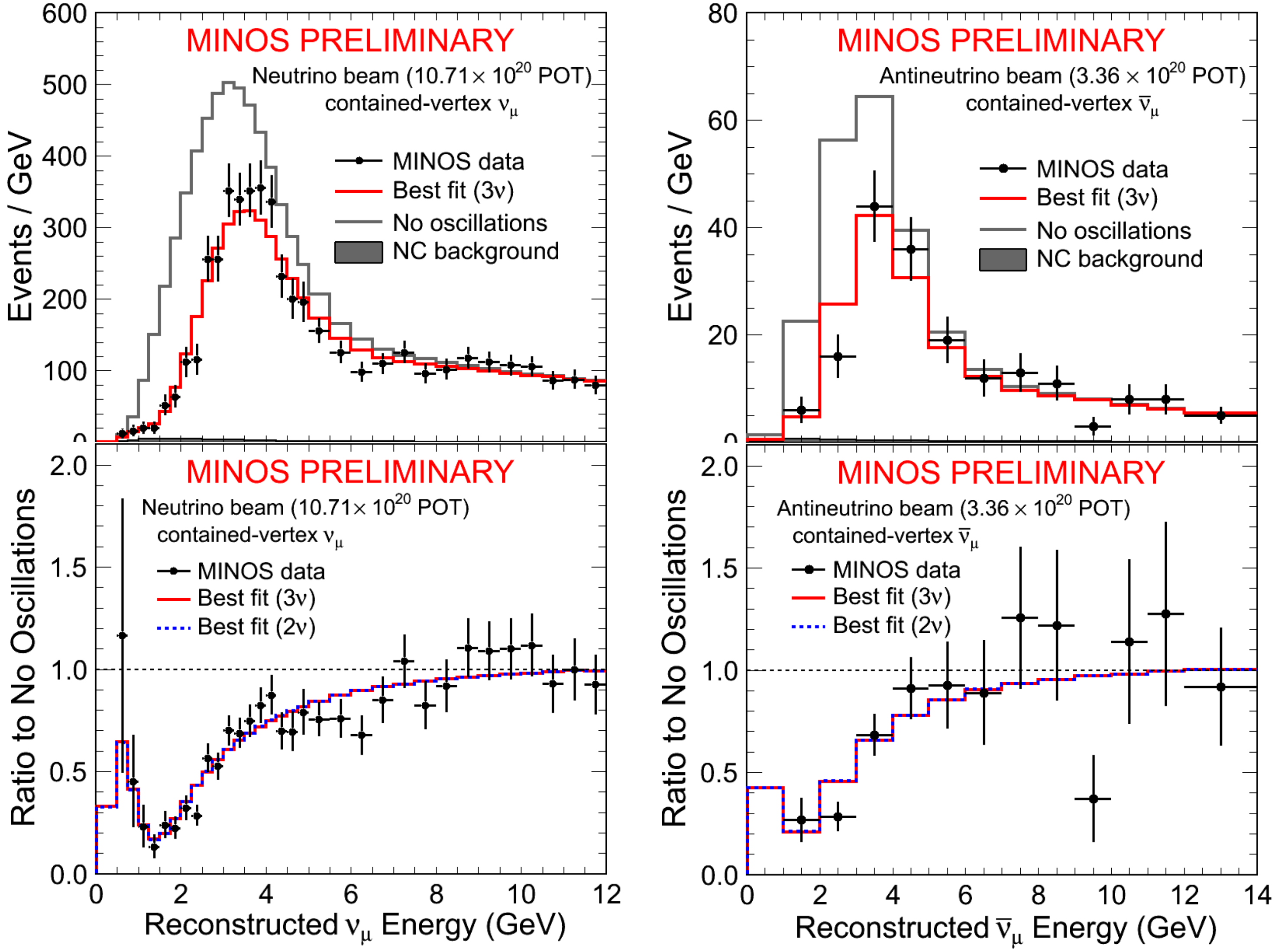
- Only small changes to beam oscillation
- Matter effects give rise to larger differences in multi-GeV, upward atmospheric events
- Effect is seen in neutrinos or antineutrinos, depending on hierarchy



# FAR DETECTOR BEAM SAMPLES

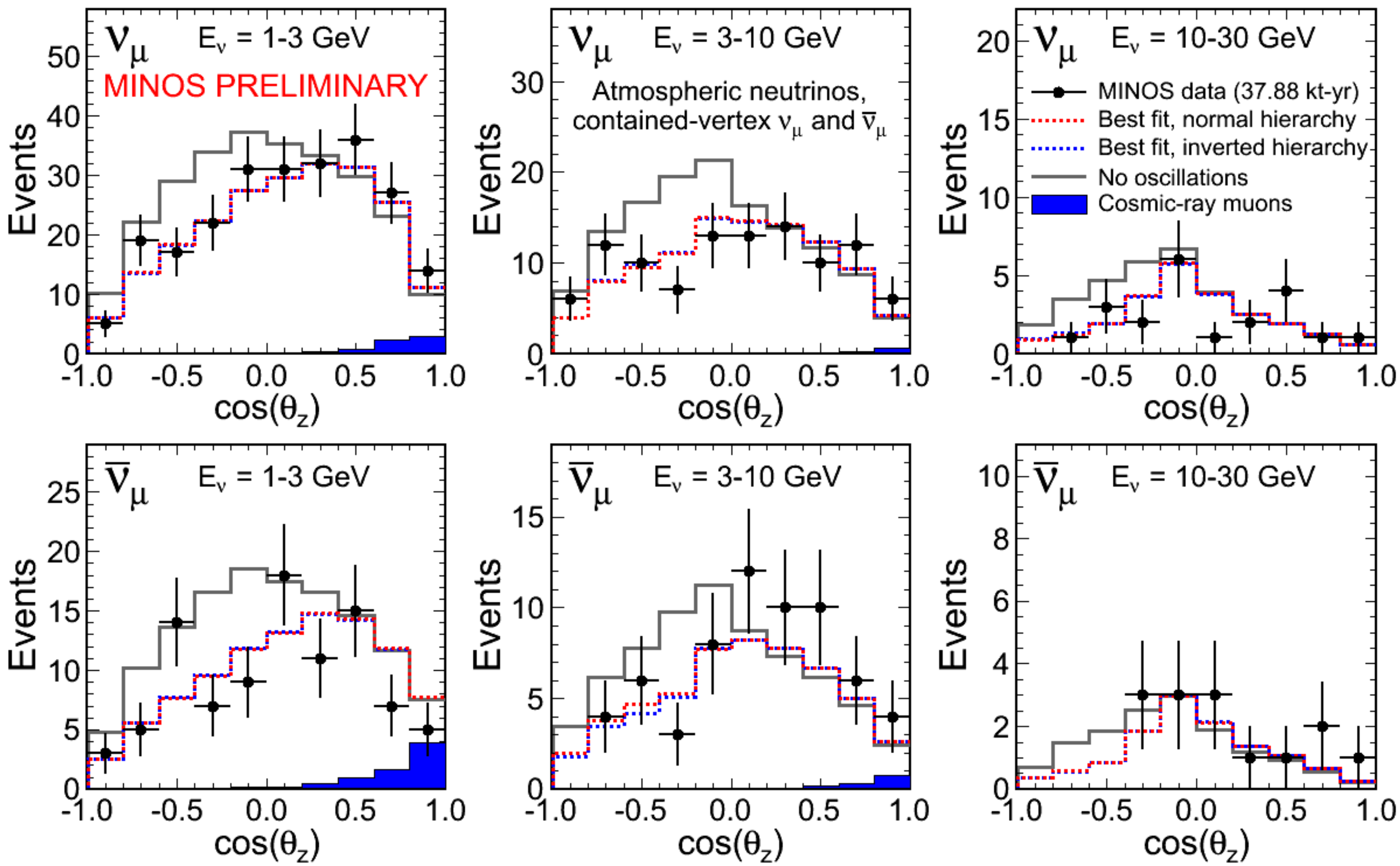
3 Flavor Oscillations fit the data, 18% of pseudo-expts have worse fit

Neutrinos | Anti-Neutrinos



# FAR DETECTOR ATMOSPHERIC SAMPLES

3 Flavor Oscillations fit the data, 18% of pseudo-expts have worse fit




- Contained vertex muon neutrino events shown
- Upward rock muon and shower events also included in fit

# Electron Neutrino Appearance

- A few percent of the missing $\nu_\mu$ could change into $\nu_e$
- Including subdominant mode enhances sensitivity to 3 flavor effects

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

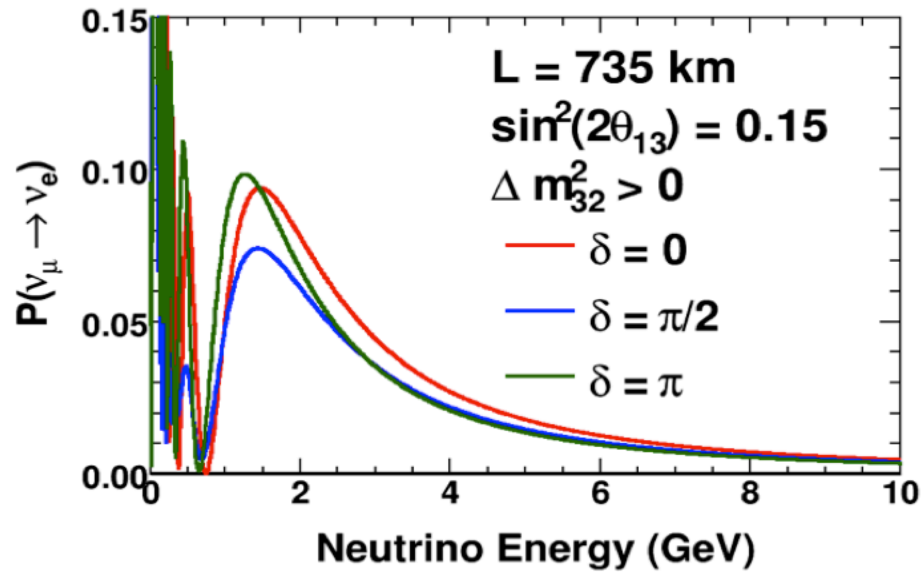
$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

"Solar" Term
<1% in MINOS

Interference Term
- for neutrinos
+ for antineutrinos

if $\delta_{CP} \neq 0$,

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$



# ELECTRON NEUTRINO APPEARANCE

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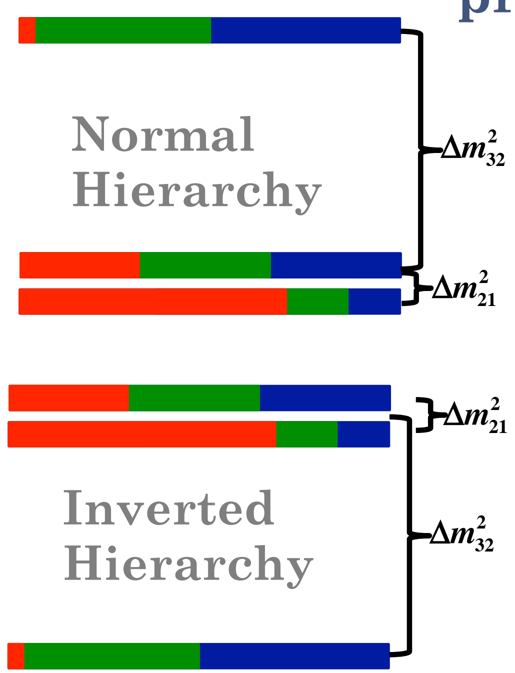
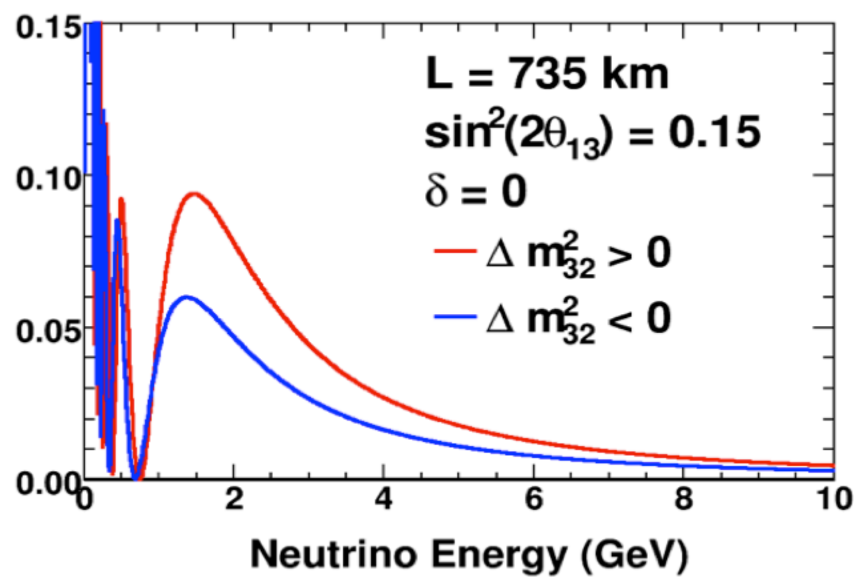
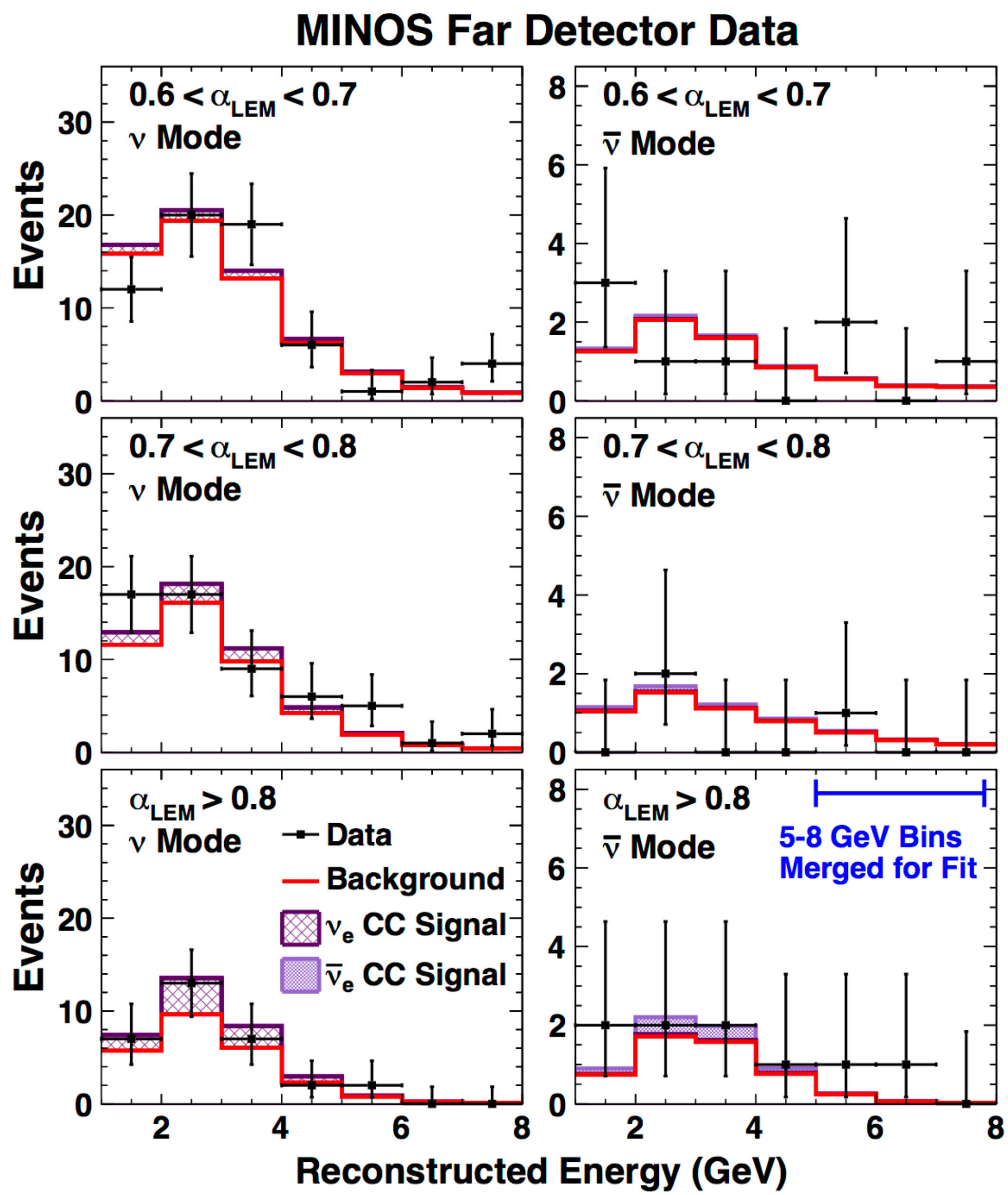
**In matter, $\nu_e$ + e CC scattering modifies oscillation probability ~30% in MINOS**

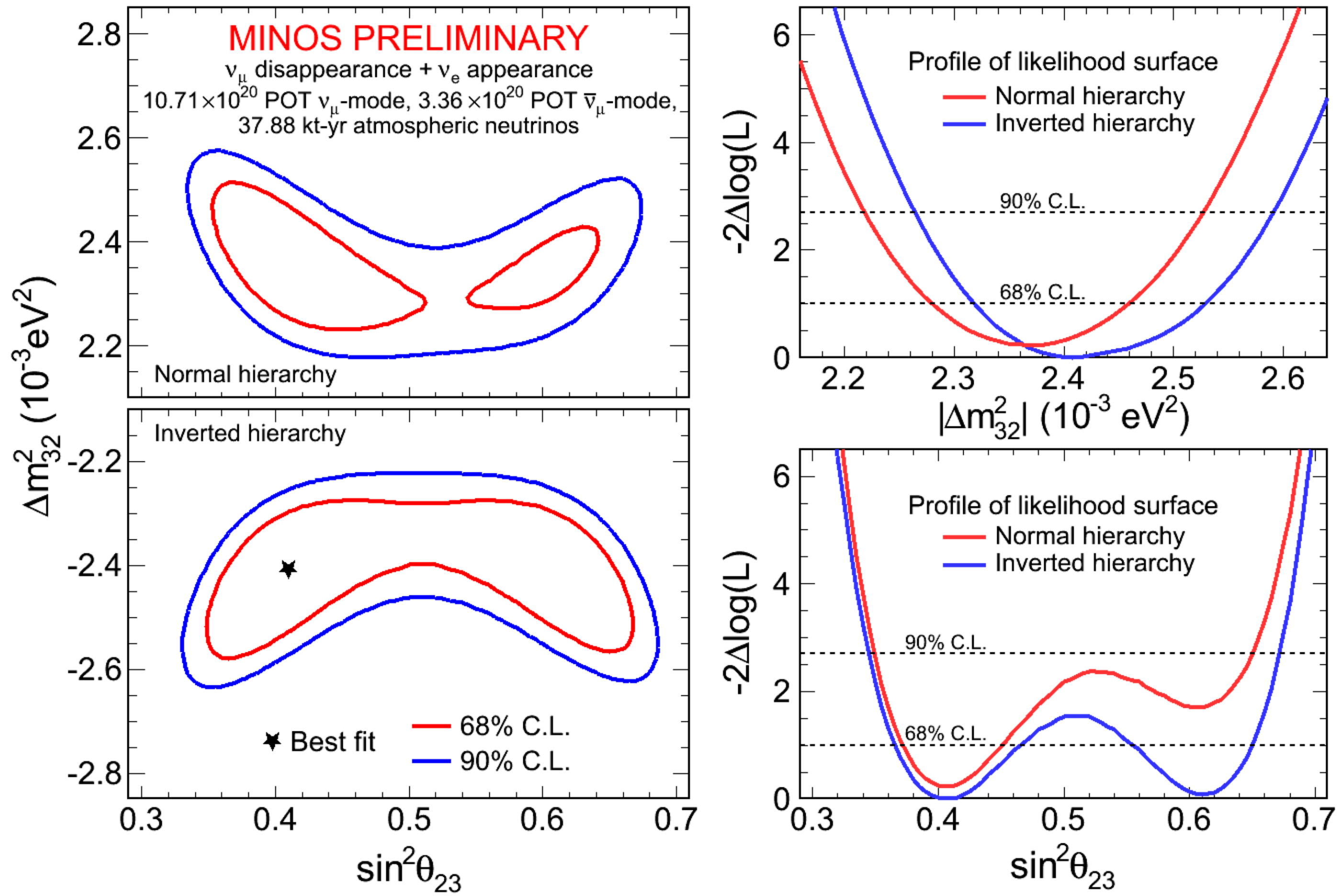


# ELECTRON NEUTRINO APPEARANCE



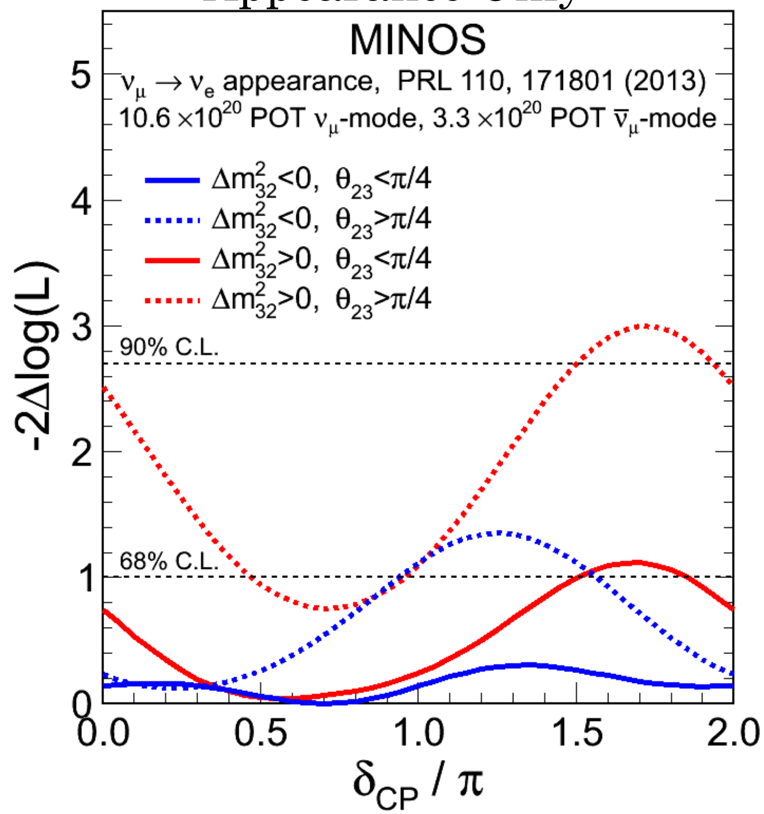
# PUTTING IT ALL TOGETHER



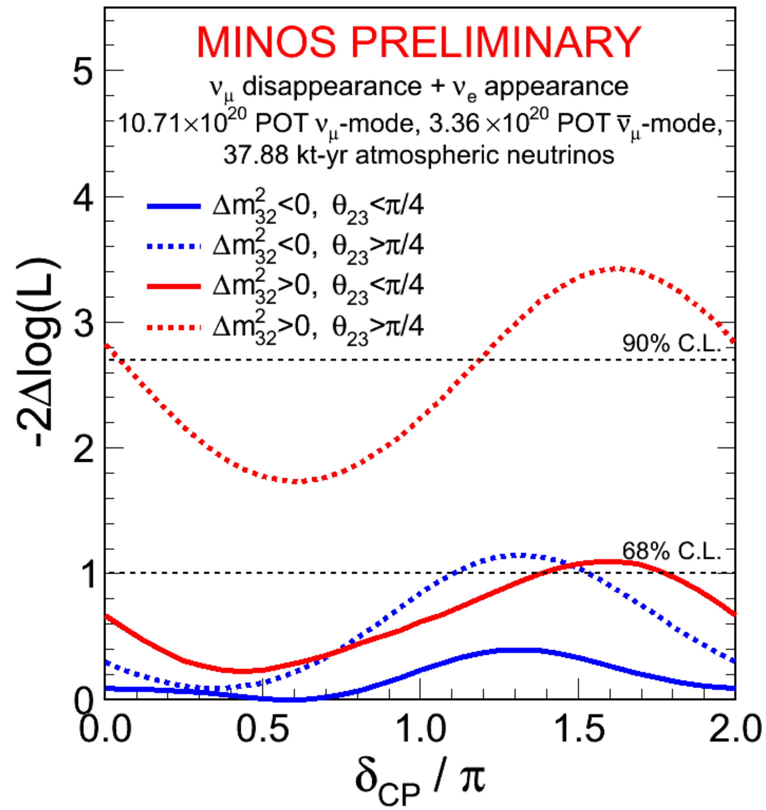

- $\delta_{CP}$, $\theta_{23}$, $\Delta m^2$ unconstrained
- Solar mixing parameters fixed
- $\theta_{13}$ fit as nuisance parameter, constrained by reactor results
- major systematic uncertainties included as nuisance parameters

# DELTA DEPENDENCE

Appearance Only




Appearance+Disappearance




- Normal hierarchy, upper octant further disfavored with inclusion of disappearance data

# Results

| Hierarchy, Octant | Best fit oscillation parameters | | | | |
|---|---|---|---|---|---|
| | $\Delta m^2_{32}$ / $10^{-3}$eV$^2$ | $\sin^2\theta_{23}$ | $\sin^2\theta_{13}$ | $\delta_{CP}/\pi$ | $-2\Delta\log(L)$ |
| 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 | $\|\Delta m^2_{32}\|/10^{-3}$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 | $\|\Delta m^2_{32}\|/10^{-3}$eV$^2$ | 2.41 | 2.32 – 2.53 (68% C.L.) |
| | $\sin^2\theta_{23}$ | 0.41 | 0.34 – 0.67 (90% C.L.) |

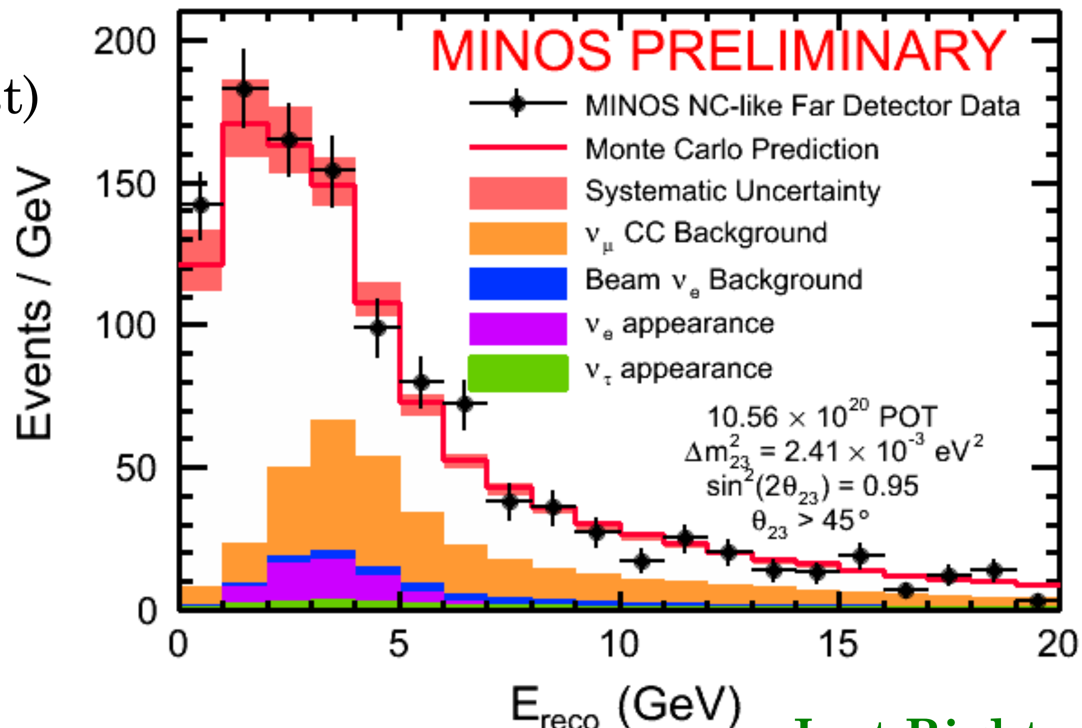
Preference for inverted hierarchy: $-2\Delta\log L = 0.23$

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

Preference for non-maximal mixing: $-2\Delta\log L = 1.54$ ($\Rightarrow$ 79% C.L.)

# NEUTRAL CURRENTS

- Neutral Current event rate should not change in 3 flavor oscillation scenario
- A deficit in the FD evidence of a sterile neutrino flavor
- We see an excess!
  - Expect 1183±50 (stat+syst)
  - Observe 1221
- Sterile mixing also causes anomalous disappearance of muon neutrinos

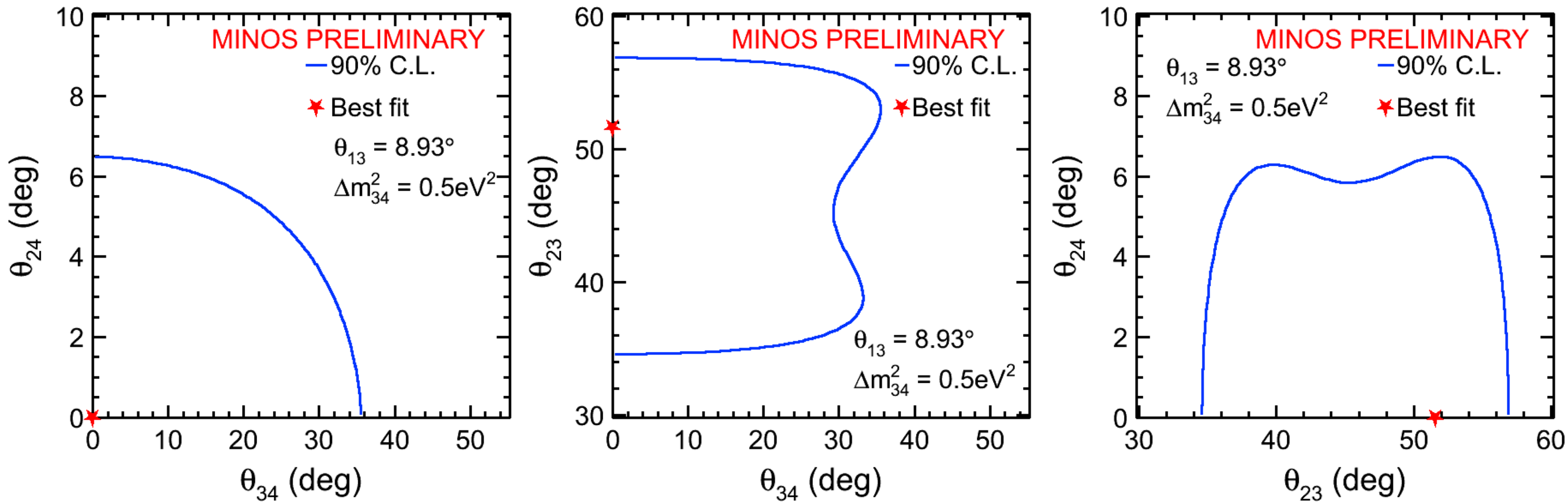



- Three regimes:
  - small $\Delta m^2$: wiggles in FD at high energies
  - medium $\Delta m^2$: rapid FD wiggles average out
  - large $\Delta m^2$: oscillations occur in ND

Tricky

Just Right

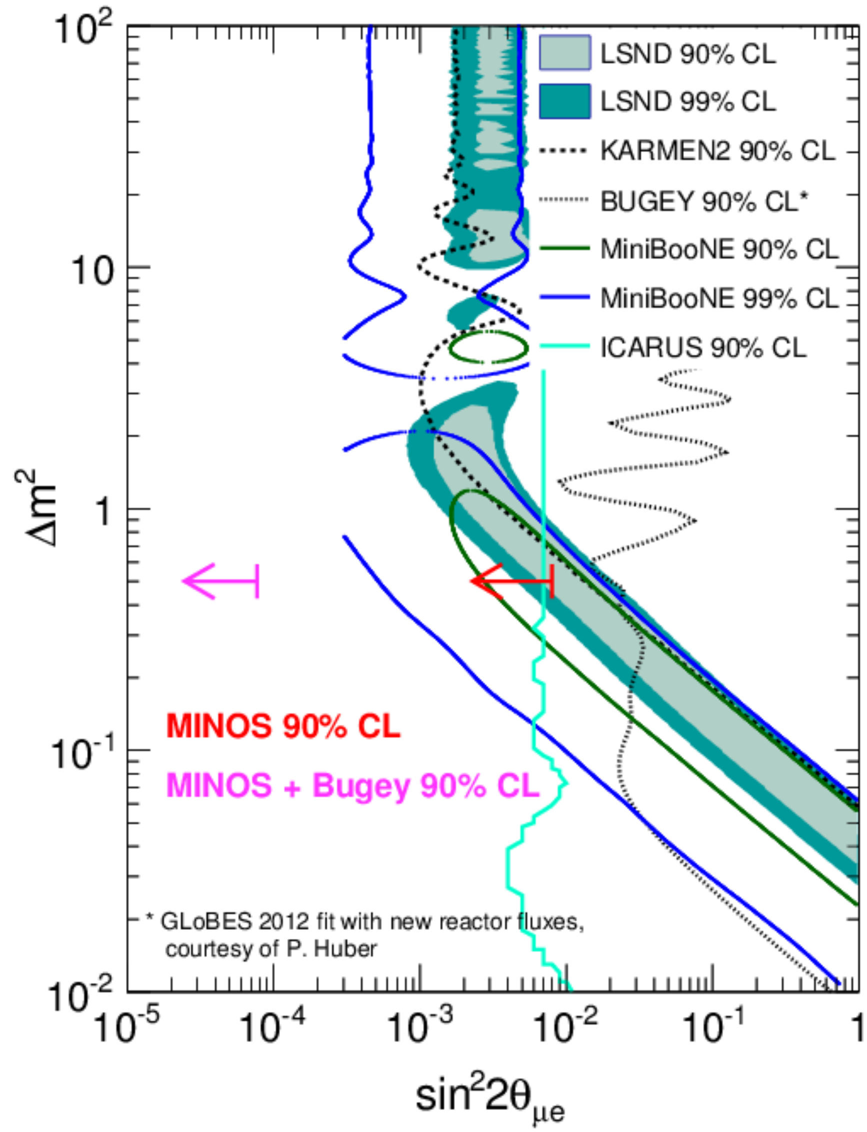
# Limits on the Angles




- $\theta_{34} < 24^o$ at 90% C.L.
- $\theta_{24} < 5^o$ at 90% C.L.

# Comparison to MiniBooNE

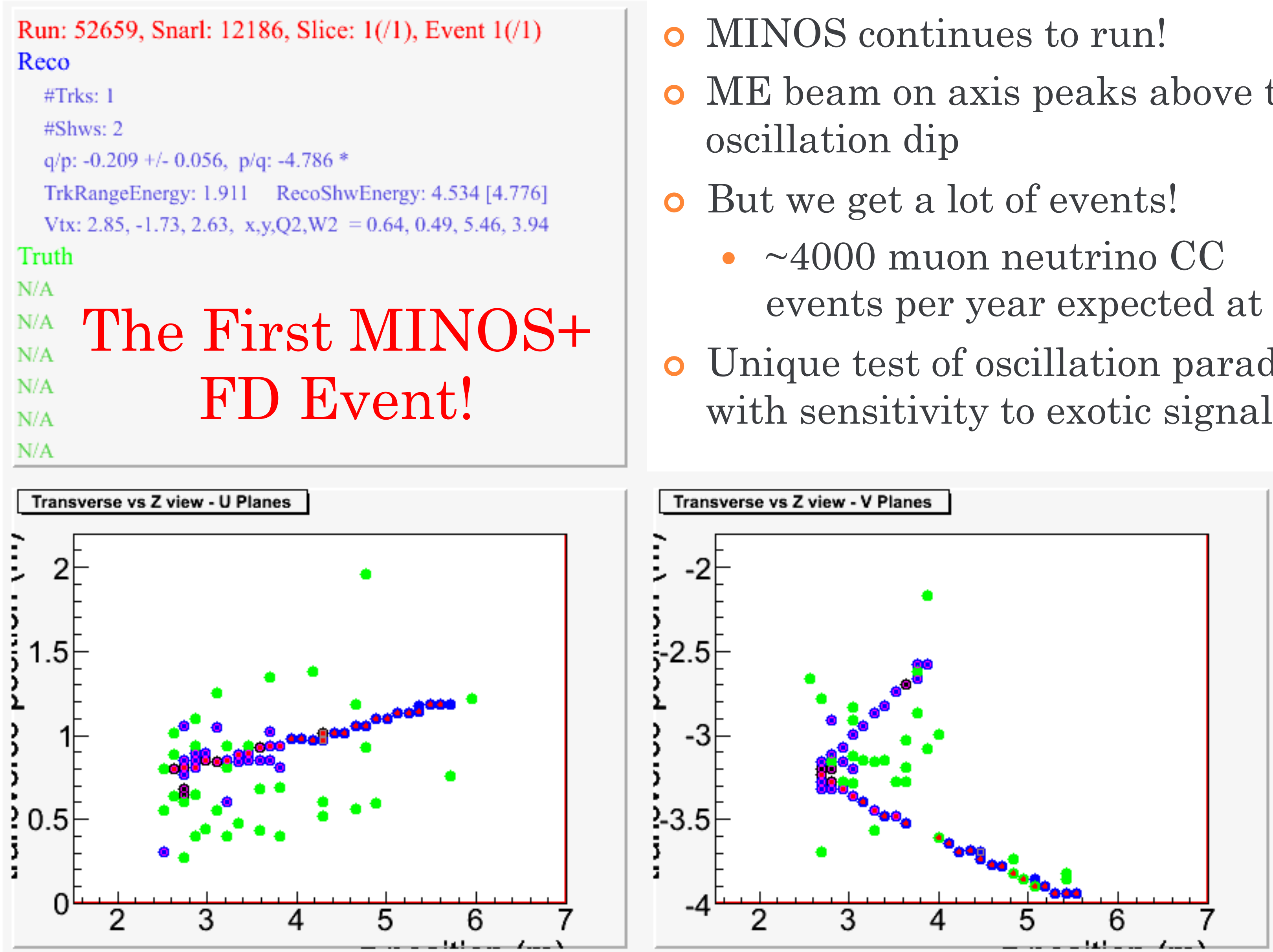
- Our limit on $\theta_{24}$ can be combined with Bugey limit on $\theta_{14}$ for comparison with MiniBooNE/ LSND
- Stay tuned for the extension to higher and lower mass splittings
- MINOS+ will continue to pursue this analysis mode




$$\sim \sin^2(2\theta_{14})\sin^2\theta_{24}$$

# THE FUTURE IS NOW

## Beam Back, Sept. 4




- MINOS continues to run!
- ME beam on axis peaks above the oscillation dip
- But we get a lot of events!
  - ~4000 muon neutrino CC events per year expected at FD
- Unique test of oscillation paradigm with sensitivity to exotic signals

# Conclusions

- New MINOS 3 flavor results

| Hierarchy, Octant | Best fit oscillation parameters | | | | |
|---|---|---|---|---|---|
| | $\Delta m^2_{32}$ / $10^{-3}$eV$^2$ | $\sin^2\theta_{23}$ | $\sin^2\theta_{13}$ | $\delta_{CP}/\pi$ | $-2\Delta\log(L)$ |
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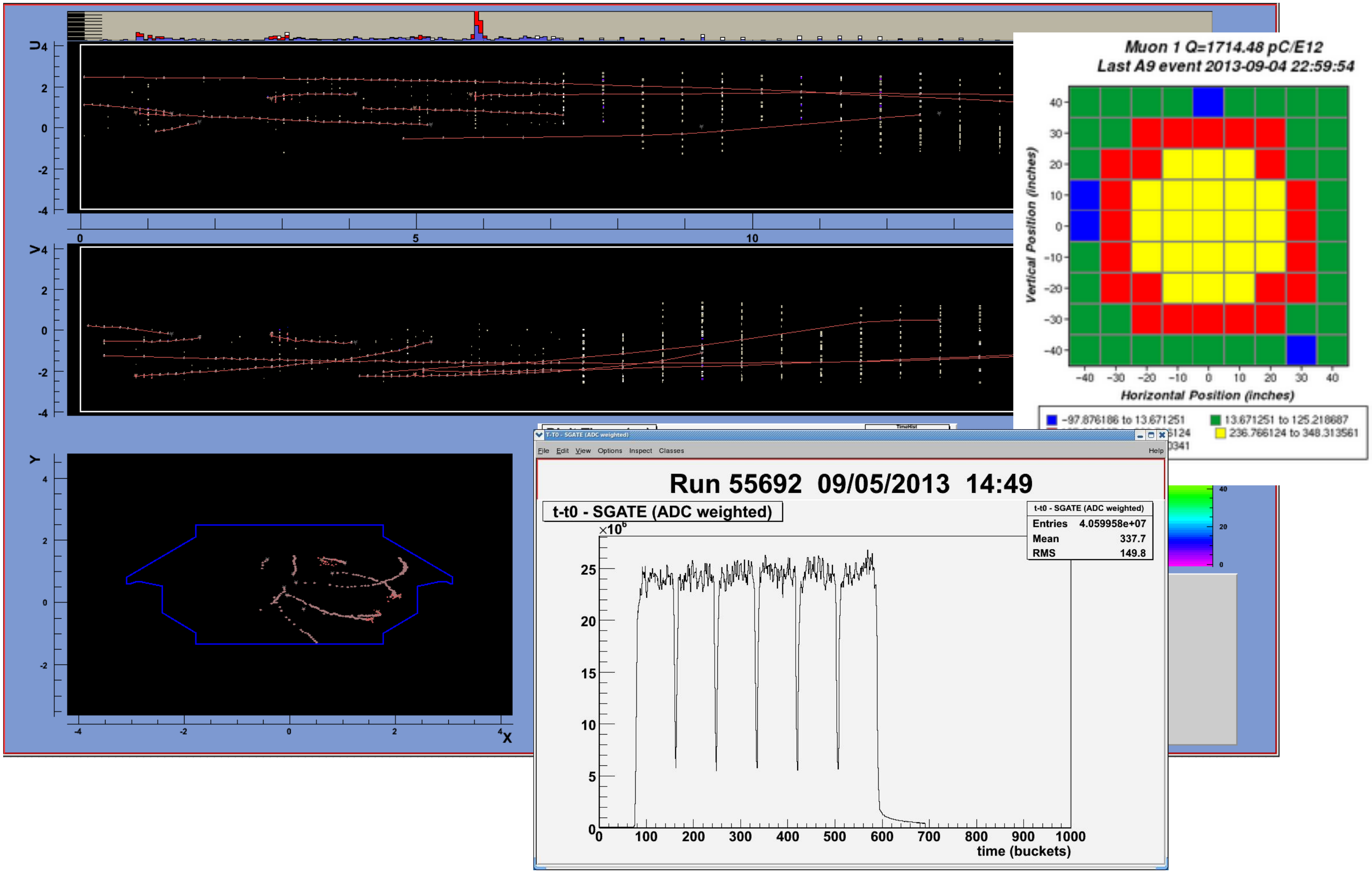
- Watch for updates on sterile mixing limits
- MINOS+ will continue to provide exciting physics in the years to come.

# Backup Slides

# The Future is Now

## Beam Back, Sept. 4!




P. Vahle, TAUP 2013

# Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation

- A neutrino created as one flavor can later be detected as another flavor, depending on:
  - distance traveled (L)
  - neutrino energy (E)
  - difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)
  - The mixing amplitudes ($U_{\alpha j}$)

# The PMNS Mixing Matrix

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

- (12) Sector: reactor + solar, L/E~15,000 km/GeV

$$^{\dagger}\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \text{eV}^2 \qquad \tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

- (23) Sector: atmospheric and accelerator, L/E~500 km/GeV

$$^{\dagger\dagger}\left|\Delta m^2_{32}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2 \qquad {}^{*}\sin^2(2\theta_{23}) > 0.96\,(90\%\ \text{C.L.})$$

- (13) Sector: reactor and accelerator, L/E~500 km/GeV

$$^{**}\sin^2(2\theta_{13}) = 0.090^{+0.008}_{-0.009}\,(\text{stat.+syst.})$$

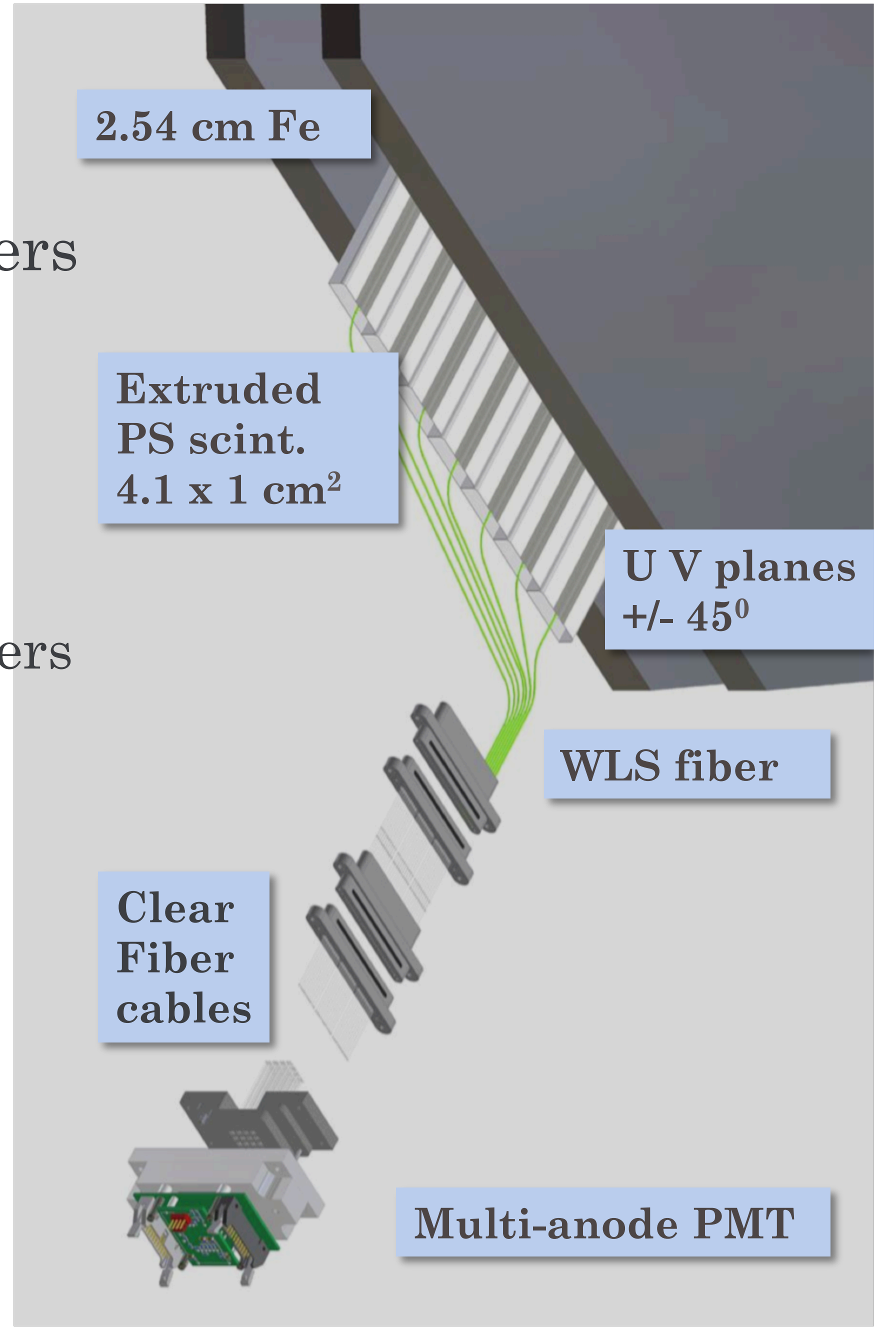
†PRD 83.052002(2011)
††PRL 106. 181801(2011)
*SuperK Preliminary, Nu2010
**Daya Bay Preliminary, NuFact2013

# Why Measure All These Angles?

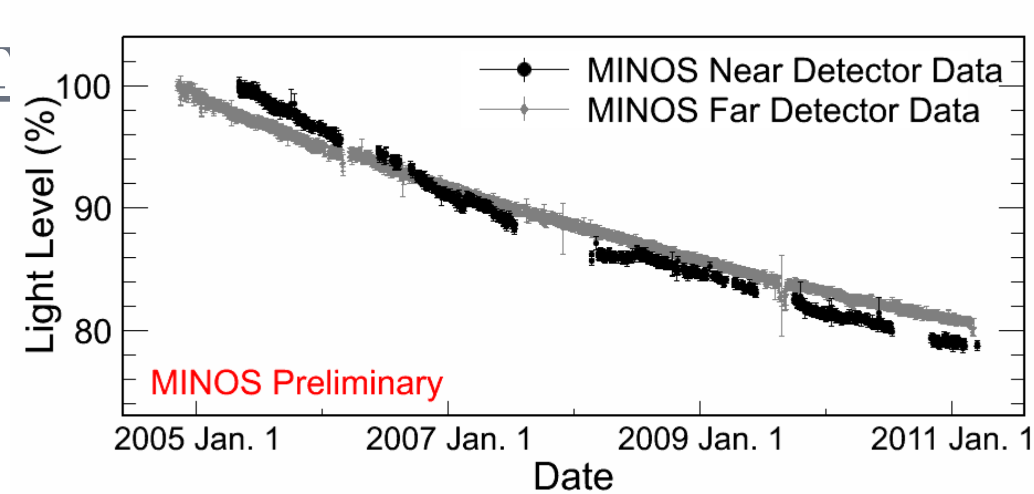
- Precision measurements provide a valuable constraints on neutrino oscillation model
- Open Questions:
  - What are the masses of the neutrinos?
  - What is the nature of neutrino mass?
  - Which neutrino is most massive?
  - Why is lepton mixing much larger than quark mixing?
  - Is there an underlying symmetry to the mixing matrix?
  - Is there CP violation in the lepton sector? Is it big enough to account for matter vs. antimatter asymmetry?
- Small neutrino mass suggests a heavy partner—Neutrinos provide a window to physics at the GUT scale!

# DETECTOR TECHNOLOGY

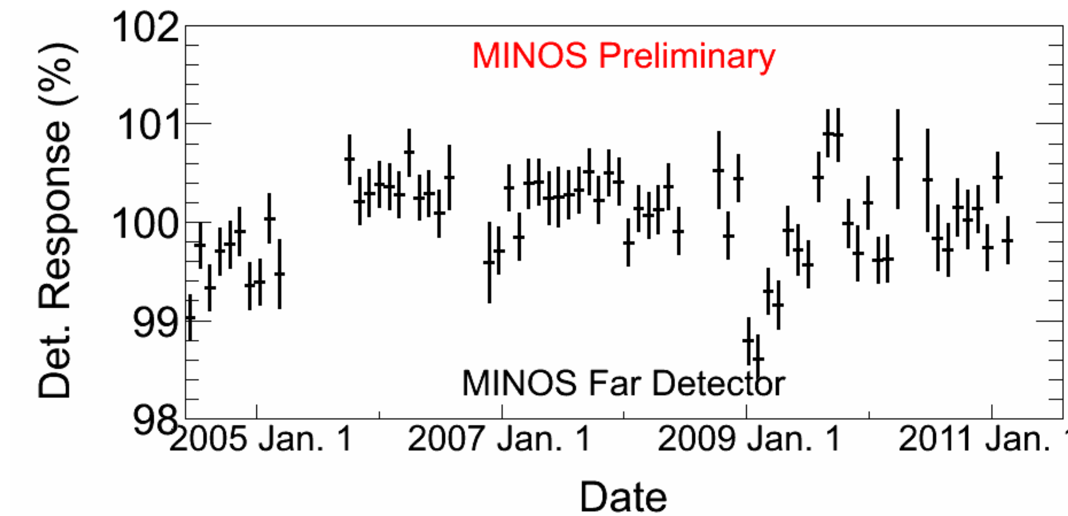
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick ($1.4\ X_0$)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/ curvature
  - distinguish μ+ from μ-
- Functionally equivalent
  - same segmentation
  - same materials
  - same mean B field (1.3 T)



# DETECTOR STABILIT

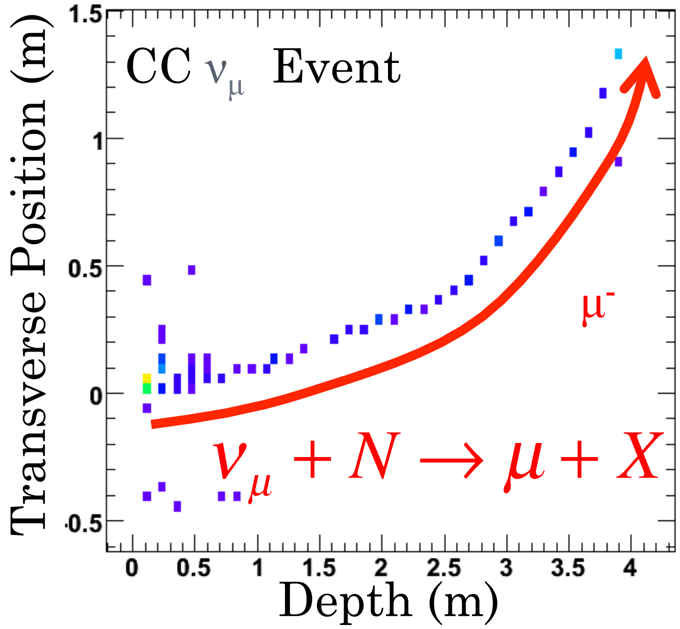


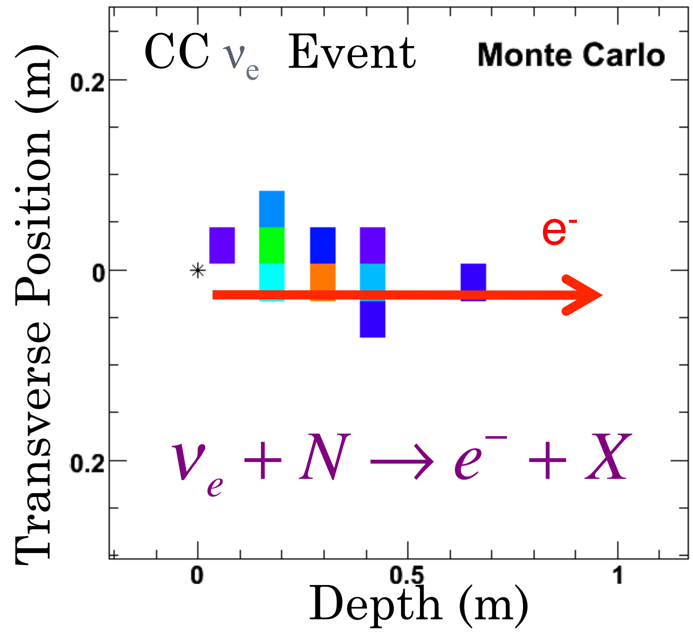

Far Detector live for 97% of Beam Exposure

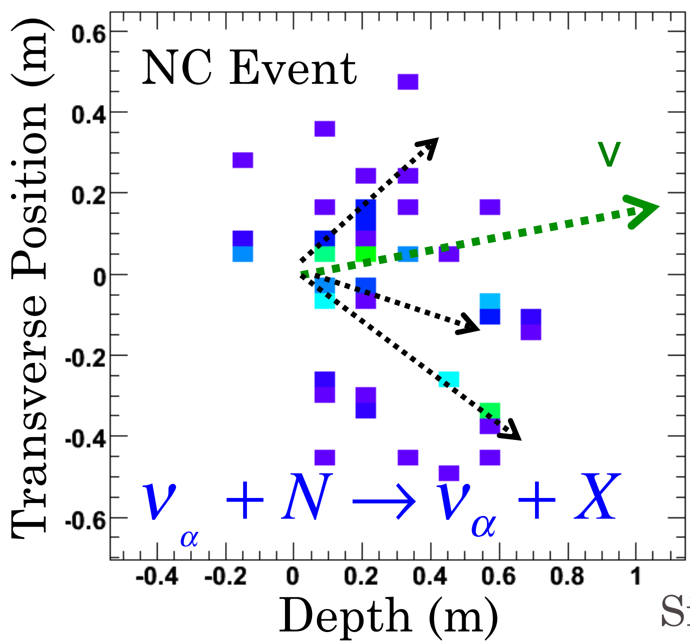



| | Near | Far |
|---|---|---|
| Gains Increase/year | 2.5% | 1.8% |
| Light Level Decrease/year | 3.5% | 3.0% |
| Overall Stability (after calibration) | 0.5% | 1.5% |

# EVENTS IN MINOS



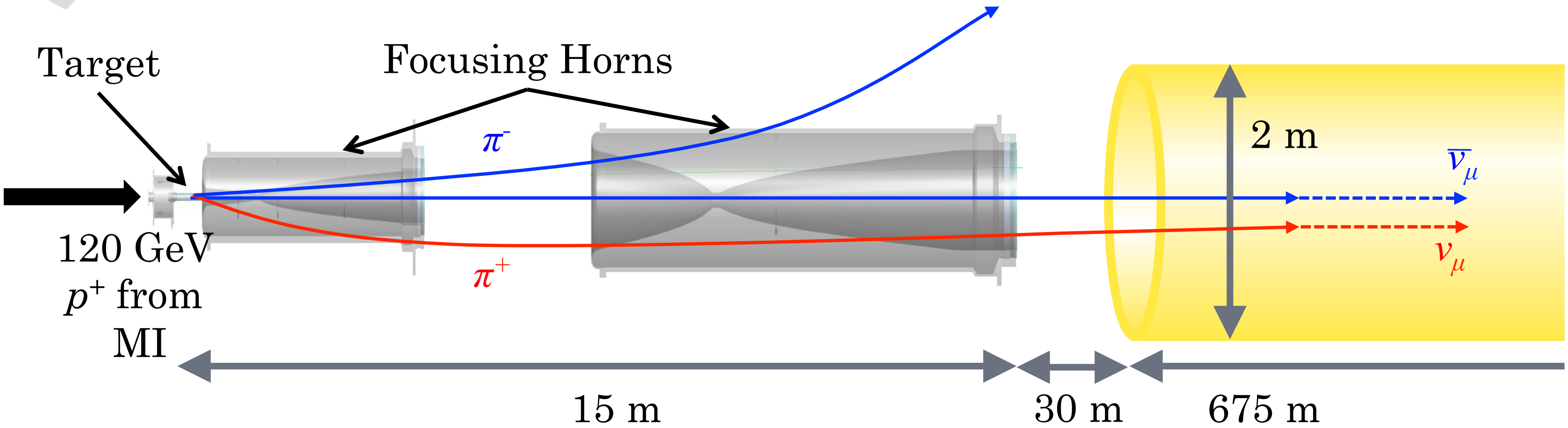



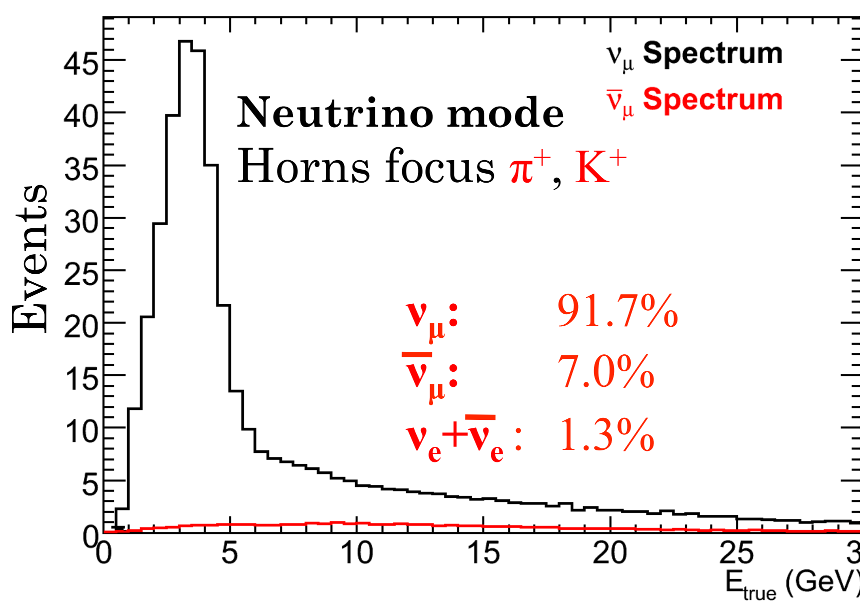



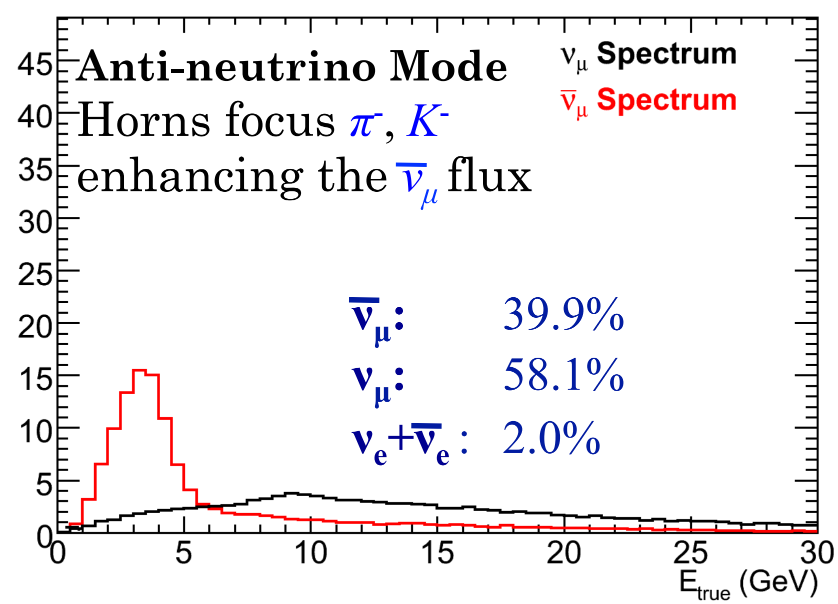

- $\nu_\mu$ Charged Current events:
  - energy from sum of muon energy (range or curvature) and shower energy
- NC or $\nu_e$:
  - energy from calorimetric response

Simulated Events

# Making a Neutrino Beam

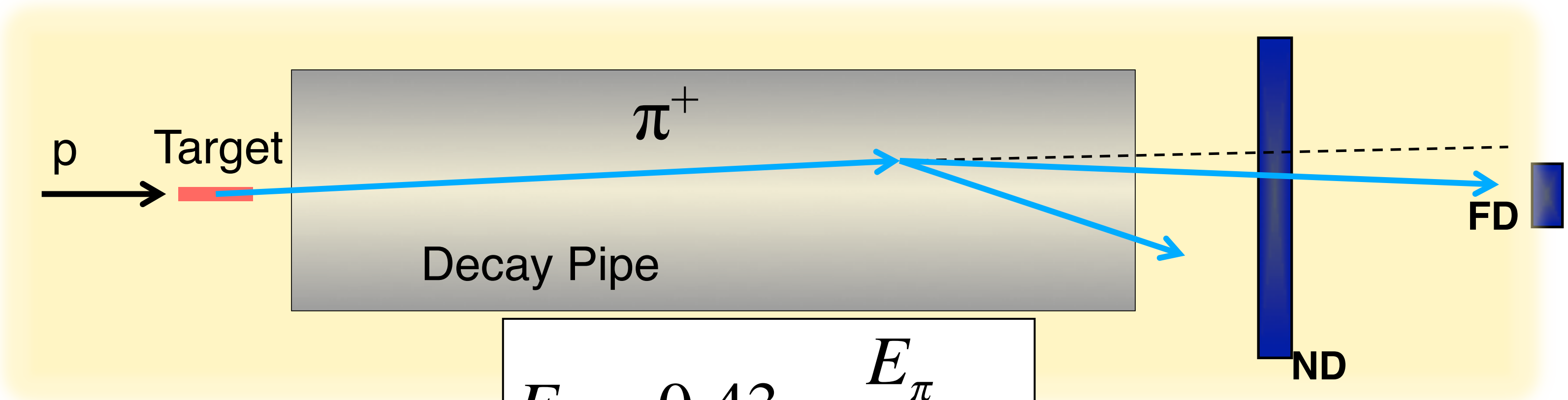


# Near to Far

**Far spectrum without oscillations is similar, but not identical to the Near spectrum!**

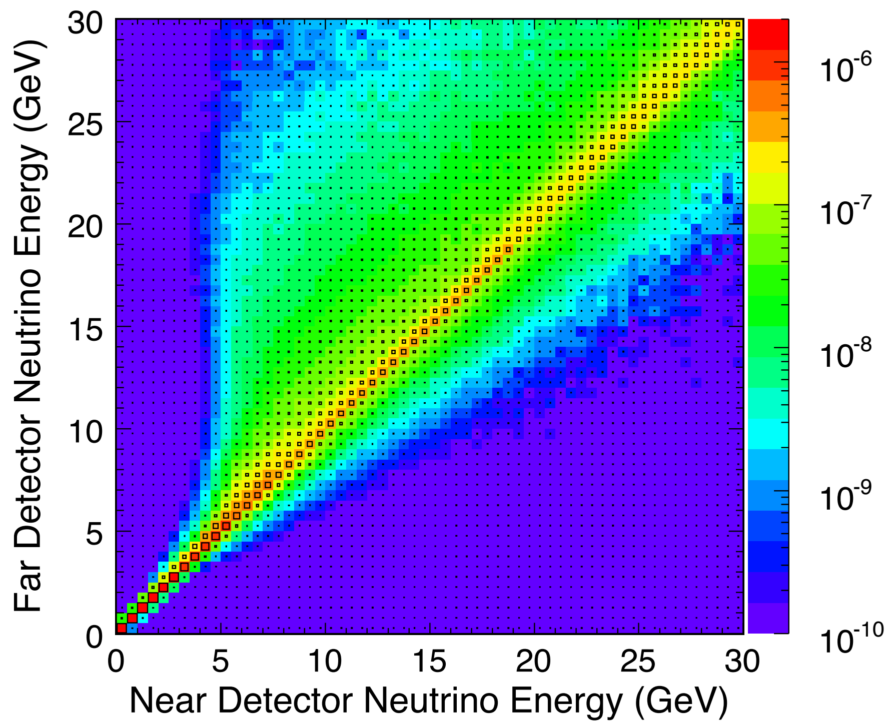


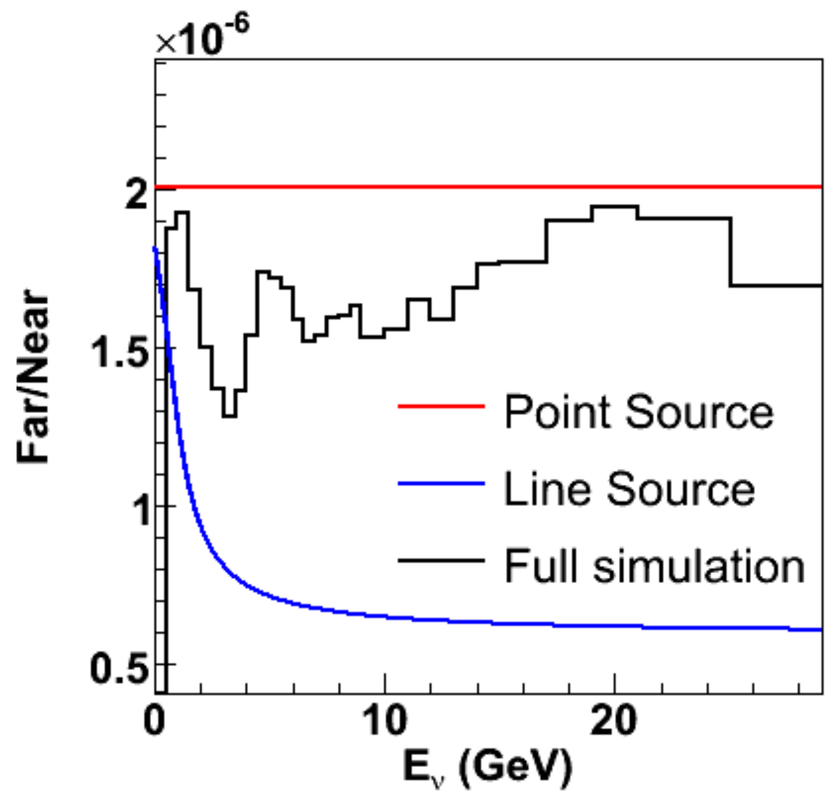

$$E_\nu \approx 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$

- Neutrino energy depends on angle wrt original pion direction and parent energy
  - higher energy pions decay further along decay pipe
  - angular distributions different between Near and Far

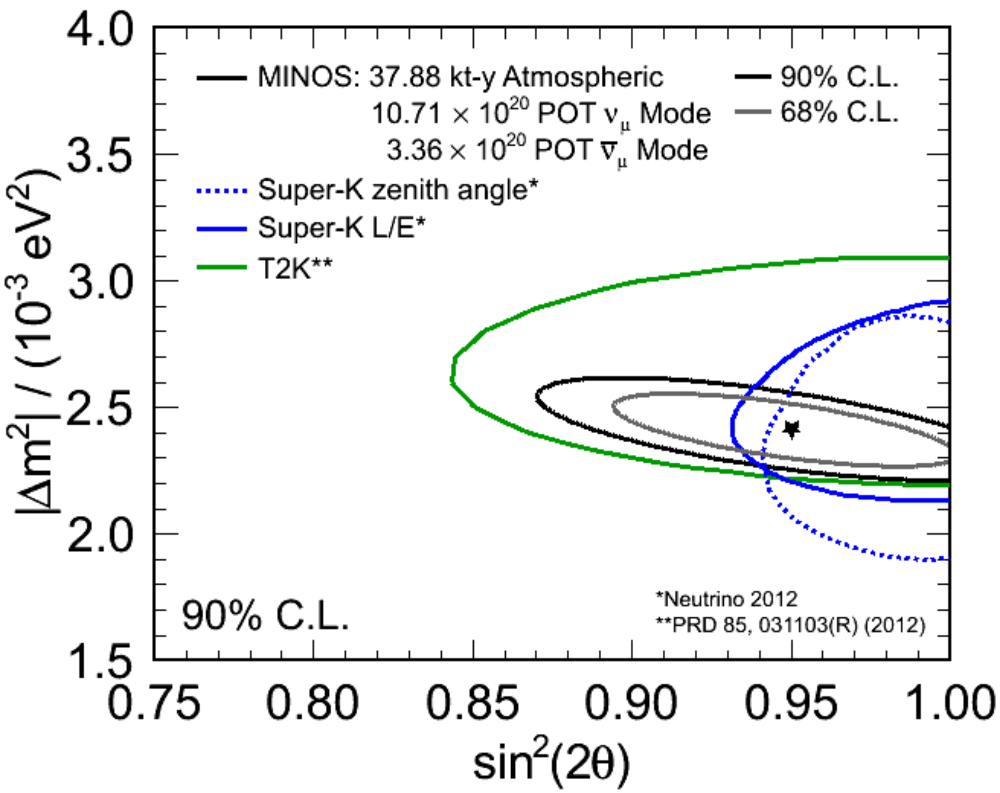
# EXTRAPOLATION

- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- Electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events



# 2 Flavor Oscillation Results




- Combined MINOS neutrino oscillation parameters:

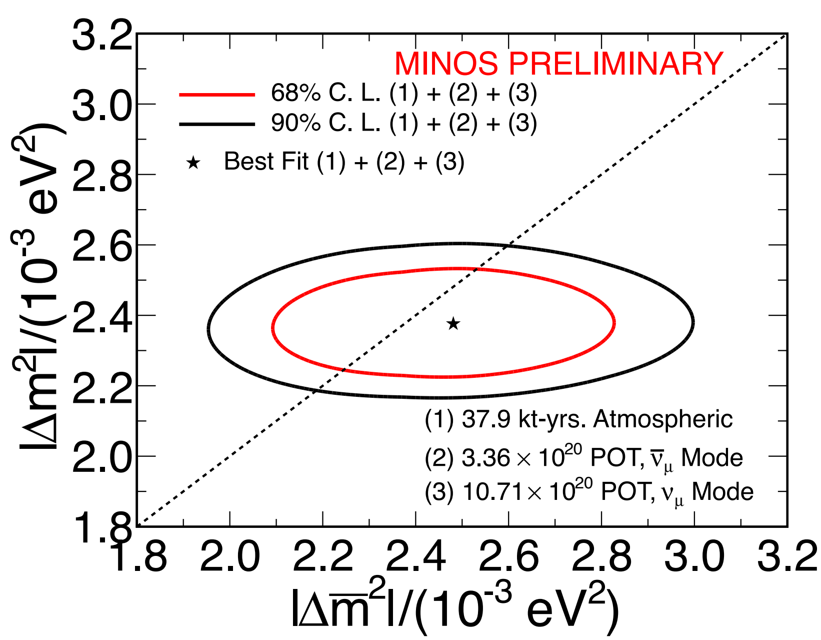
$$\left|\Delta m^2\right| = 2.41^{+0.09}_{-0.10} \times 10^{-3}\,\mathrm{eV}^2$$

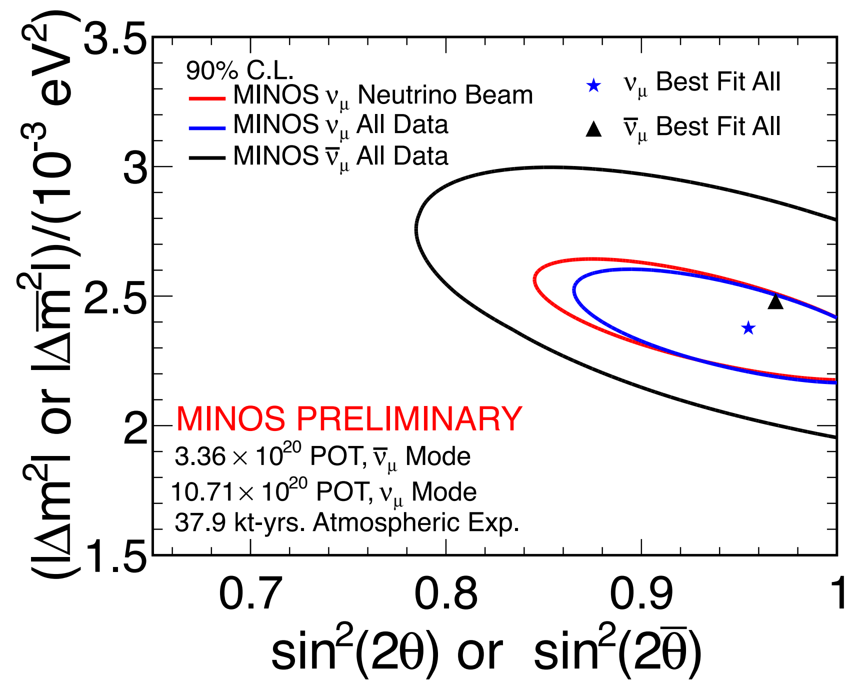
$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$$

$$\sin^2(2\theta) > 0.890 \text{ (90\% C.L. )}$$

All beam and atmospheric samples in a two parameter fit (assumes neutrinos and antineutrinos oscillate the same)

# Comparing Neutrinos and Antineutrinos



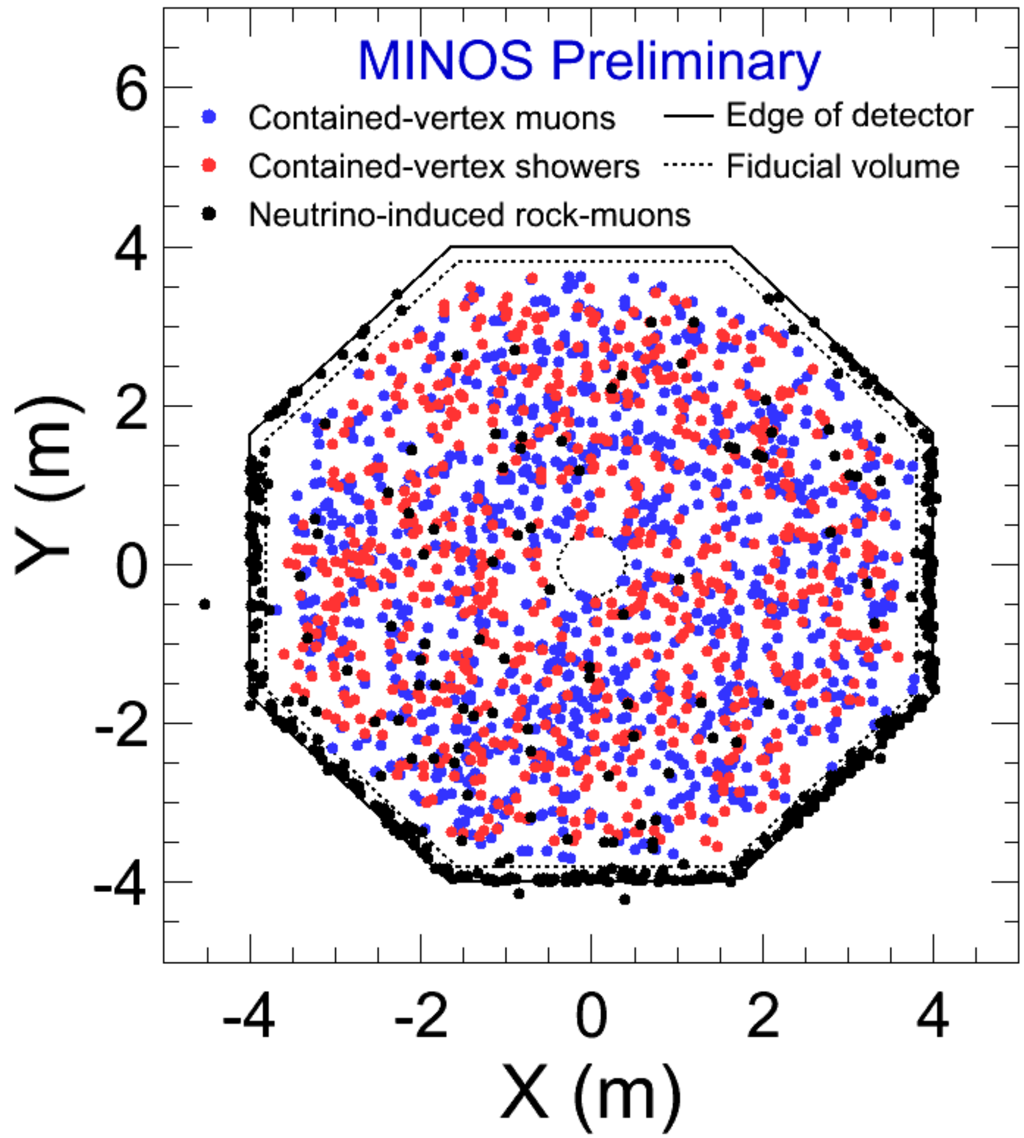




$$\left|\Delta \bar{m}^2\right| - \left|\Delta m^2\right| = 1.0^{+2.4}_{-2.8} \times 10^{-4}\,\mathrm{eV}^2$$

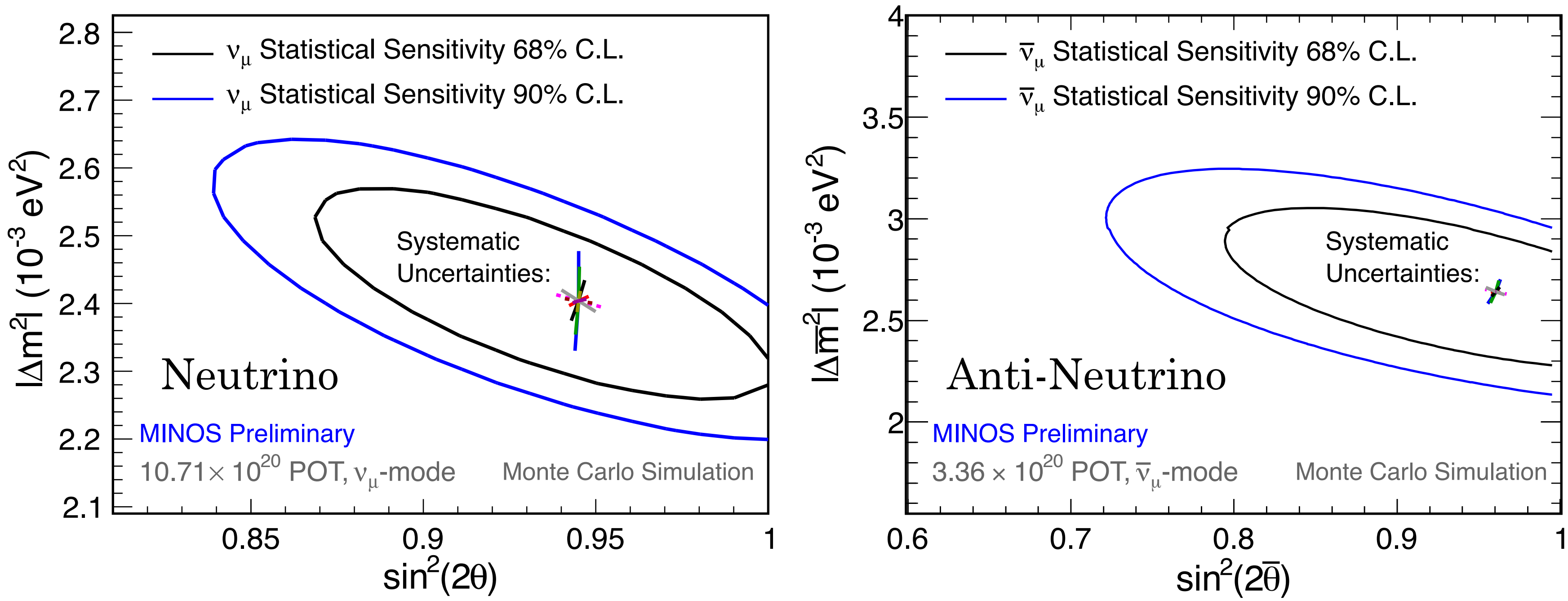
New data has resolved tension between neutrino and antineutrino results

# Atmospheric Neutrinos

- 37.9 kton years of atmospheric neutrino data collected since 2003
- 2072 additional neutrino events
  - 905 contained vertex muon events
  - 466 neutrino induced rock muon events
  - 701 contained vertex showers

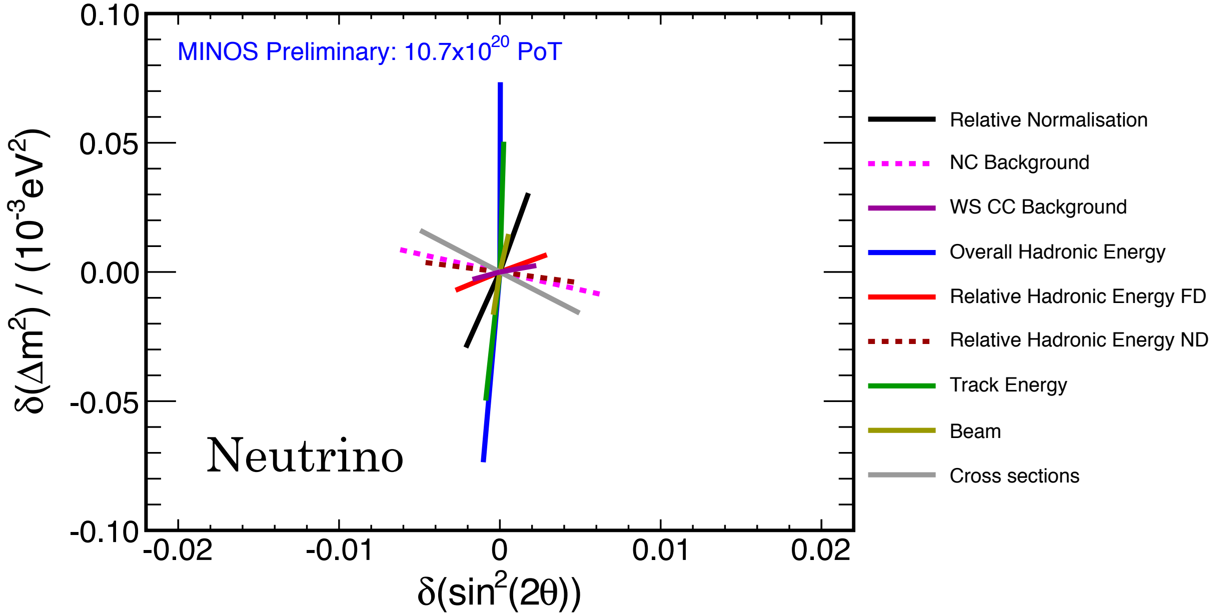


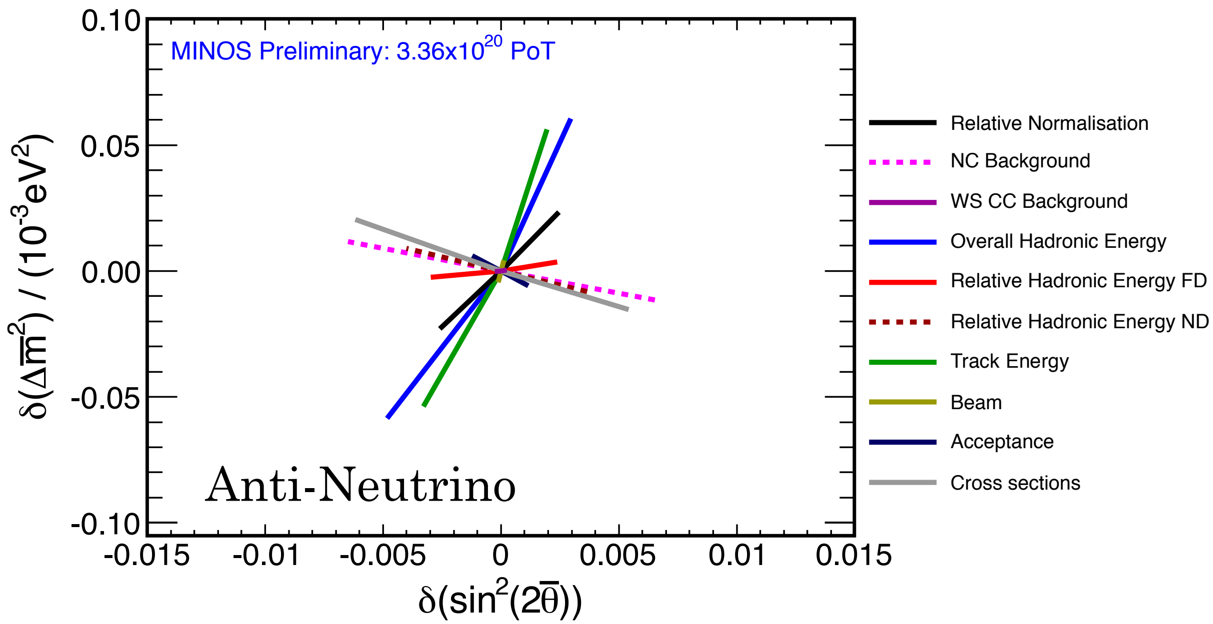
# Systematics




- Largest sources of systematic uncertainty:
  - Hadronic Energy Scale
  - Track Energy Scale
  - Neutral Current background
- Still statistics dominated in both modes

# Muon Neutrino Systematics



# ASSUMPTIONS ON EARTH DENSITY

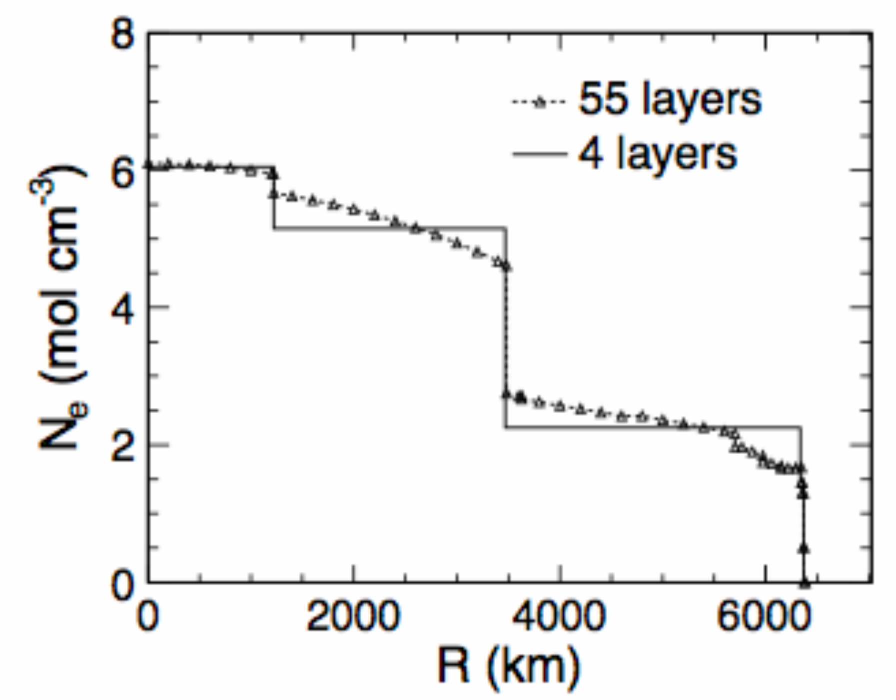



Figure 3: Comparison of the 4-layer earth density model used in this three-flavour oscillation analysis with a more precise 55-layer model based on the PREM model.

| Region | Radius (km) | Earth density (mol cm$^{-3}$) |
|---|---|---|
| Crust | > 6336 | 1.45 |
| Mantle | 3470 – 6336 | 2.25 |
| Outer Core | 1220 – 3470 | 5.15 |
| Inner Core | < 1220 | 6.05 |

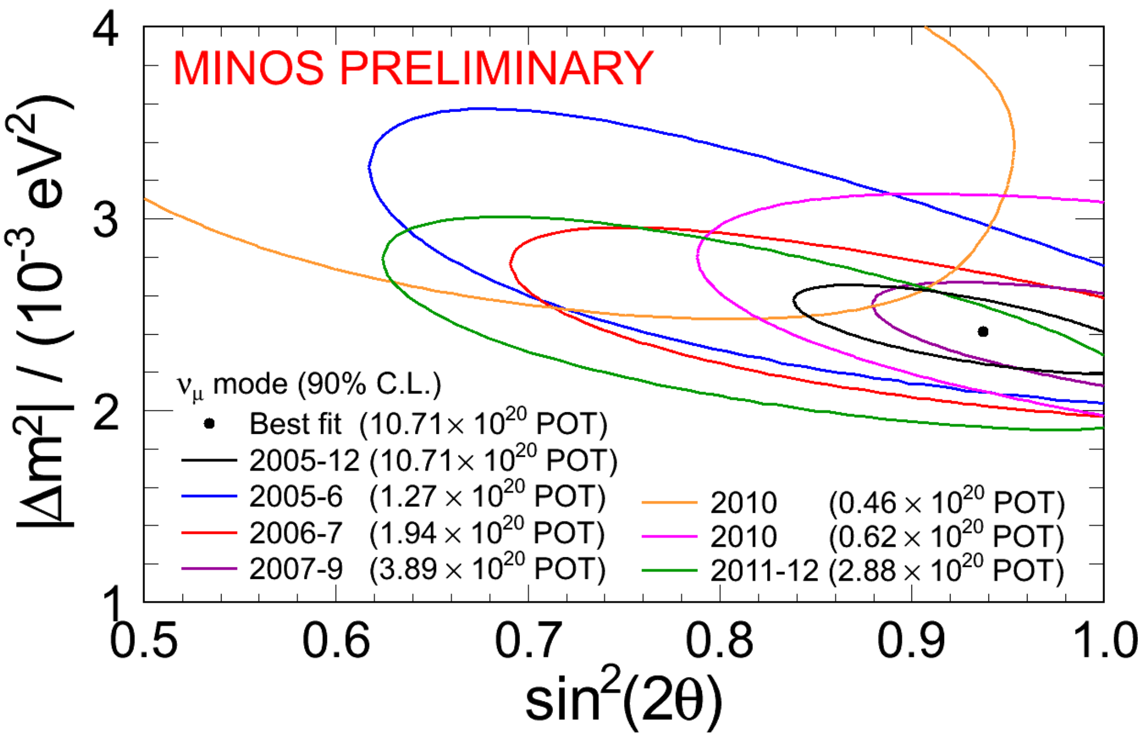
Table 1: The radius and earth density of each layer used in the four-layer earth model.

# STATISTICS

| Beam Events | No Oscillations | Observed |
|---|---|---|
| FHC Neutrinos | 3564 | 2894 |
| FHC Antineutrinos | 224 | 188 |
| RHC Antineutrinos | 312 | 226 |

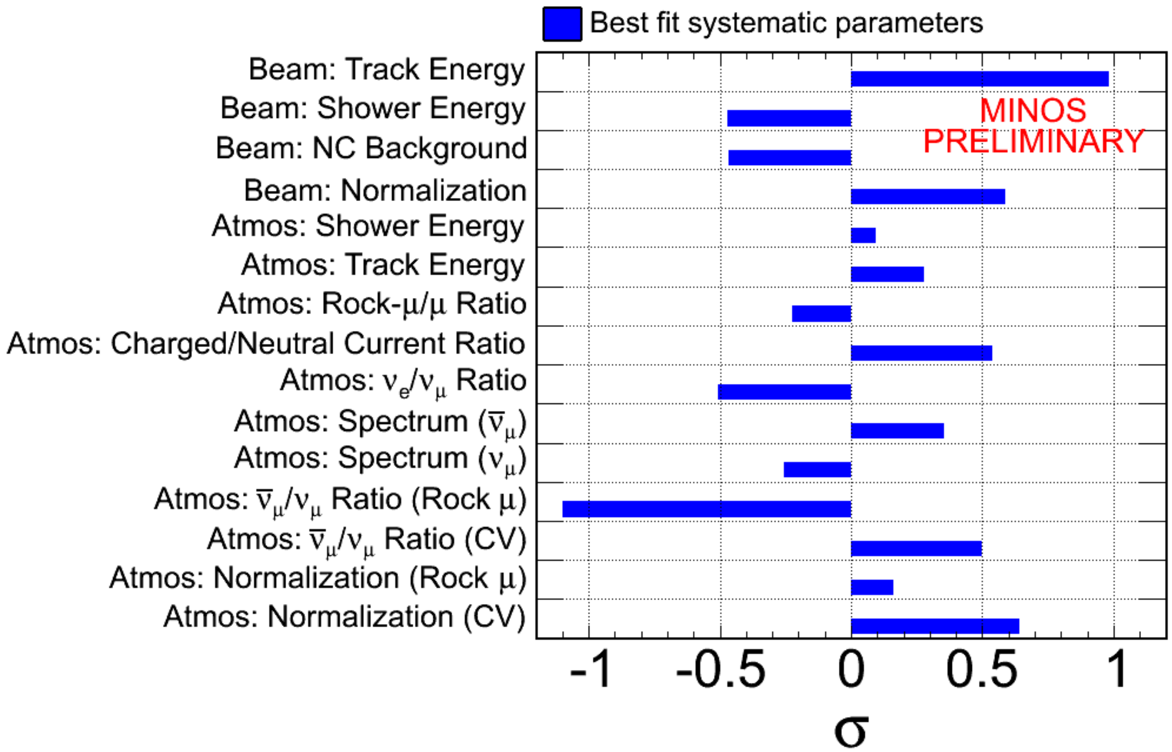
| Atmospheric | No Oscillations | Observed |
|---|---|---|
| Contained CC | 1100 | 905 |
| Rock Vertex | 570 | 466 |
| Showers | 727 | 701 |

# CONTOUR EVOLUTION



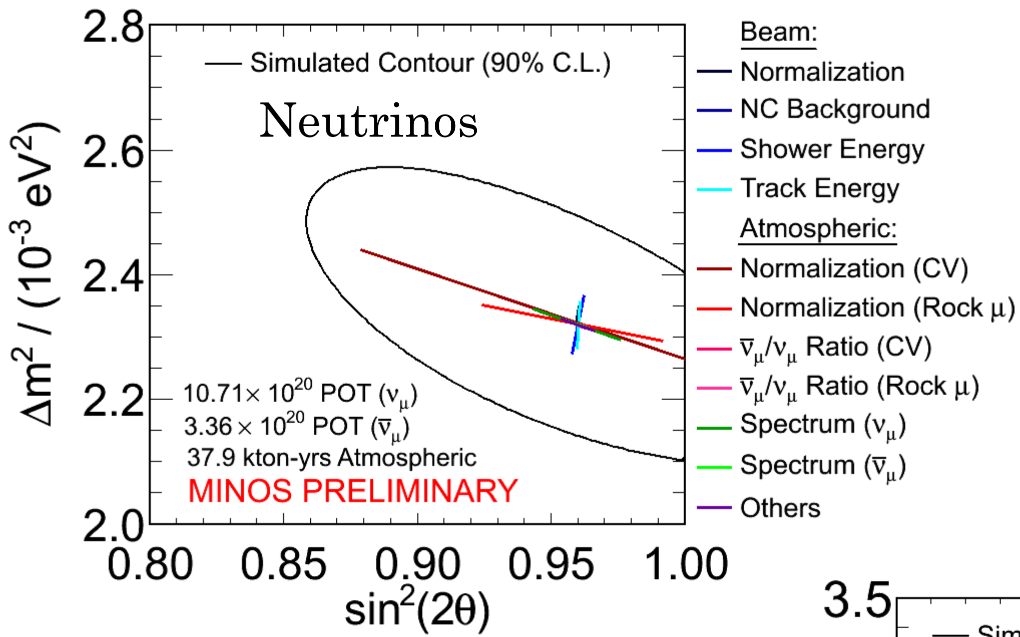

| Run | I | pHE | II | III | V | VI | X | All |
|---|---|---|---|---|---|---|---|---|
| POT ($\times10^{20}$) | 1.27 | 0.15 | 1.94 | 3.89 | 0.46 | 0.62 | 2.88 | 10.71 |
| Events | 317 | 119 | 509 | 1034 | 113 | 154 | 648 | 2894 |
| $\Delta m^2$ ($\times10^{-3}$ eV$^2$) | 2.62 | 2.52 | 2.38 | 2.37 | 3.66 | 2.56 | 2.41 | 2.41 |
| $\sin^2(2\theta)$ | 0.89 | 1.00 | 0.94 | 1.00 | 0.73 | 1.00 | 0.84 | 0.94 |

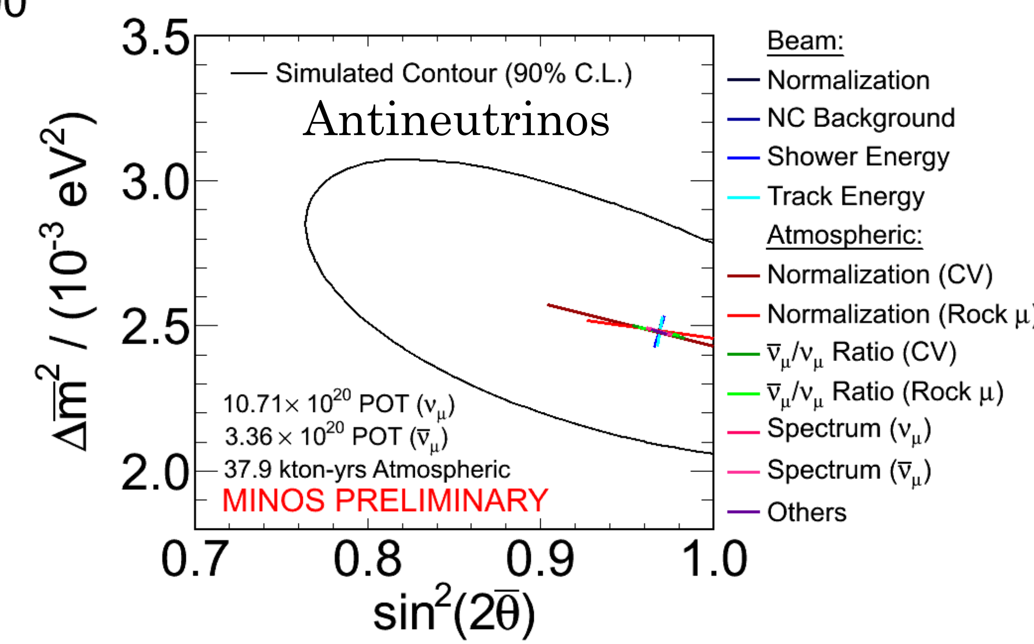
# THE METHOD




- 15 systematic effects included in fit as nuisance parameters
- Most systematic parameters fit within 1 sigma of their nominal value

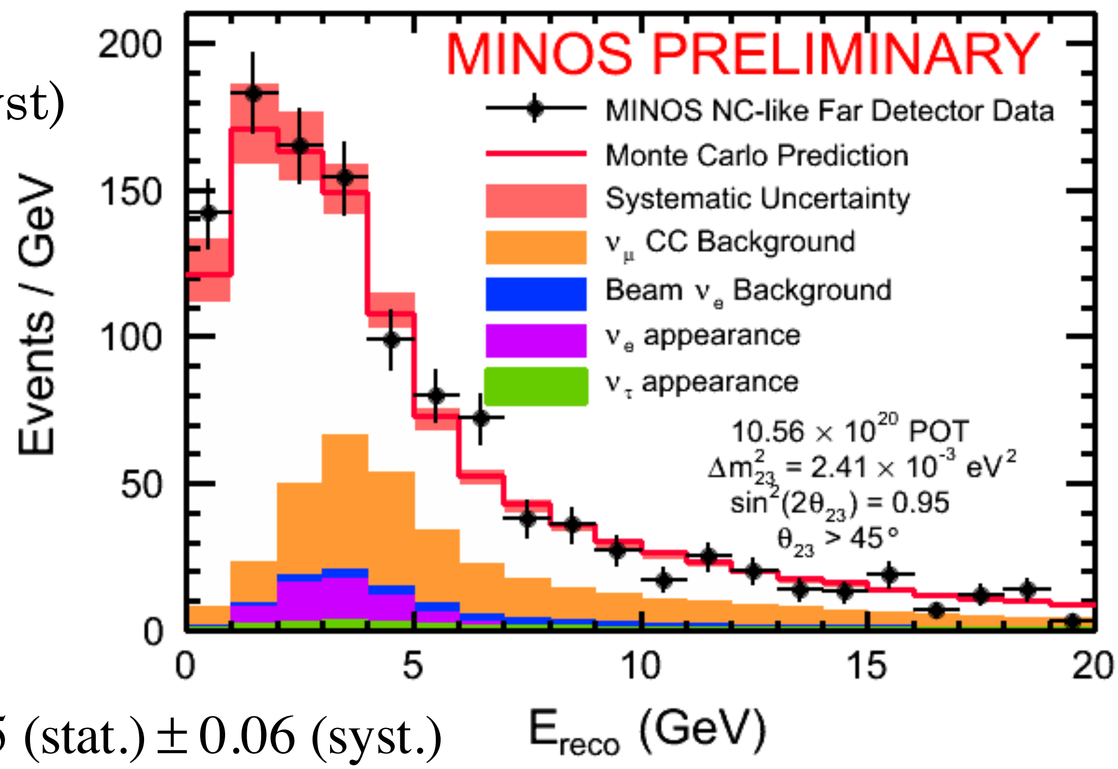
# Combined Fit Systematics



# Neutral Currents

- Neutral Current event rate should not change in 3 flavor oscillation scenario
- A deficit in the FD could be evidence of a sterile neutrino flavor
- We see an excess!
  - Expect 1183±50 (stat+syst)
  - Observe 1221

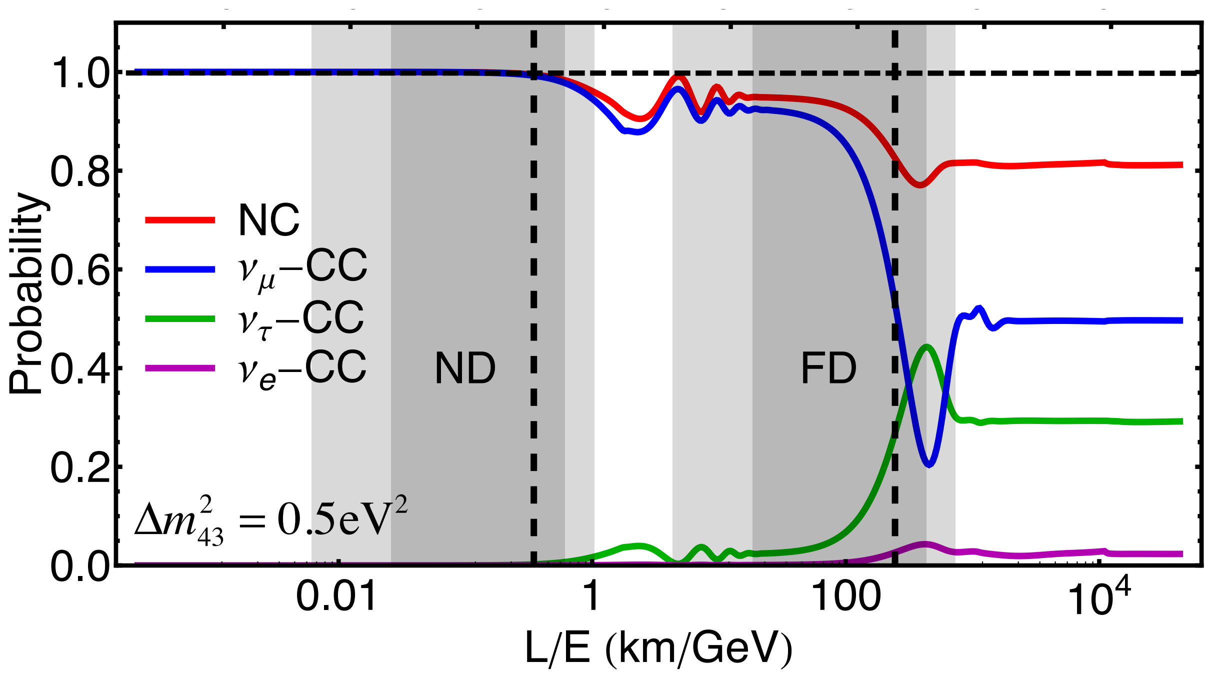



$$R = \frac{N_{data} - BG}{S_{NC}}$$

$$0 - 200 \text{ GeV: } 1.05 \pm 0.05 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

$$0 - 3 \text{ GeV: } 1.09 \pm 0.06 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$$

- Mixing with steriles also causes anomalous disappearance of muon neutrinos




- Three regimes:
  - small $\Delta m^2$: wiggles in FD at high energies
  - medium $\Delta m^2$: rapid FD wiggles average out
  - large $\Delta m^2$: oscillations occur in ND

Tricky

Just Right

- Compare candidate events to a library of simulated signal and background events
- Discriminating variables formed using information from 50 best matches

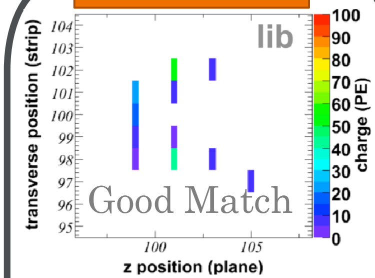
Input Event (data or MC)

Compare to MC Library

$$L = \sum_{i=1}^{N_{strips}} \ln \left( \int_{0}^{\infty} P(n_A^i;\lambda) P(n_B^i;\lambda)\, d\lambda \right)$$

$$\Delta L = -(L_{lib} - L_{self})$$

Library Event #

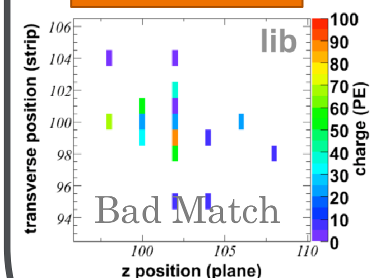



Library Event #

Library Event #

. . .

Library Event #




. . .

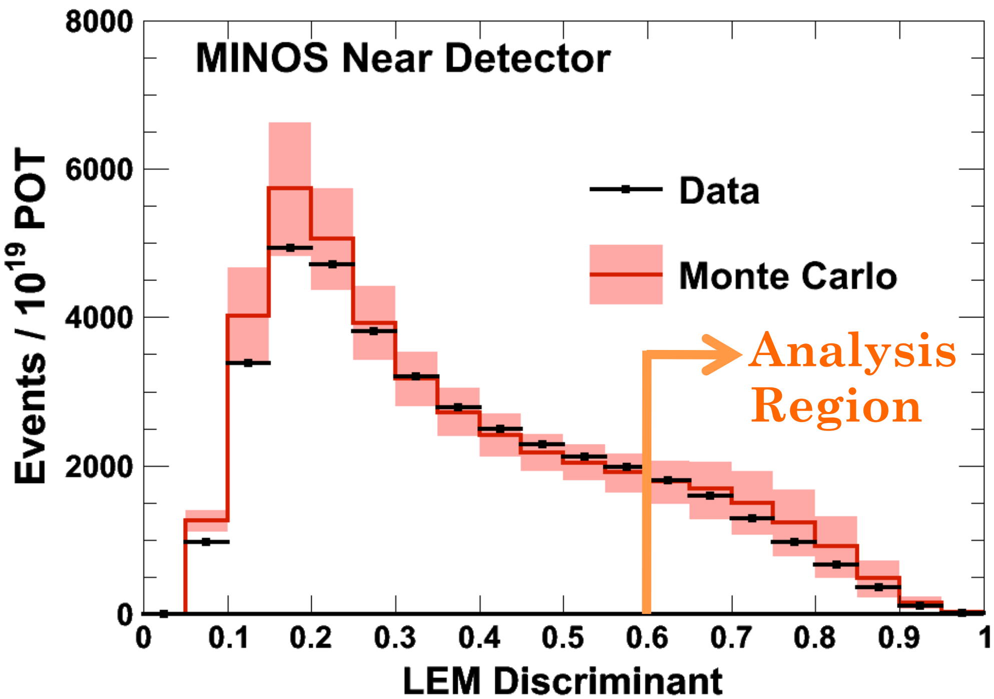
Library Event #30M

Compute PID using information from best N matches

- Use ND to determine expected background
- Fit FD in bins of event discrimination variable and energy

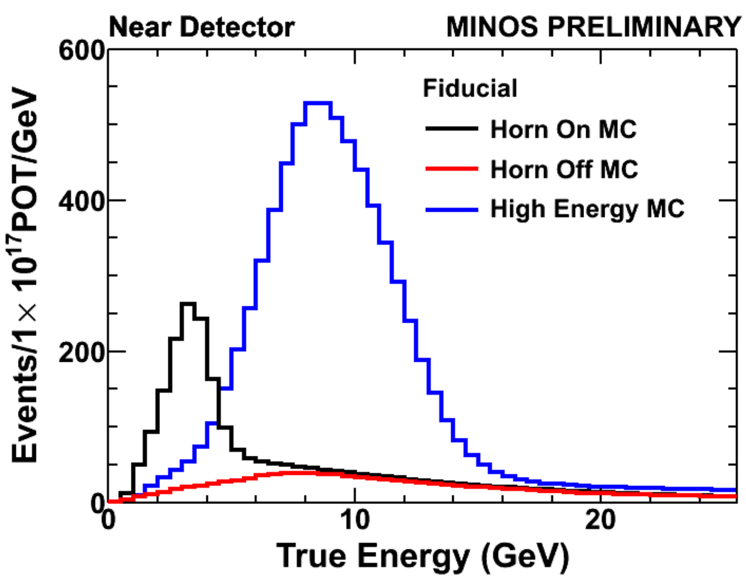
# Selecting Electron Neutrinos

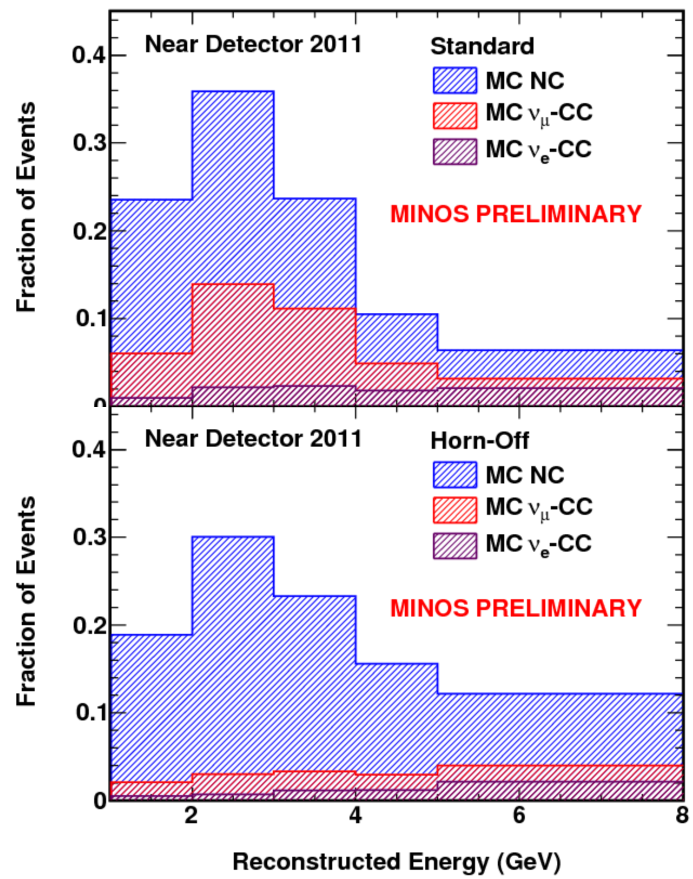
- Coarse detector granularity makes $\nu_e$ CC identification challenging
  - Compare candidate events, strip-by-strip, to a library of MC events
  - Compute discriminating variables based on truth information from library events that best match the candidate
- Apply selection to ND for background determination



# ELECTRON NEUTRINO APPEARANCE

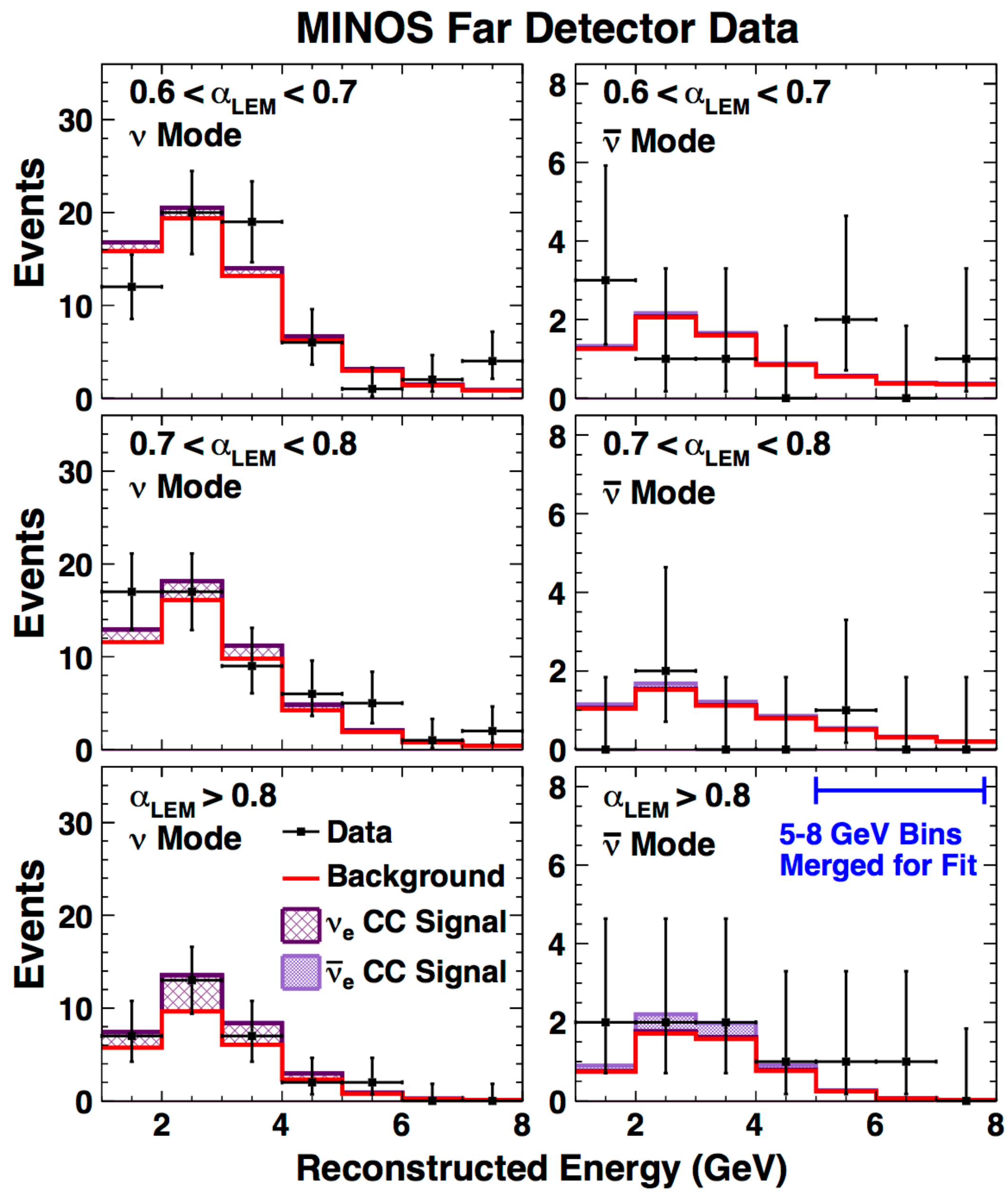
- Selected ND data comprised of NC, $\nu_\mu$ CC, and beam $\nu_e$ events
- Each extrapolates to FD differently
- Use ND data in different configurations to extract relative components of background



# Electron Neutrino Appearance

| | $\nu$-beam | $\bar{\nu}$-beam |
|---|---|---|
| $\theta_{13} = 0$ | 69.1 | 10.5 |
| $\theta_{13} = 0.1$ | +26.0 | +3.1 |
| Obs. | 88 | 12 |



# Combined Electron Neutrino Appearance Contour

for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1,$

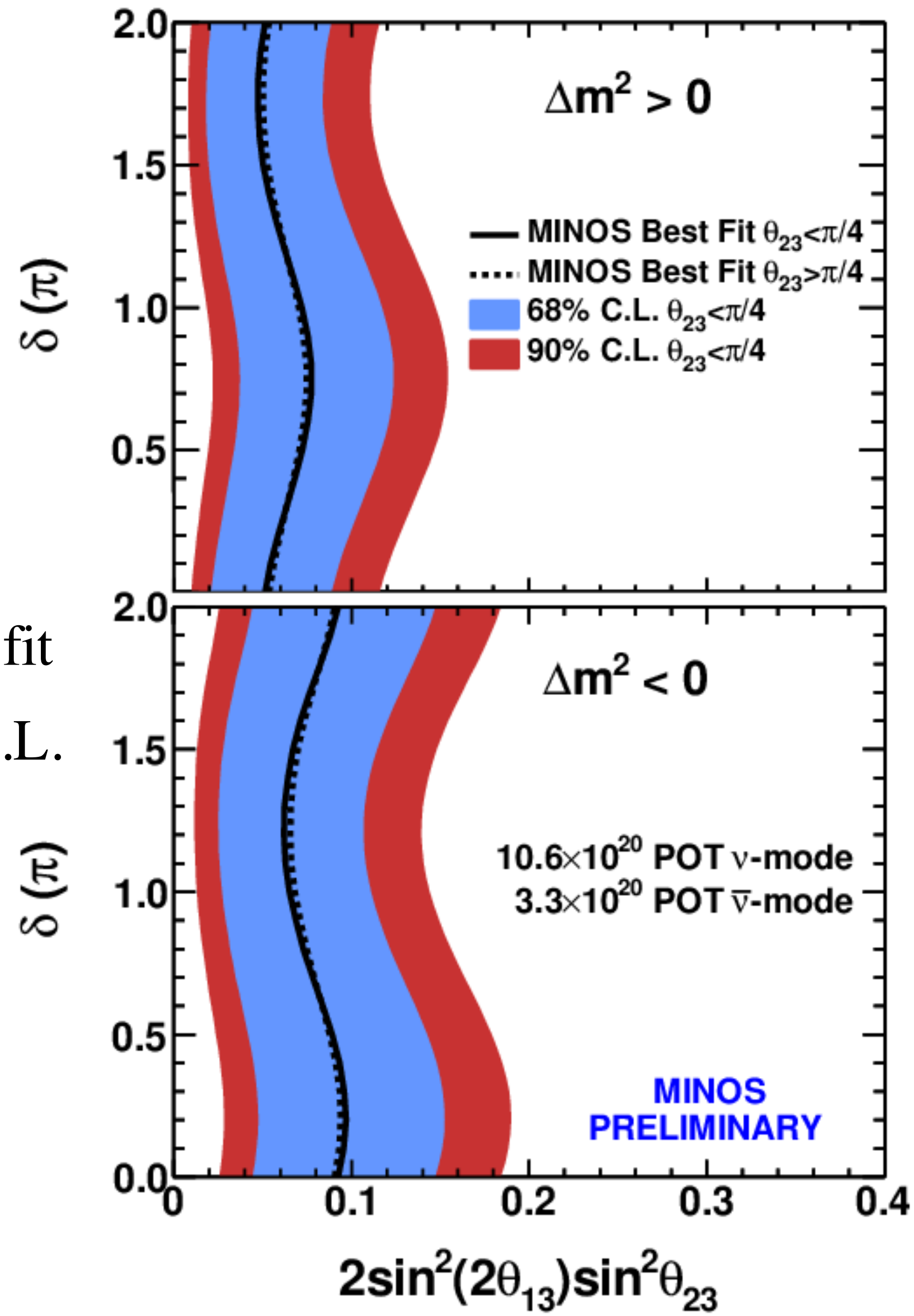
normal (inverted) hierarchy

$\sin^2(2\theta_{13}) = 0.053 \ \ (0.094)$ at best fit

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

(0.03) (0.19)

$\sin^2(2\theta_{13}) = 0$ excluded at 96%



# RHC Electron Neutrino Appearance Contour

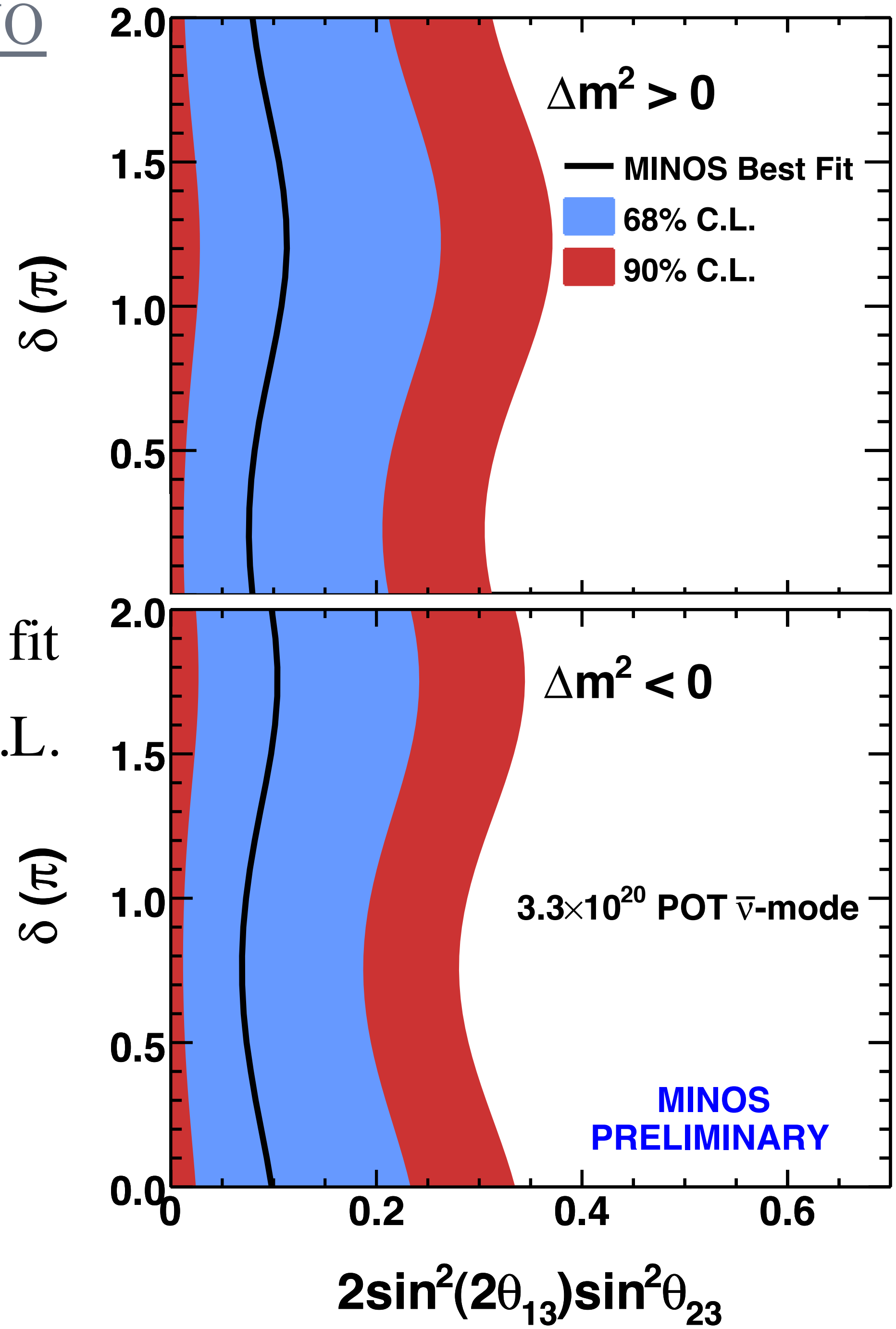
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1$,

normal (inverted) hierarcy:

$\sin^2(2\theta_{13}) = 0.079 \ \ (0.098)$ at best fit

$\sin^2(2\theta_{13}) < 0.31 \ \ (0.34)$ at 90% C.L.

$\sin^2(2\theta_{13}) = 0$ excluded at 80%



## Normal hierarchy

Y. Itow, Nu2012

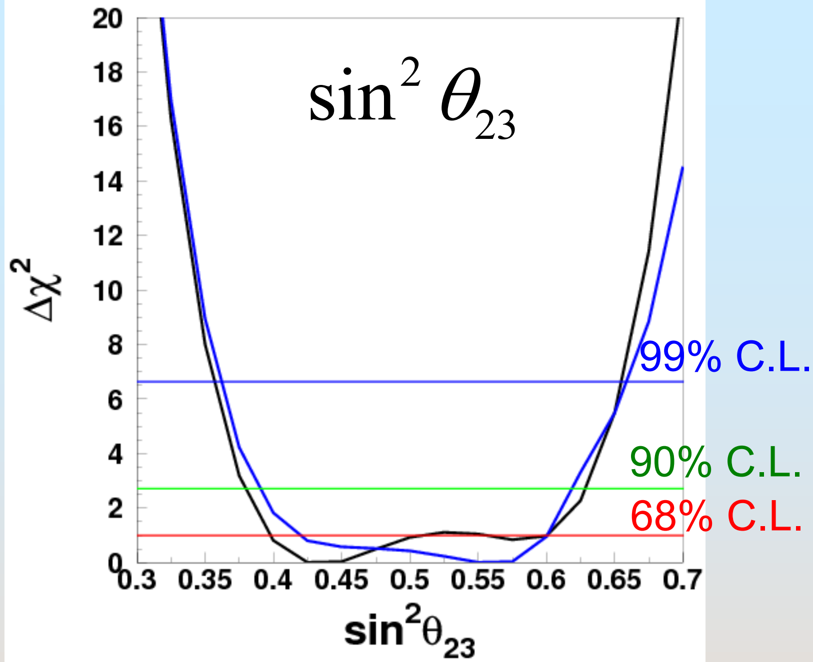
*$\sin^2\theta_{13}$ fixed to be 0.025 (reactor)

$\chi^2_{min}$ = 556.7 / 477 dof

| | | |
|---|---|---|
| $\Delta m^2_{32}$ | $2.66^{+0.15}_{-0.40} \times 10^{-3} eV^2 (1\sigma)$ | |
| $\sin^2\theta_{23}$ | 0.425 | 0.391 - 0.619 at 90%CL |
| δCP | 300° | All allowed at 90% CL |

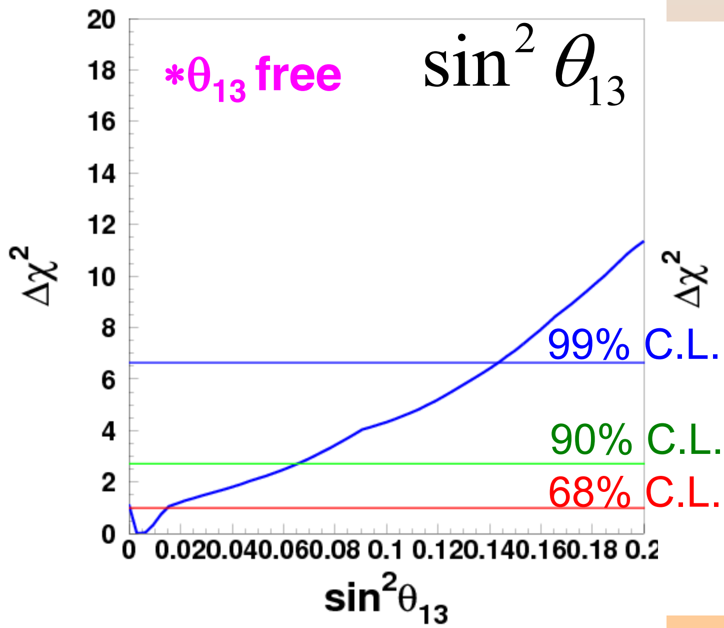
*$\sin^2\theta_{13}$ fitted

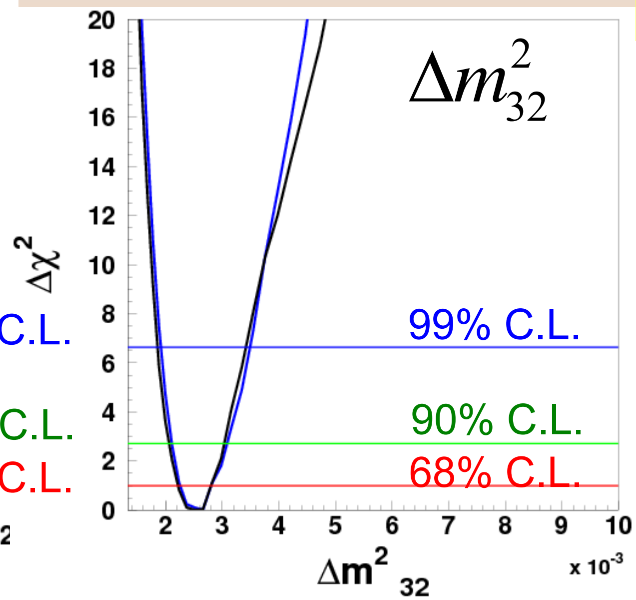
| | | |
|---|---|---|
| $\sin^2\theta_{13}$ | 0.003 | 0 - 0.0655 |

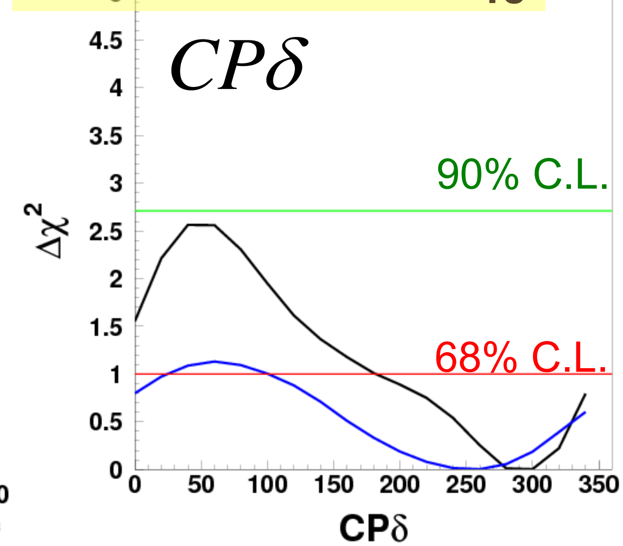



**Free $\theta_{13}$**

**Fixed reactor $\theta_{13}$**



## Inverted hierarchy

Y. Itow, Nu2012

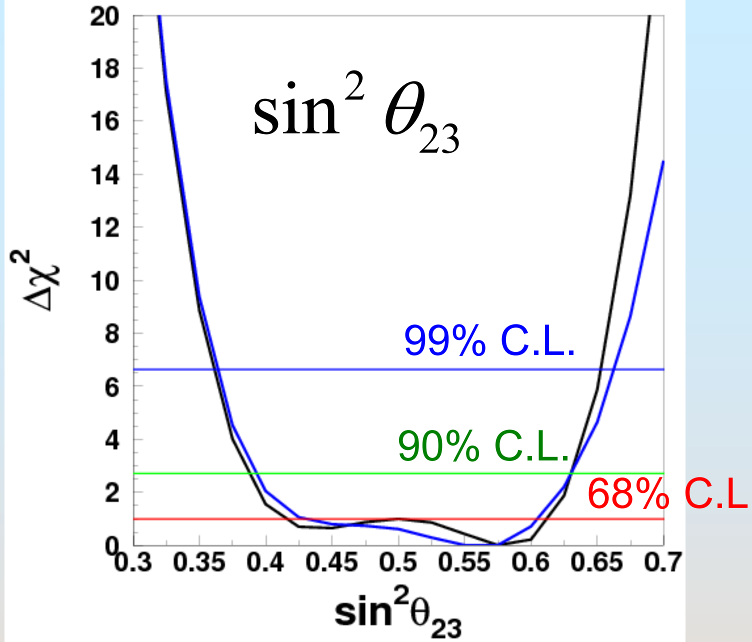
**$^*\sin^2\theta_{13}$ fixed to be 0.025 (reactor)**

**$\chi^2_{min}$ = 555.5 / 477 dof**

| | | |
|---|---|---|
| $\Delta m^2_{32}$ | $2.66^{+0.17}_{-0.23} \times 10^{-3}\, eV^2 (1\sigma)$ | |
| $\sin^2\theta_{23}$ | 0.575 | 0.393 - 0.630 at 90%CL |
| $\delta$CP | 300° | All allowed at 90% C.L. |

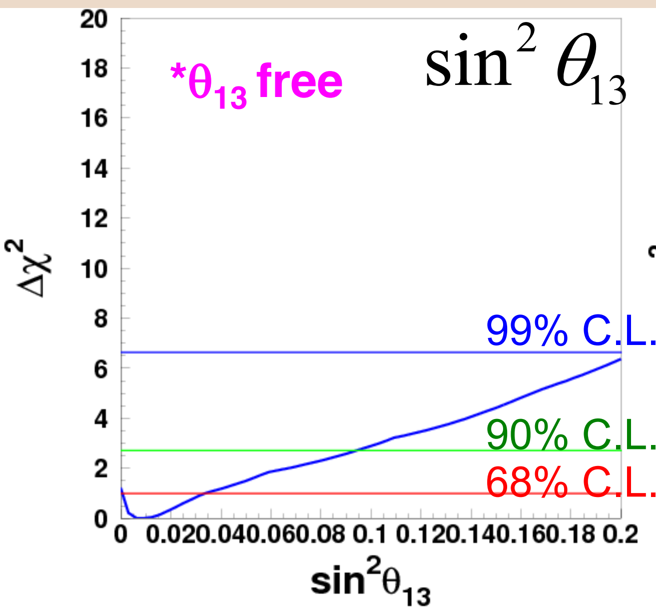
**$^*\sin^2\theta_{13}$ fitted**

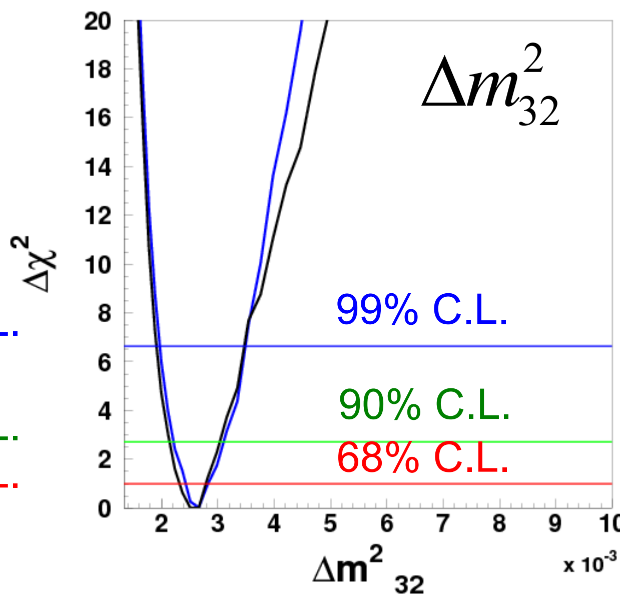
| | | |
|---|---|---|
| $\sin^2\theta_{13}$ | 0.006 | 0 - 0.0944 |

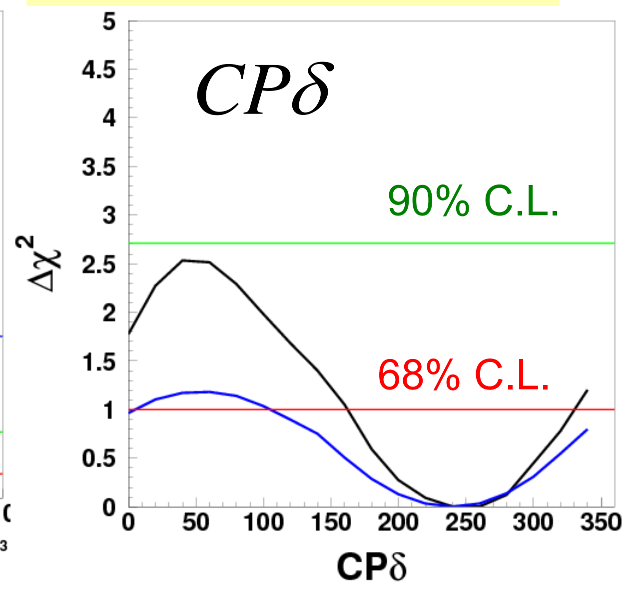



**Free $\theta_{13}$**

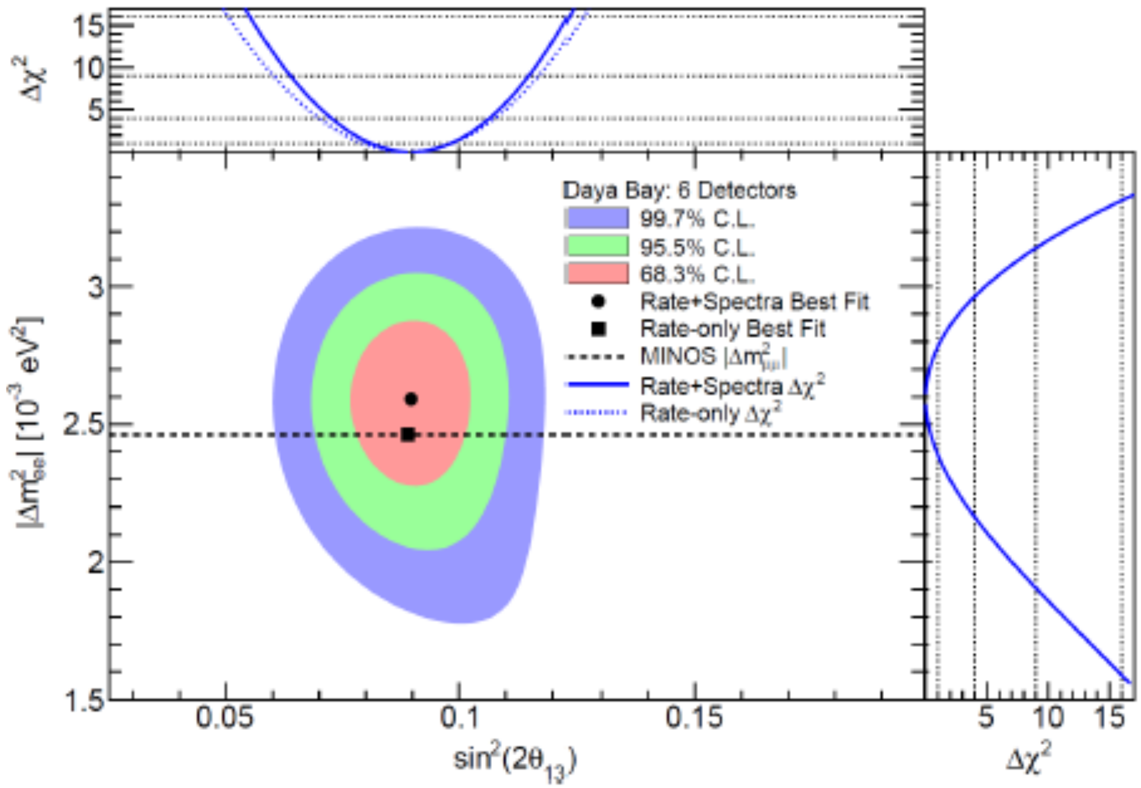
**Fixed reactor $\theta_{13}$**



# Rate and Spectral Analysis




$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

$$\chi^2/NDF = 162.7/153$$

$$\sin^2\Delta_{ee} = \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$$

$$\Delta m^2_{32} = 2.54^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

(Normal Mass Hierarchy)

$$\Delta m^2_{23} = 2.64^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

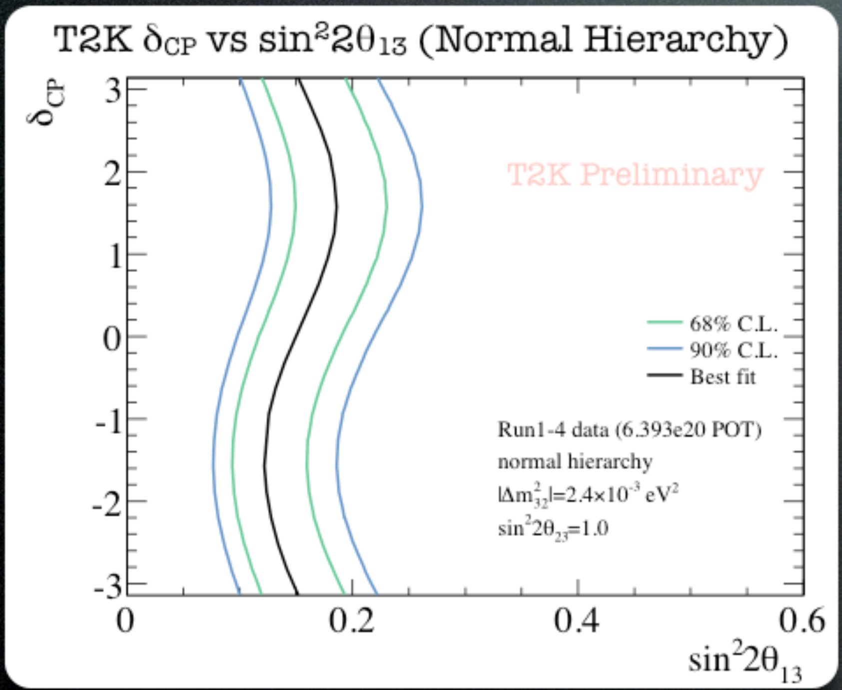
(Inverted Mass Hierarchy)

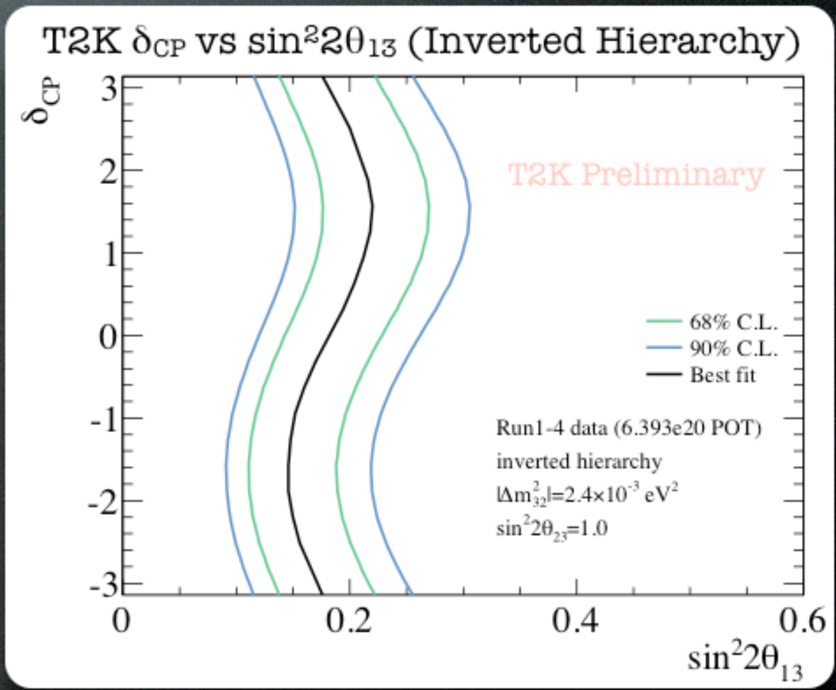
- Far vs. near relative measurement. [Absolute rate is not constrained.]
- Consistent results obtained by independent analyses, different reactor flux models.
- Result consistent with $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (eV^2)$ result from MINOS.

# $\nu_e$ Appearance Results

- **Observed 28 events** (expected 20.4 ± 1.8 for $\sin^2 2\theta_{13}=0.1$)
- Comparing the best p-θ fit likelihood to null hypothesis gives a **7.5σ significance for non-zero $\theta_{13}$**

(For $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy)



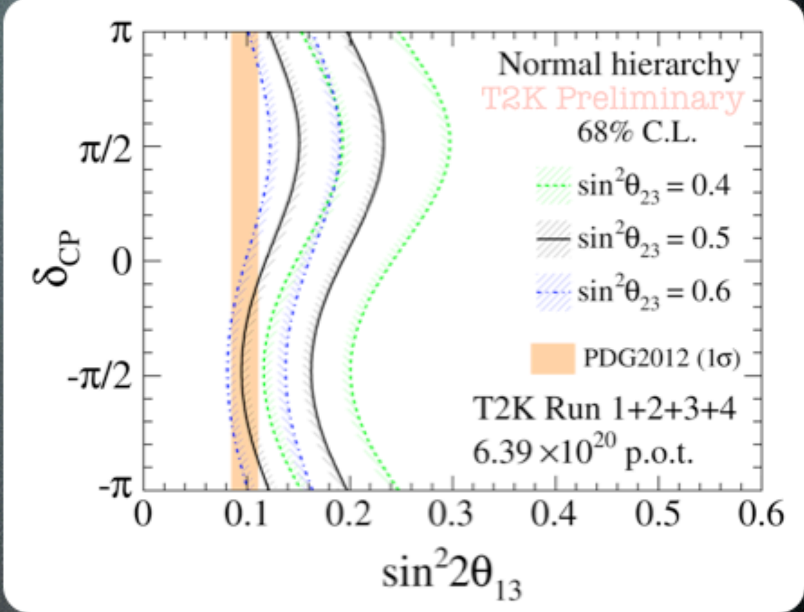

**First ever observation (>5σ) of an explicit ν appearance channel**

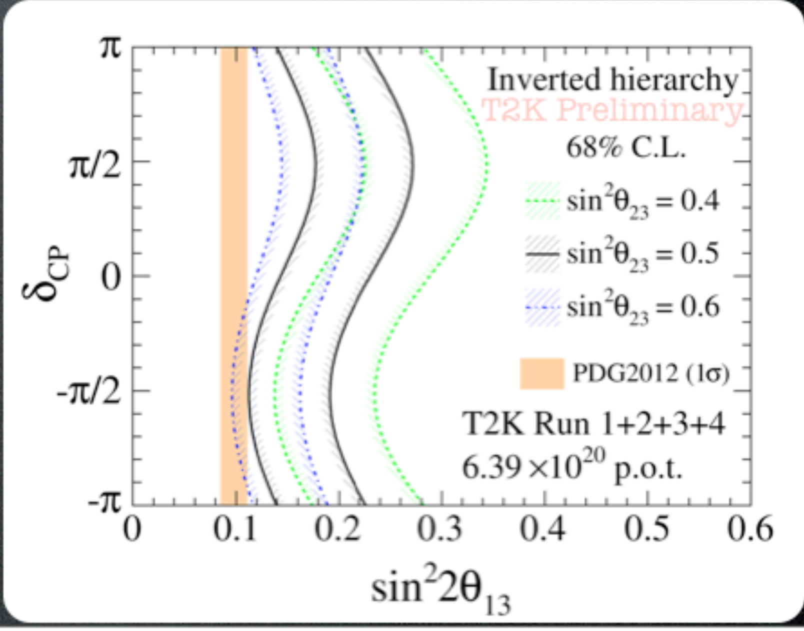
M. Wilkings EPS 2013

P. Vahle, TAUP 2013

# Effect of $\theta_{23}$ Uncertainty

- $\nu_e$ appearance probability also depends on the value of $\theta_{23}$
- If $\theta_{23}$ is fixed at values near the edge of the current allowed region, the fit contours shift
- Future improved measurements of $\theta_{23}$ will be important to extract information about other oscillation parameters (including $\delta_{CP}$) in long-baseline experiments
    - A T2K combined $\nu_e$+$\nu_\mu$ analysis is underway



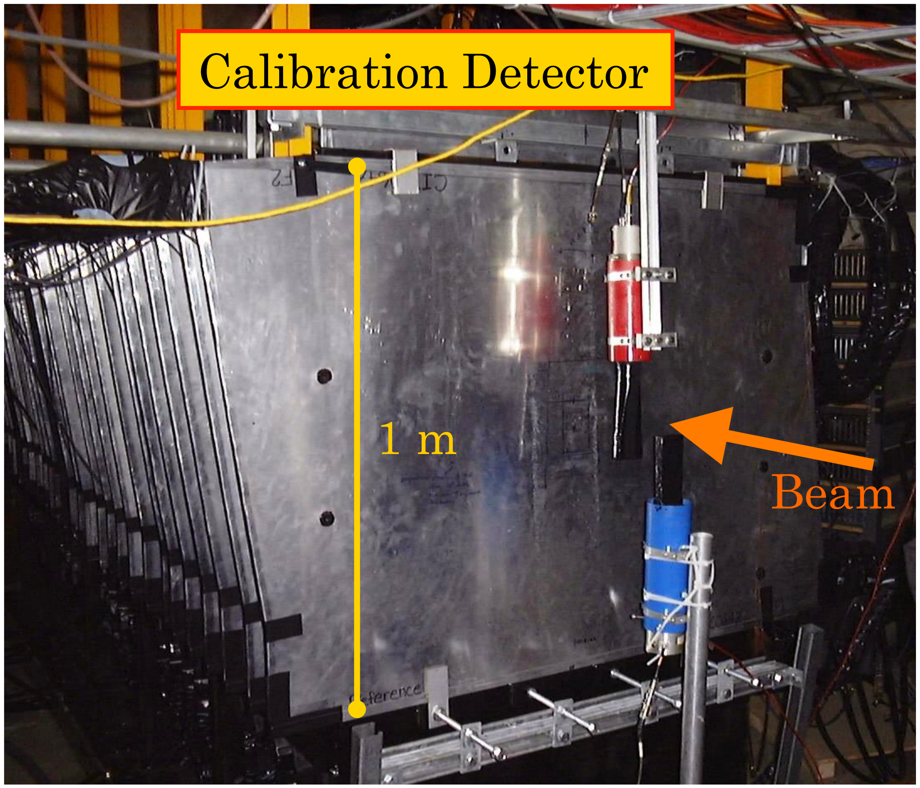




Note: these are 1D contours for various values of $\delta_{CP}$, not 2D contours

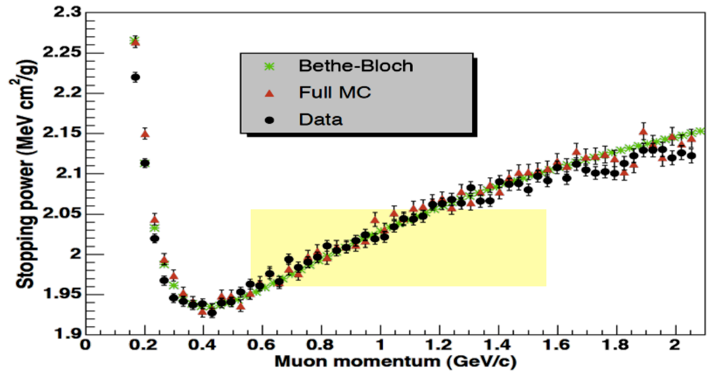
M. Wilkings EPS 2013

# Calibration Detector

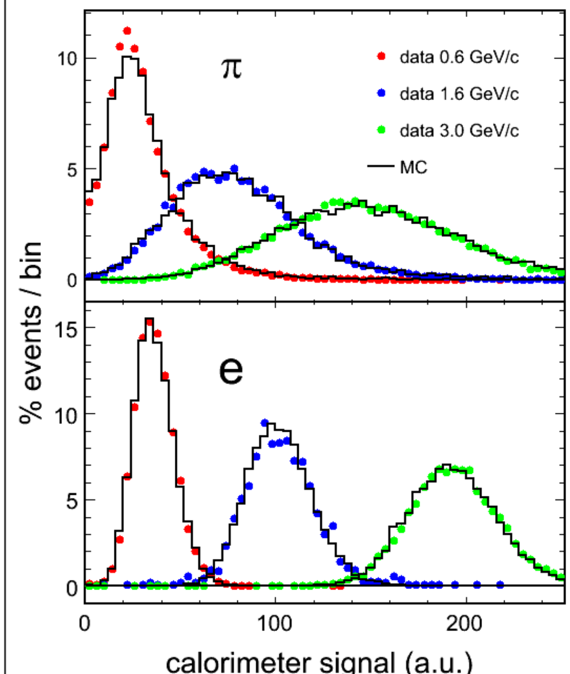
- Dedicated calibration module run in test beams at CERN, 2001-2004
- Characterize response of detector to e, pi, p




Stopping μ calibration

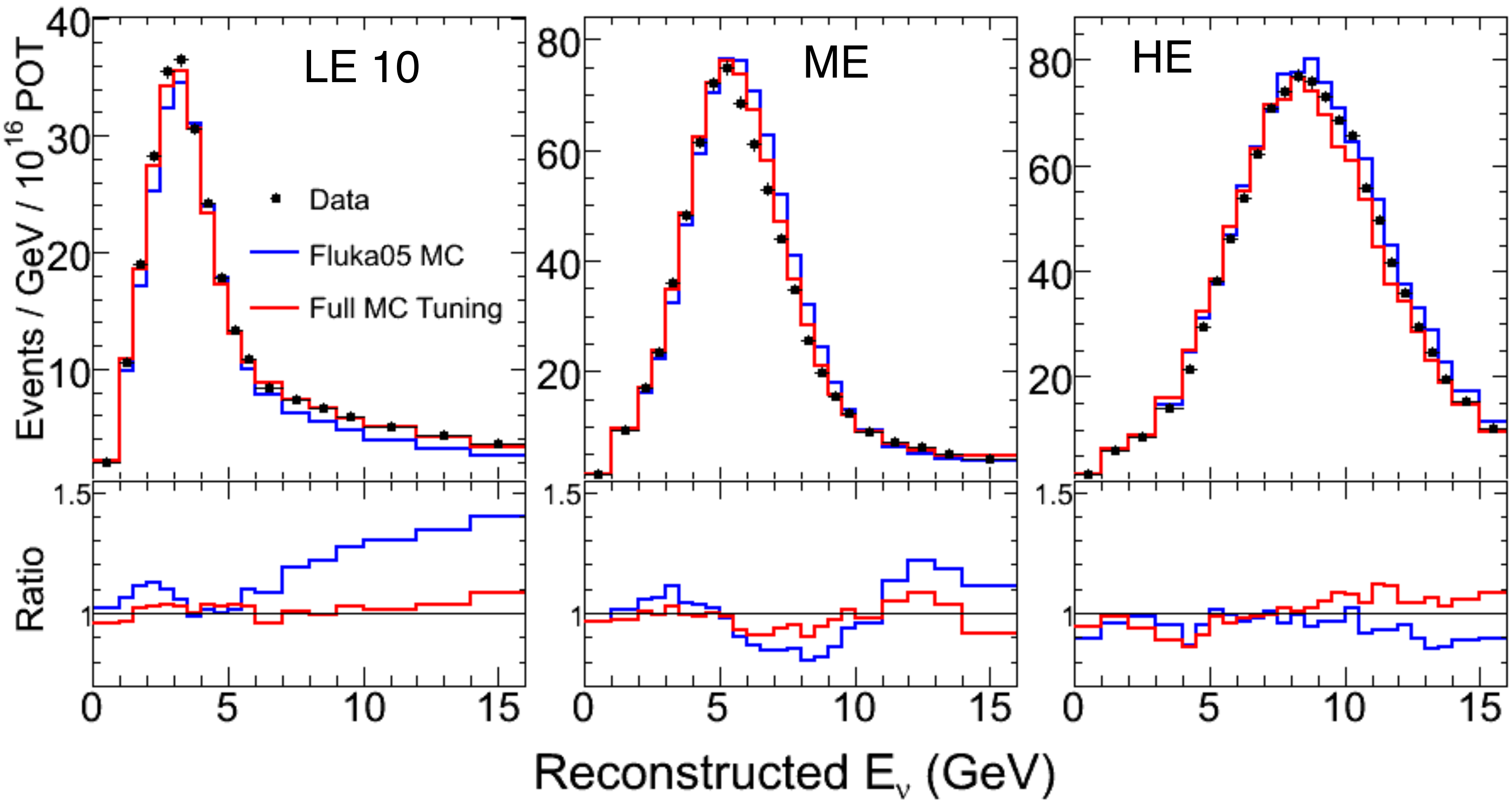



Shower Response



# Neutrino Spectrum

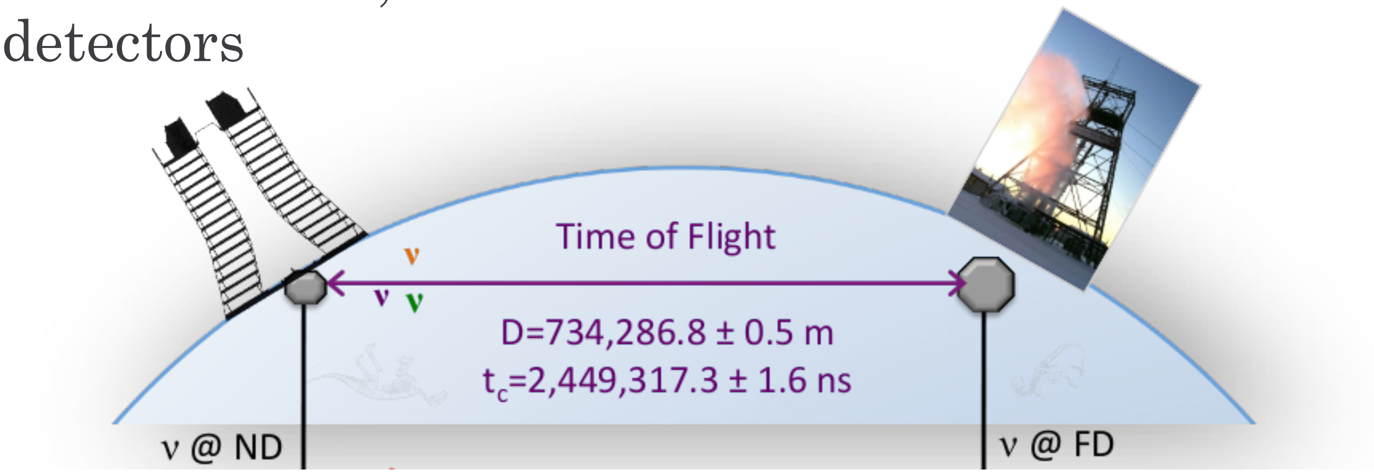
- Use flexibility of beam line to constrain hadron production, reduce uncertainties due to neutrino flux



# Neutrino Time of Flight

# MEASURING NEUTRINO TIME OF FLIGHT

- Measure the time it takes for NuMI neutrinos to travel the 734,286.8 ± 0.5 m between the two MINOS detectors




- Initial result after first year of data indicated neutrinos arrived at FD earlier than expected:

  126 ±32 (stat.) ± 64 (syst.) ns†

- OPERA 2011 also saw neutrinos early:

  57.8 ± 7.8 (stat.) +8.3/-5.9 (syst.) ns‡

- Update! now neutrinos come late:

  1.6 ± 1.1 (stat.) +6.1/-3.7 (syst.) ns*

†Phys. Rev. D76 (2007) 072005 ‡arXiv:1109.4897v2 *Neutrino 2012

# Phased Approach

- Phase I:
  - Update 2007 analysis with a factor of 8 more events
  - Remeasure delays and review systematics
- Phase II:
  - Work done in collaboration with NIST and USNO
  - Collect new data with upgraded GPS and cesium clocks
  - Constant monitoring of optical fiber delays
  - Account for environmental changes, etc.
- Ultimately aim for 2-5 ns accuracy

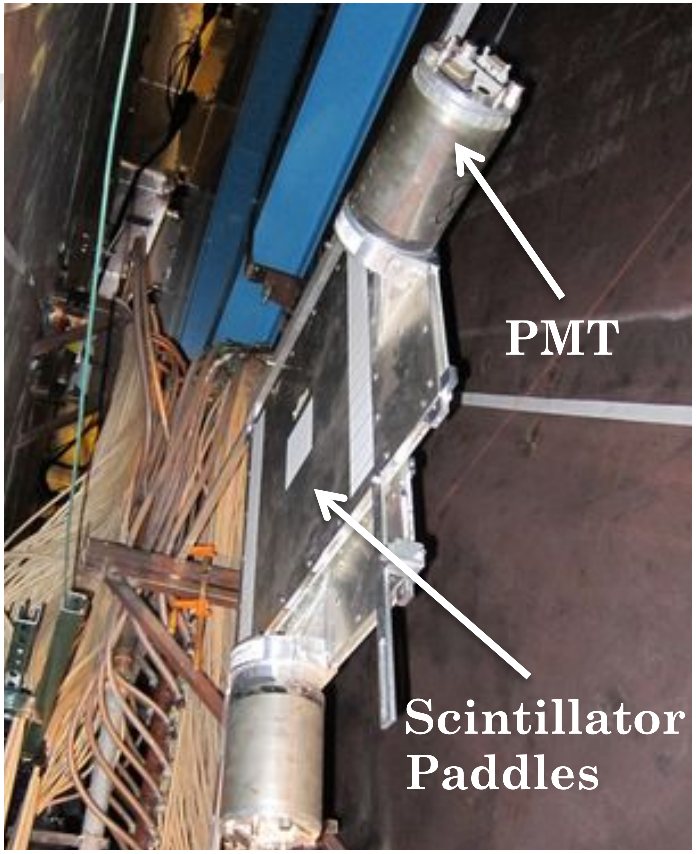

Phase II equipment provides refined understanding of current timing system systematic uncertainties

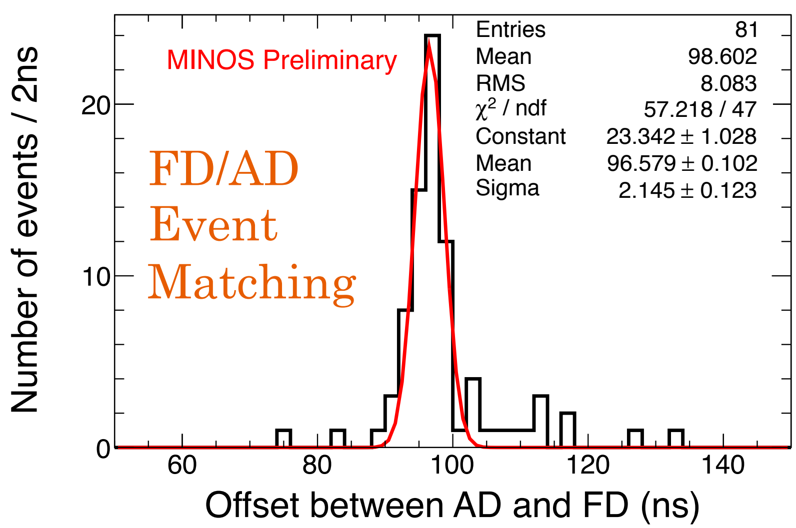
# Major Systematic Uncertainties

- Arrival times as recorded at each detector must be corrected for (sizeable) cable delays and electronics latencies
- Dominant systematics in first analysis largely mitigated by new, precision measurements of delays

| | 2007 | 2012 |
|---|---|---|
| GPS antenna to ND cable delay | 1275 ± 29 ns | 1309 ± 1 ns |
| GPS antenna to FD cable delay | 5140 ± 46 ns | 5098 ± 2 ns |

# THE AUXILIARY DETECTORS (AD)

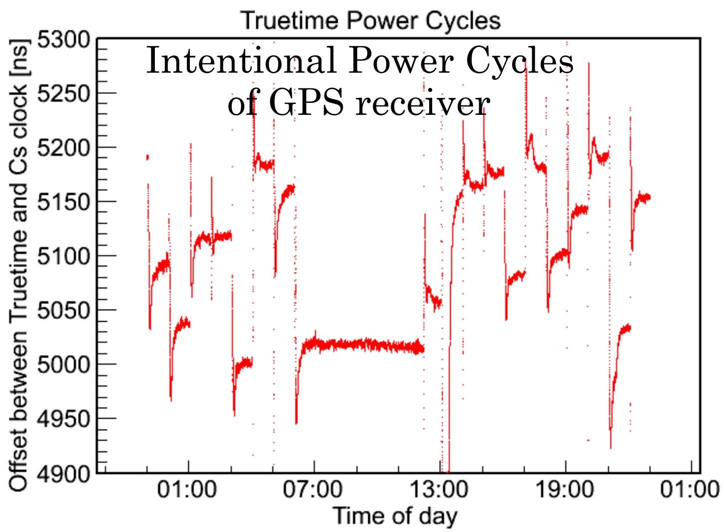


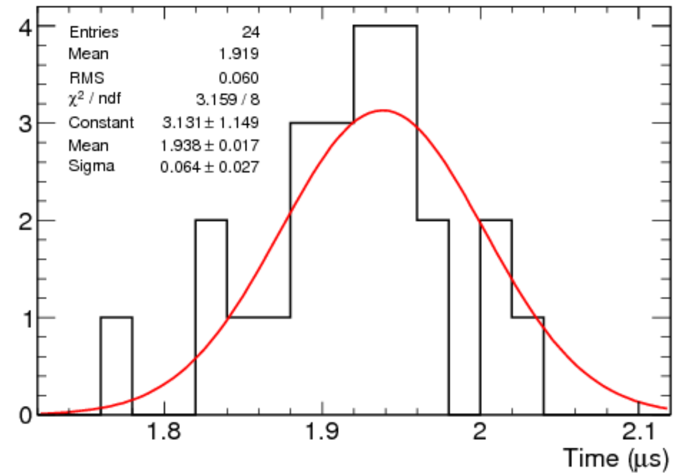




- Scintillator paddles with PMTs
- Two independent readouts
- Match muons in MINOS detectors with muons crossing AD
- Difference in matched event times recorded in each device measures latency in neutrino detector relative to AD latency
- Compare Near to Far Detector latencies, AD latency cancels
- Relative latency 24 ± 1 ns

# Timing System Stability

- Recent measurements of the MINOS GPS receivers against cesium clocks reveal GPS time discontinuities after power cycles




- Stable to within 10ns between power cycles
- 60 ns RMS jitter upon power cycles
- Data recorded over past 7 years include 27 power cycles
  - Do not know new GPS offset after power cycle, but we do know when power cycles occurred
  - Analysis approach: average over many power cycles cancels the effect of this random jitter

# ADDITIONAL SYSTEMATIC UNCERTAINTIES

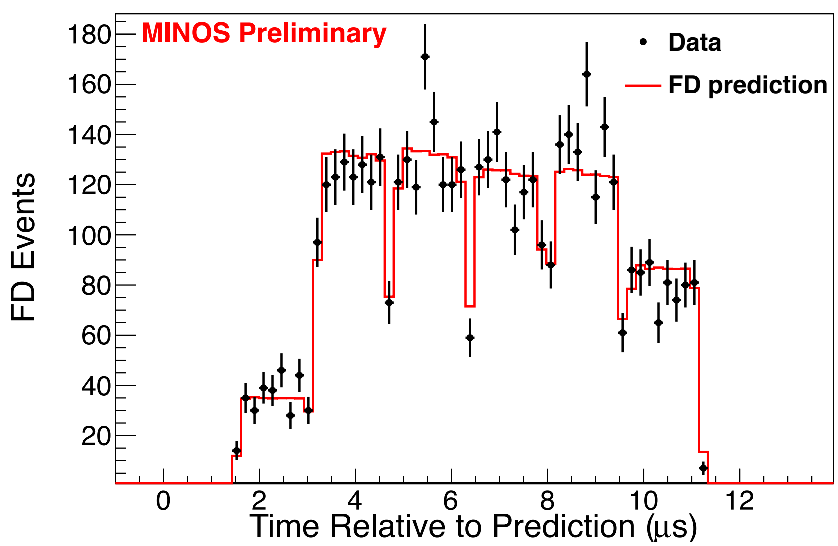
- Calibrating ND/FD GPS receivers
  - Traveling USNO TWSTT-capable GPS receiver visited FNAL and Soudan
  - Two receivers exchange timing synchronization information via the satellite
  - Comparison of ND/FD GPS time to traveling receiver reveals mean time offset between ND and FD: 22 ± 21 ns
- ND Spill trigger delay
  - Delay between beam extraction signal and issue of ND beam trigger is bimodal
  - Incur systematic uncertainty of 19 ns

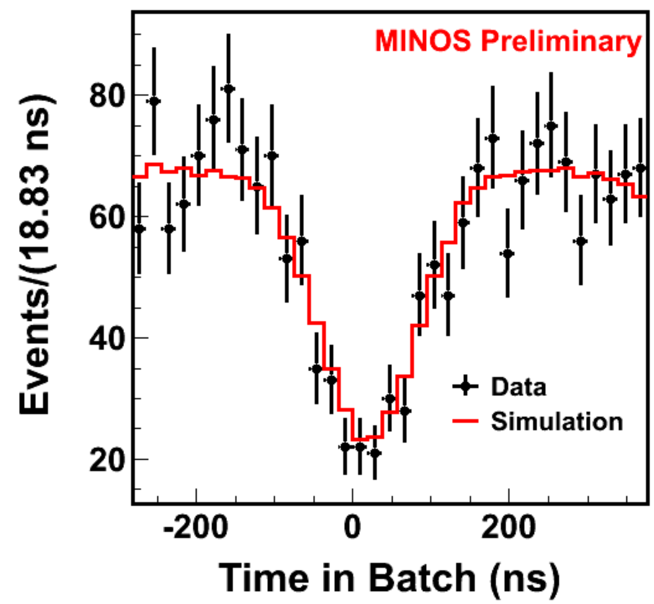
Total Systematic Error: 29 ns

# THE ANALYSES

- NuMI neutrinos span a 10 us spill
  - spill subdivided into 1.619 us batches
  - 95 ns gap between batches

## Two Analysis Approaches:



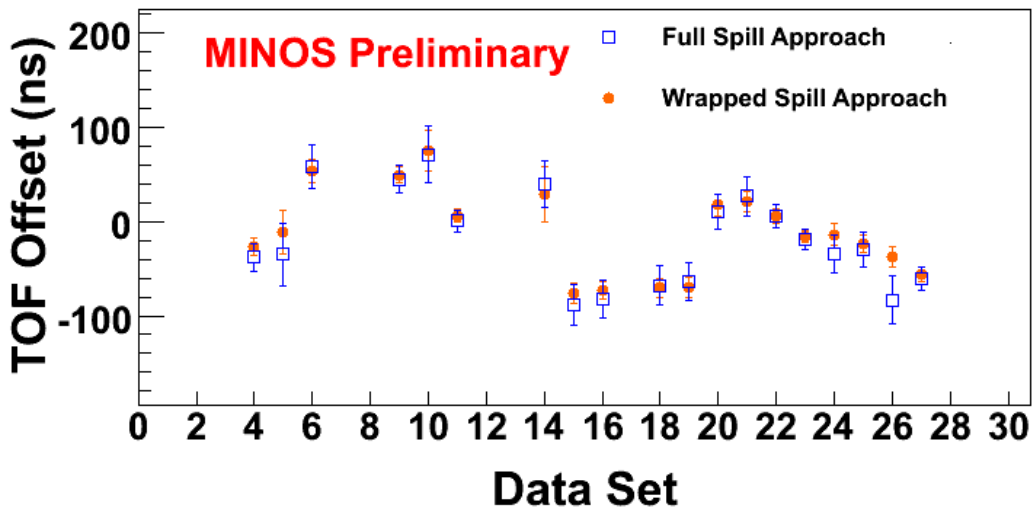




- Full spill approach
  - event time within spill in ND predicts FD distribution
  - Vary time of flight to match data

- Wrapped Spill approach
  - Measure event time within batch
  - Find batch gap time in each detector
  - Subtract for time of flight

# COMPARING THE APPROACHES

- Divide data set into subsets between timing system power cycles




- Individual results change with power cycles
- Average over individual results for final TOF result
- Error on mean taken as the statistical error on the result

# Phase I Results

- In Full Spill approach, neutrinos arrive earlier than expected by:

  $18 \pm 11$ (stat.) $\pm 29$ (syst.) ns

- In Wrapped Spill approach, neutrinos arrive earlier than expected by:

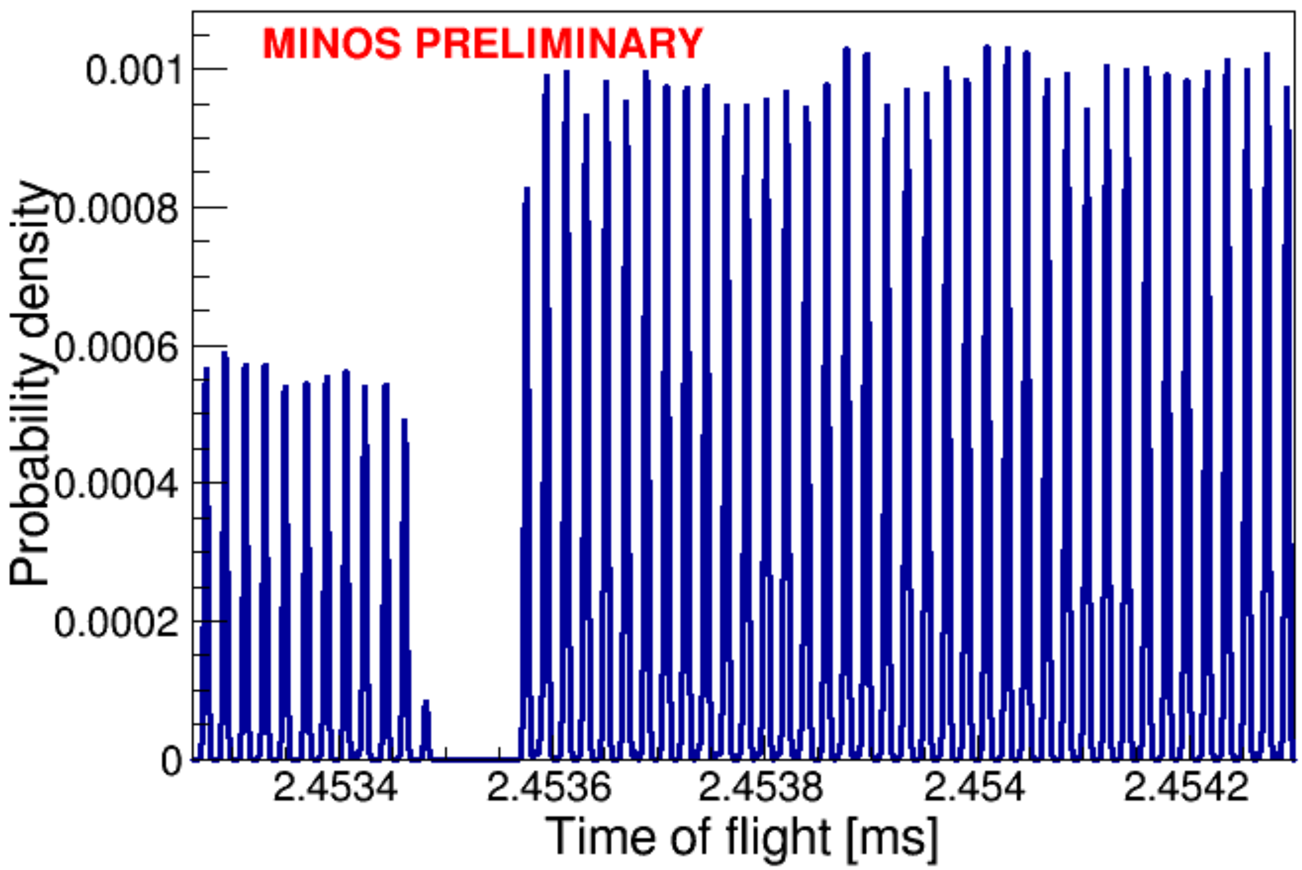
  $11 \pm 11$ (stat.) $\pm 29$ (syst.) ns

- The two approaches give results consistent with one another
- The two results are consistent with neutrinos traveling at the speed of light
- Analysis with improved timing system pending
  - ~200 contained CC events collected with new timing system operational

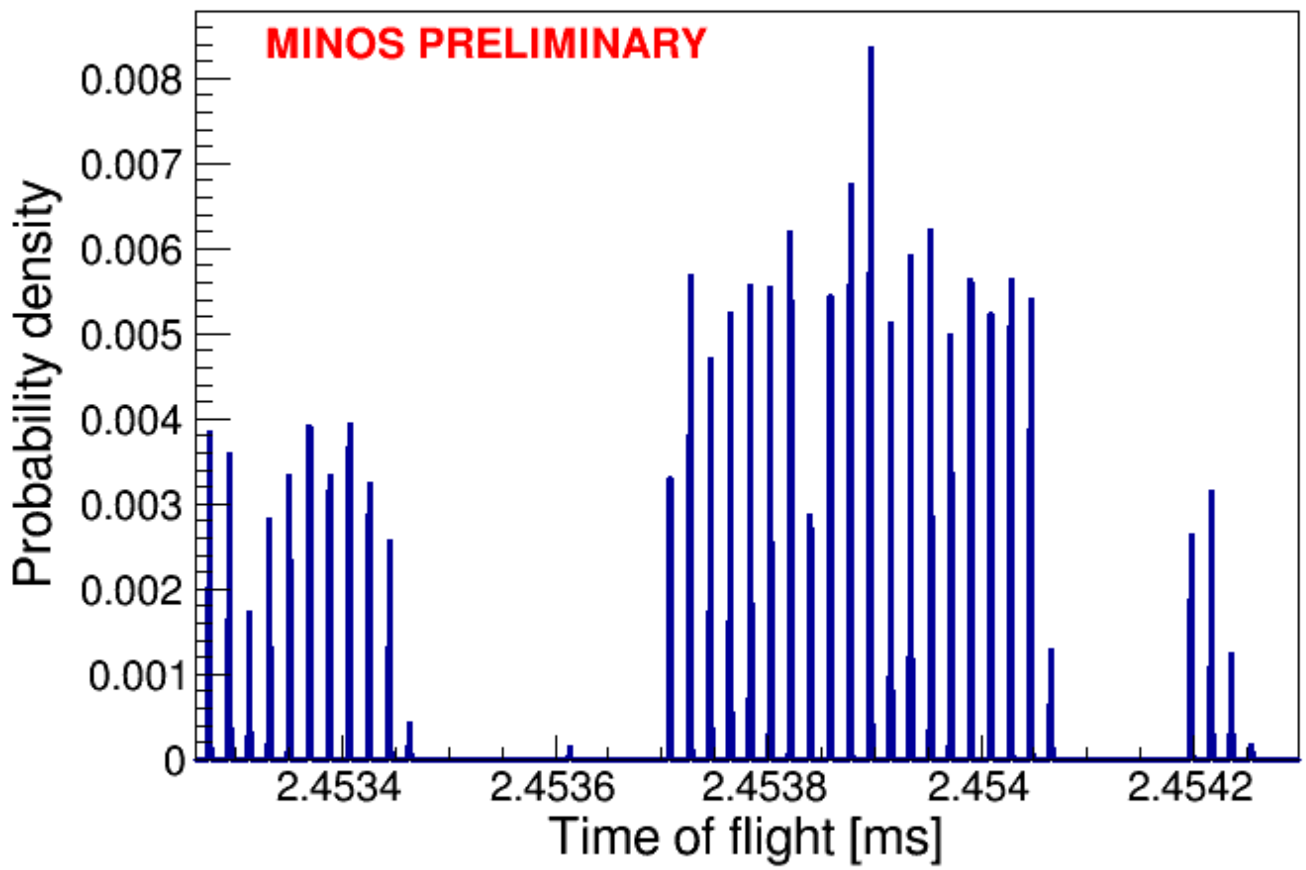
# A NEW TIMING EFFORT

- Old GPS quoted 200ns accuracy
  - Actually does better
  - MINOS @Neutrino 2012: ns
- Need to do better - went looking for help
  - NIST Time and Frequency Division
  - USNO Time Service Department
- Rapid deployment
  - Money available at Christmas
  - Partial system running end February

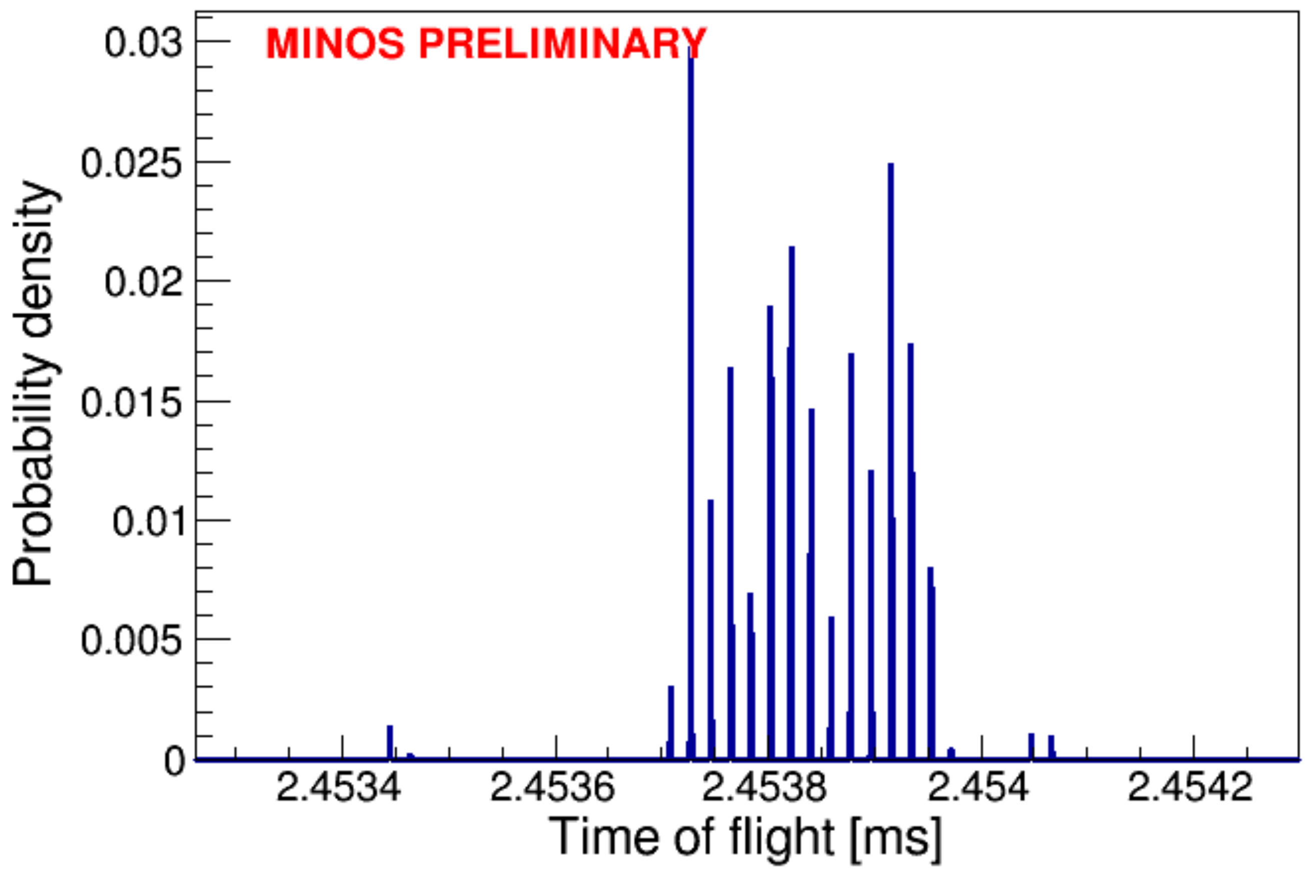
# Time of flight after 1 event



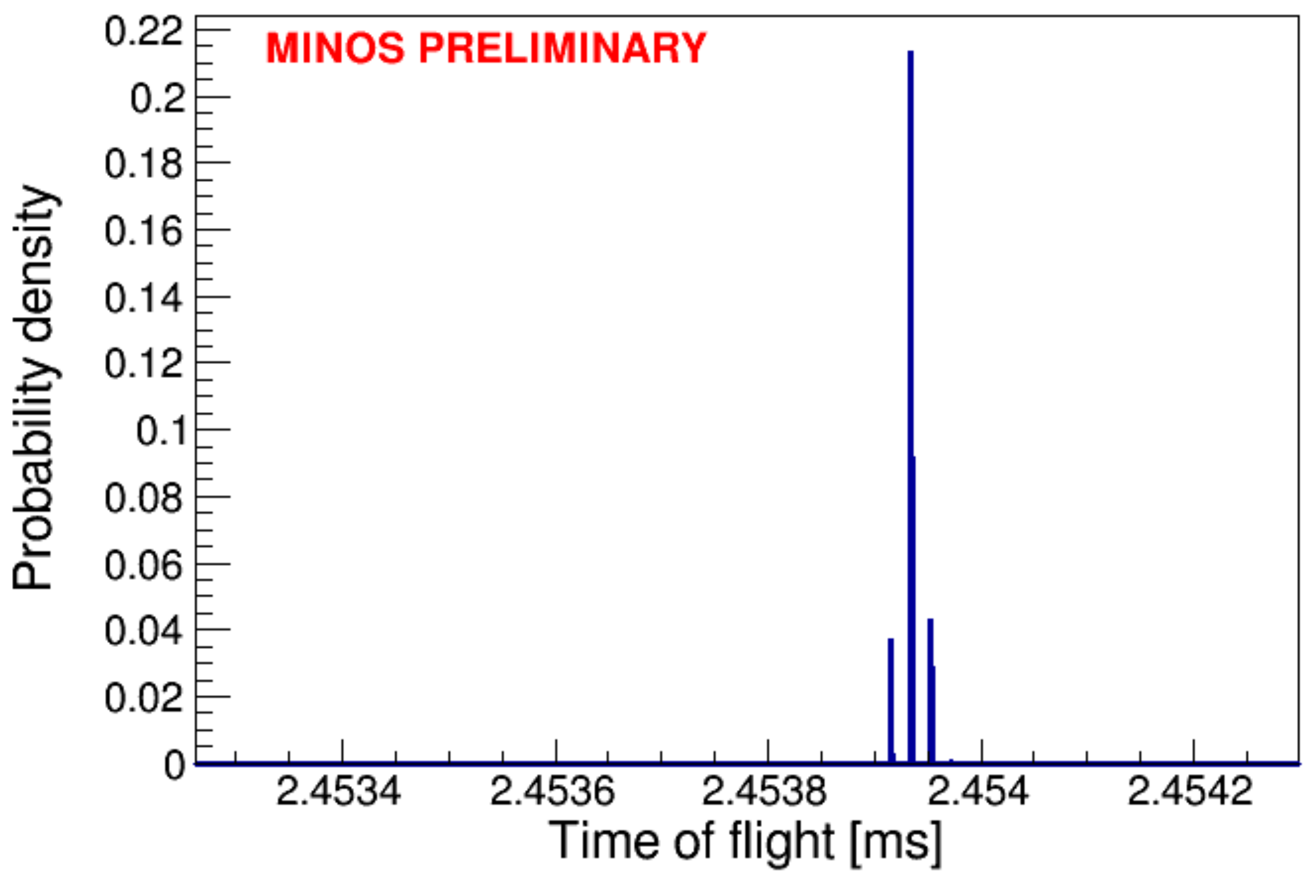
# AFTER 10 EVENTS



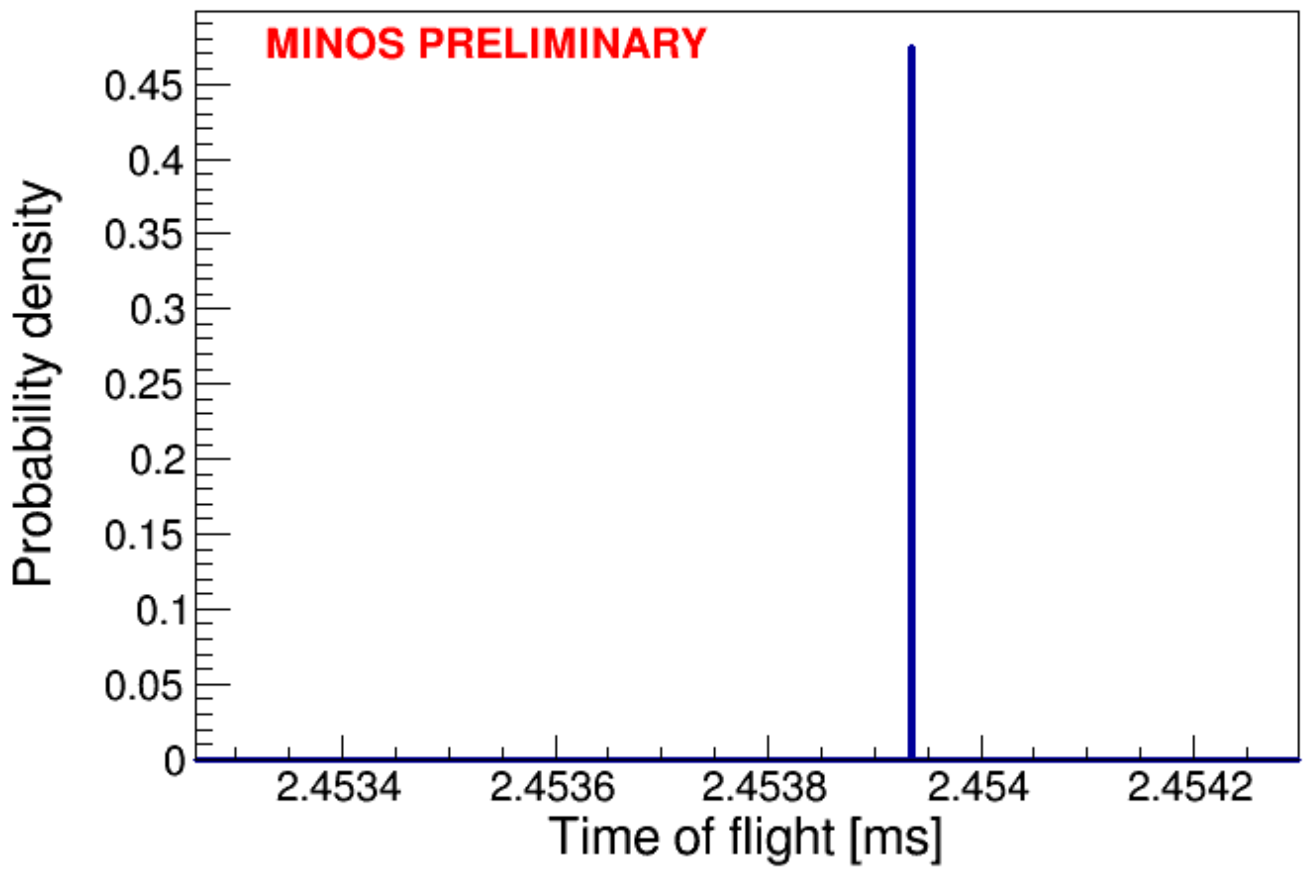
# After 30 events



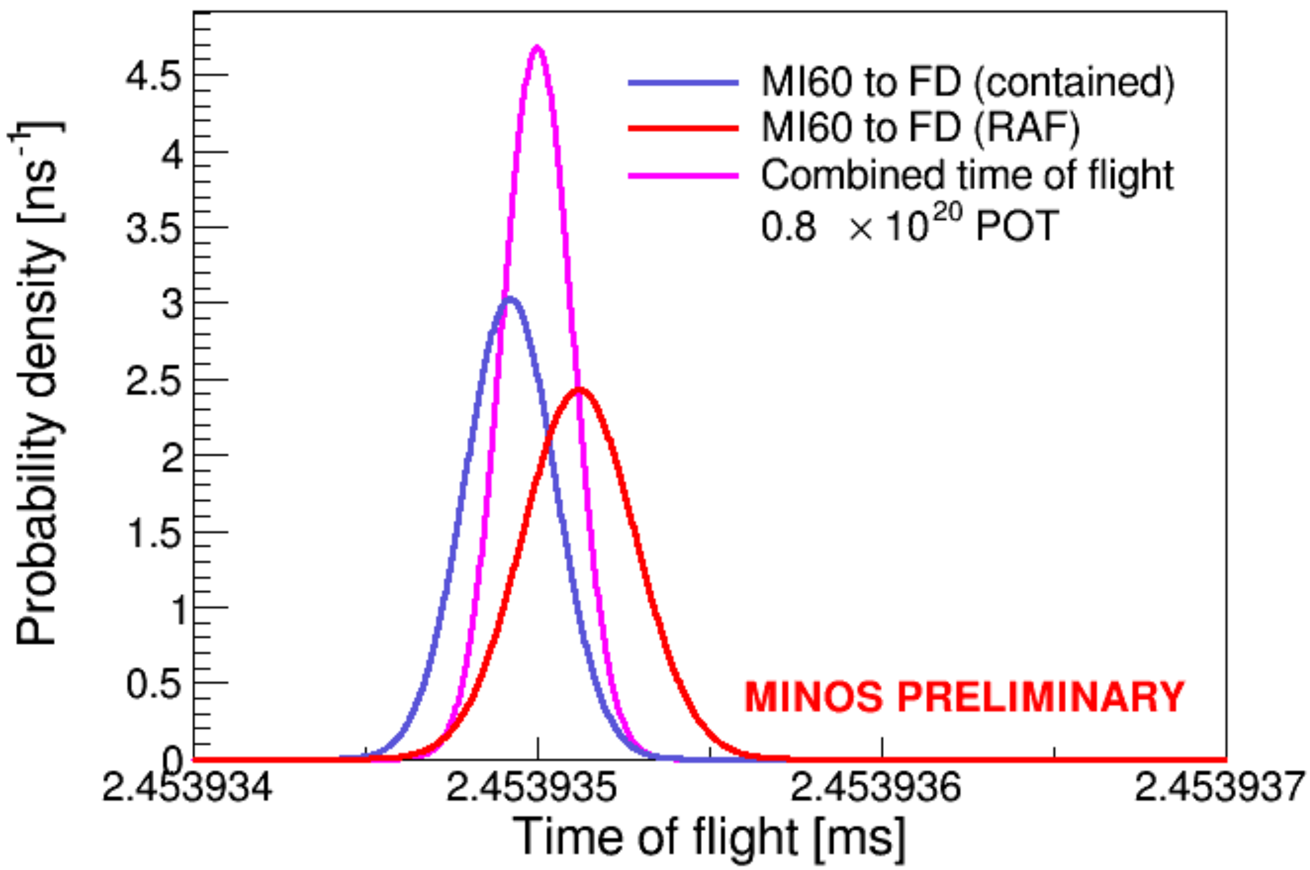
# After 60 events



# AFTER 195 EVENTS



# TOF from MI60 to FD



## THE ANSWER

| Systematic uncertainty | Value |
|---|---|
| Inertial survey at FD | 2.3 ns |
| Relative ND-FD latency | 1.0 ns |
| FD TWTT between surface and underground | 0.6 ns |
| GPS time transfer accuracy | 0.5 ns |
| **TOTAL** | **2.6 ns** |

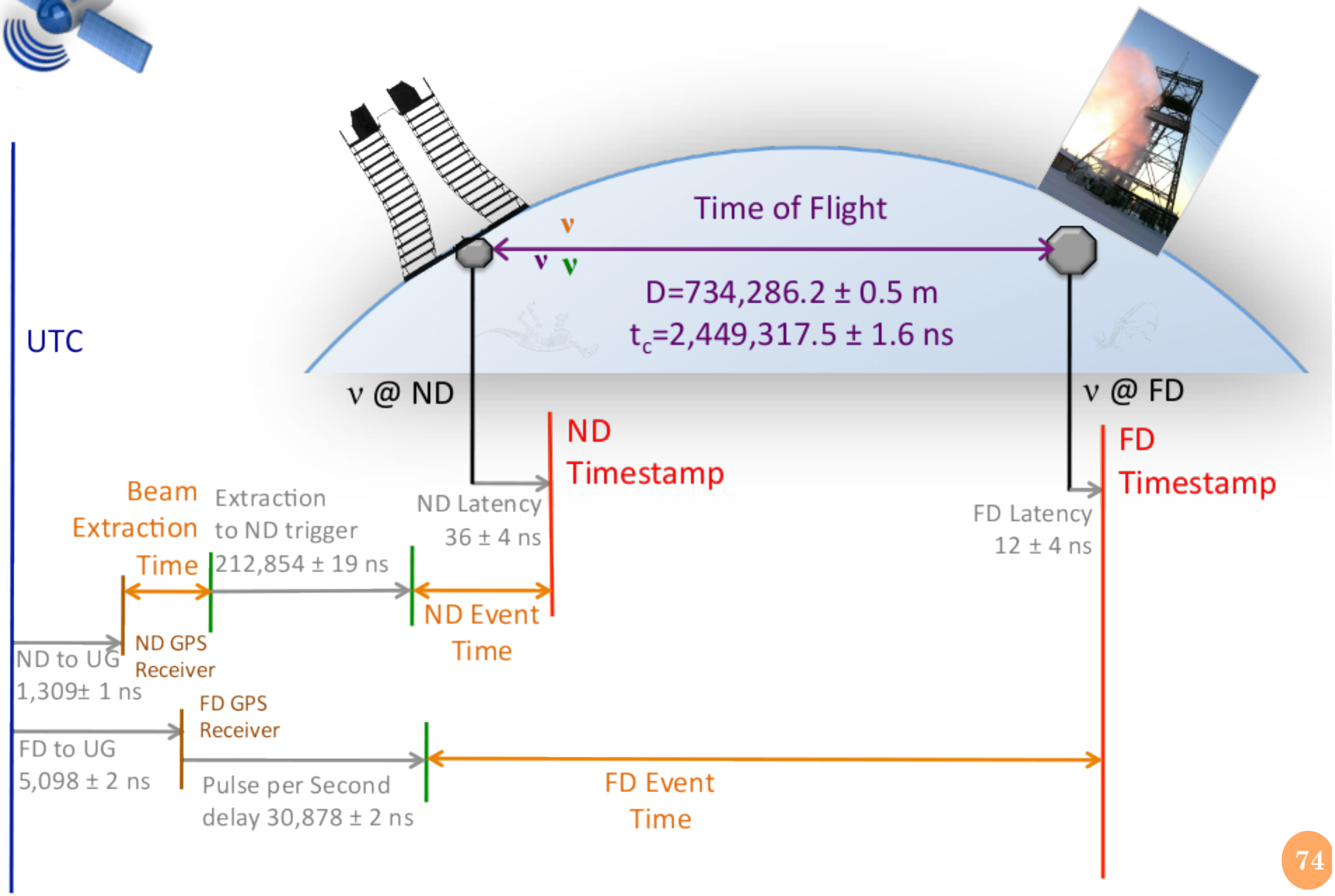
- Baseline ND – FD = 2,449,316.3 ns
- Time of flight ND – FD = 2,453,935.0 ± 0.1-4621.1 = 2,449,313.9 ns

- So difference from light speed

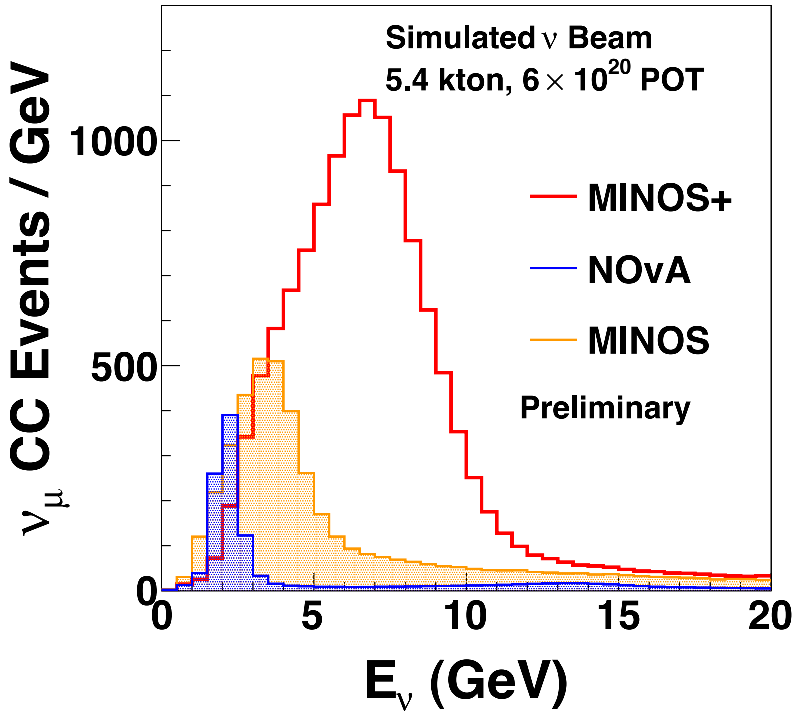
$$\delta = -2.4 \pm 0.1\ (\text{stat.}) \pm 2.6\text{ns}\ (\text{syst.})$$

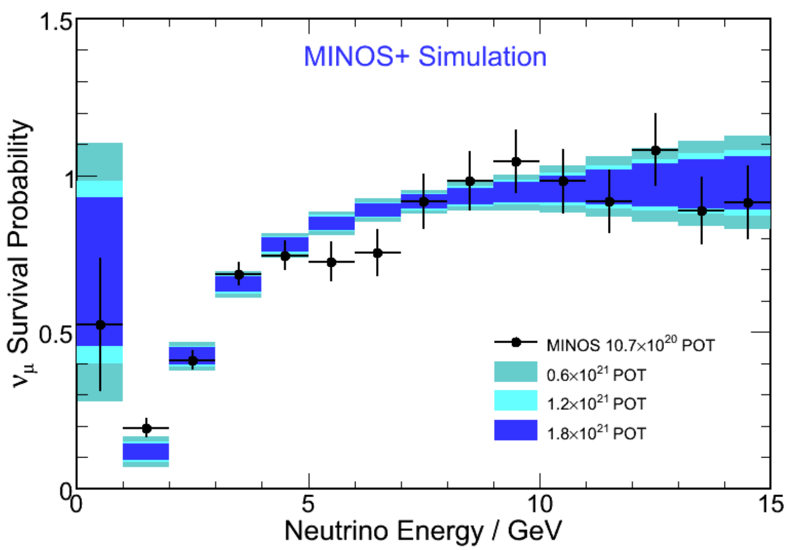
$$\left({}^{v}/_{c} - 1\right) = (1.0 \pm 1.1)\ \times\ 10^{-6}$$

# Timing Diagram



# MINOS+

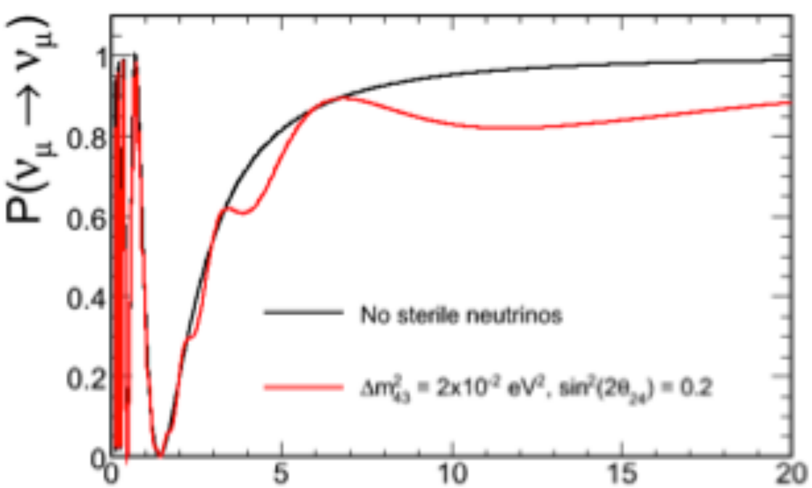


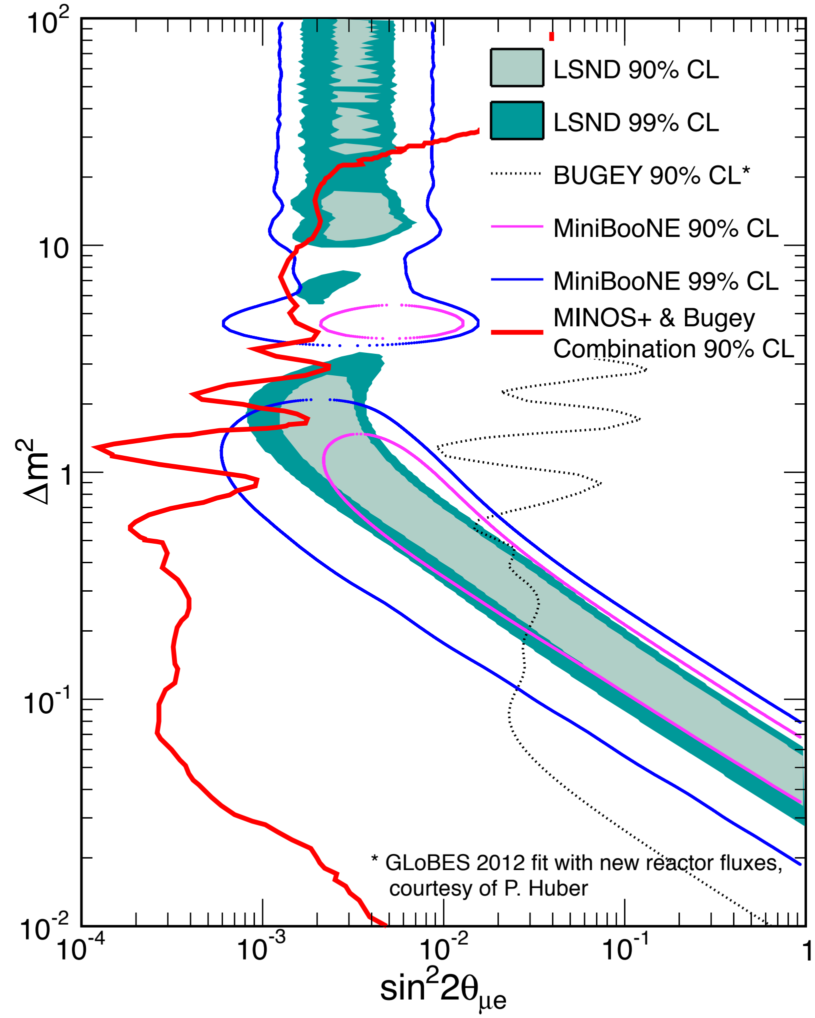




- MINOS will continue to run in the NOvA era
- ME beam peaks above the oscillation dip on axis
- But we get a lot of events!
  - ~4000 muon neutrino CC events per year expected at FD
- Unique test of oscillation paradigm with sensitivity to exotic signals

# MINOS+

- Using complementary information from Bugey, MINOS+ can almost rule out the the low mass LSND region



# ENuMI

# More NoVA

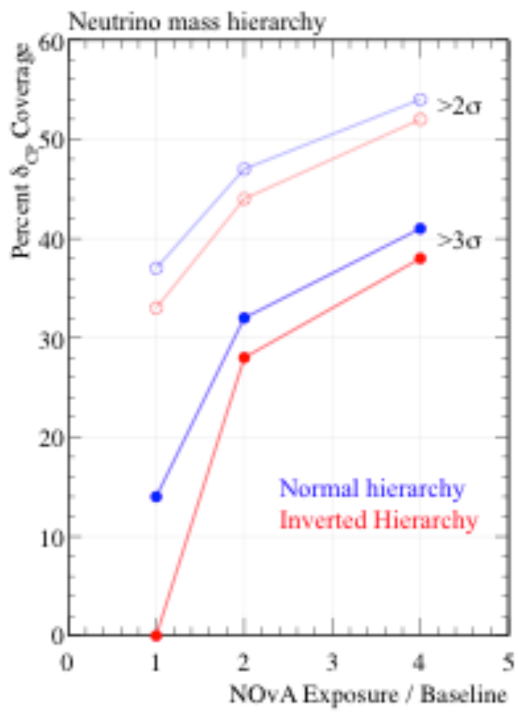



Figure 2: The percent of $\delta_{CP}$ values for which NOvA can resolve the neutrino mass hierarchy at 2 and $3\sigma$ C.L.

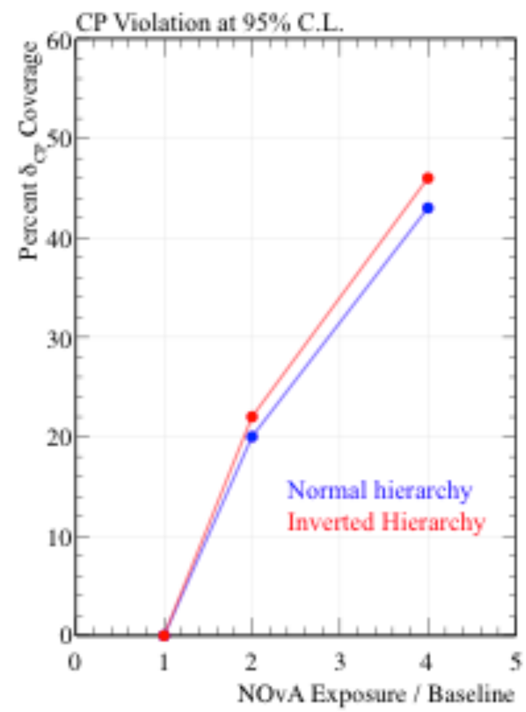



Figure 3: The percent of $\delta_{CP}$ values for which NOvA can establish CP violation at 95% C.L. or better.

# RADAR

- Add LAr detector at Ash River

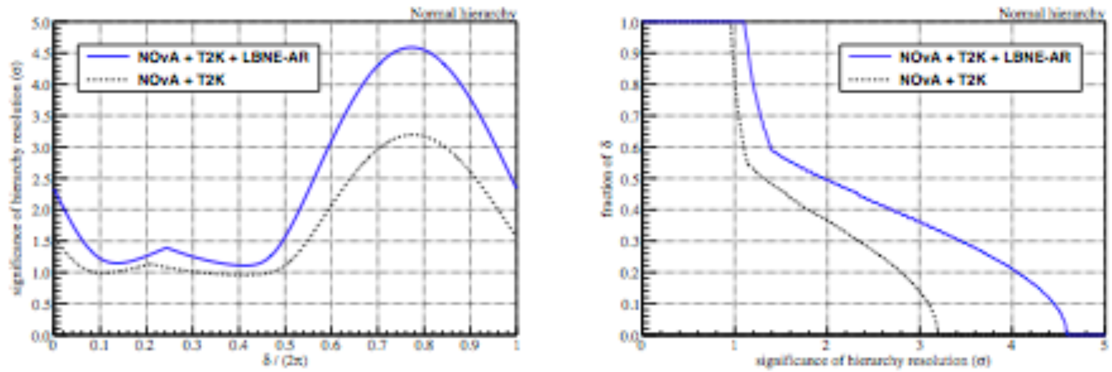



Figure 1: The significance of hierarchy resolution for NO$\nu$A +T2K alone (black dashed) and with LBNE-AR added (blue solid), shown both as a function $\delta$ (left) and in terms of the fraction of $\delta$ values covered at a given confidence level. Normal hierarchy and maximum mixing are used.

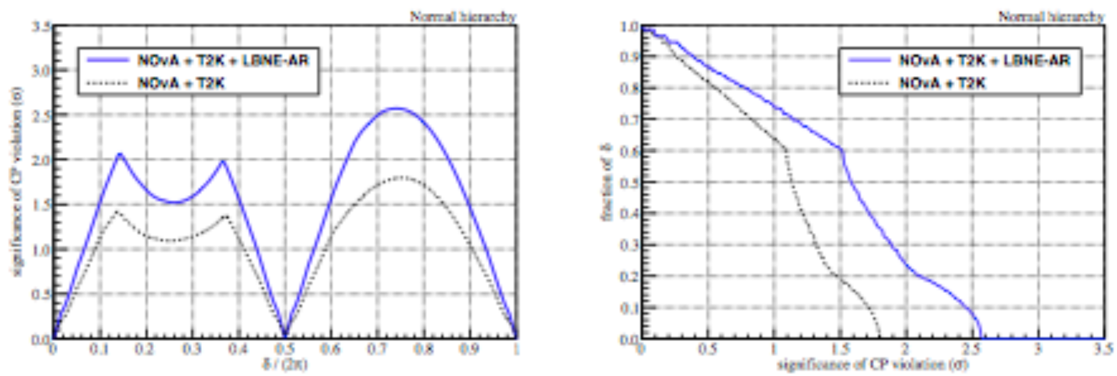



Figure 2: The significance of CP violation for NO$\nu$A +T2K alone (black dashed) and with LBNE-AR added (blue solid), shown both as a function $\delta$ (left) and in terms of the fraction of $\delta$ values covered at a given confidence level. Normal hierarchy and maximum mixing are used.

# CHIPS Physics Reach

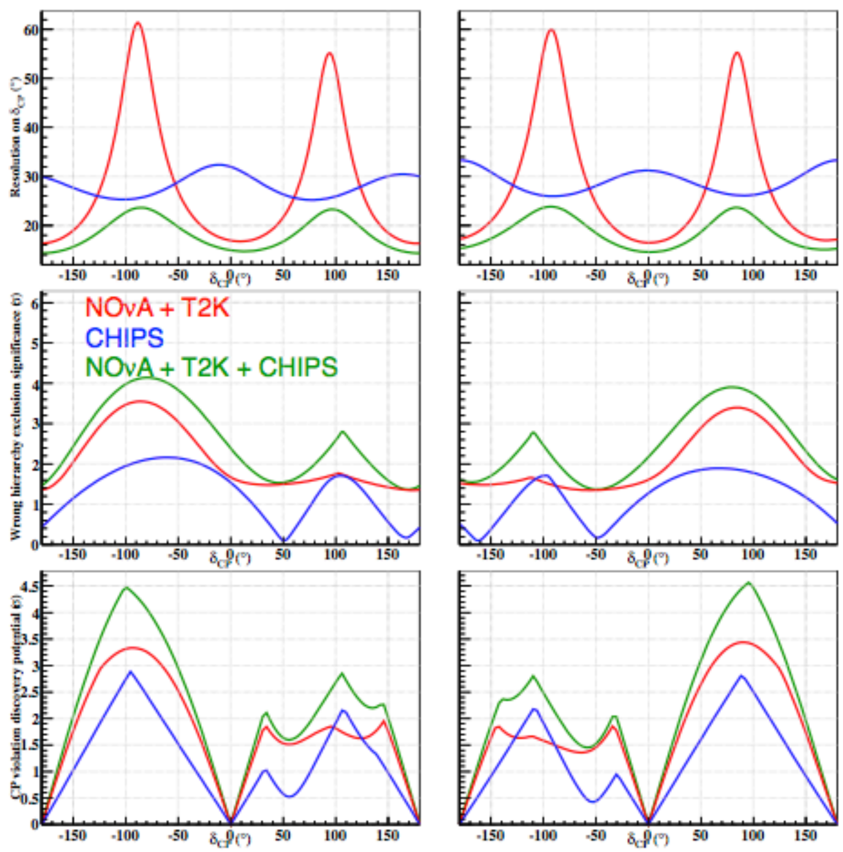



*Figure 3: CHIPS physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOνA (5+5y) and T2K(8.8e21 POT), and CHIPS(3+3y). (Top) $\delta_{CP}$ resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOνA and T2K, the blue line is CHIPS and the green is the combination.*

# CHIPS IN LBNE

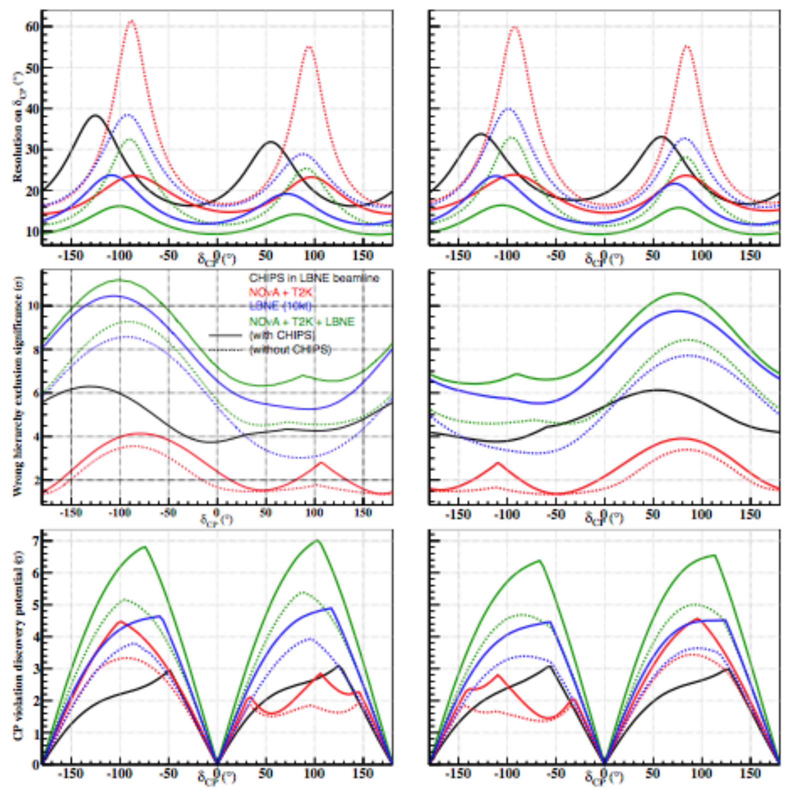



*Figure 8: Physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOνA+T2K, 10 kton LAr LBNE, and CHIPS in the LBNE beam at 20 mrad. (Top) $\delta_{CP}$ resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOνA and T2K, the blue line is a 10 kton LAr detector on-axis in the LBNE beam, and the green is the combination of those experiments. Solid black line is for CHIPS, from both a NuMI and LBNE run. Dotted lines show each experiment (or combination of experiments) without a CHIPS run. Solid lines show the effect of adding CHIPS to the results.*