Long-Baseline Experiments with the NuMI Beam

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OUTLINE

- The Story of Neutrino Oscillations
- Overview of MINOS and Results from the Full Run
  - Three flavor results
  - Sterile Neutrino Search
- Overview and outlook of NOvA
- The future of NuMI

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?

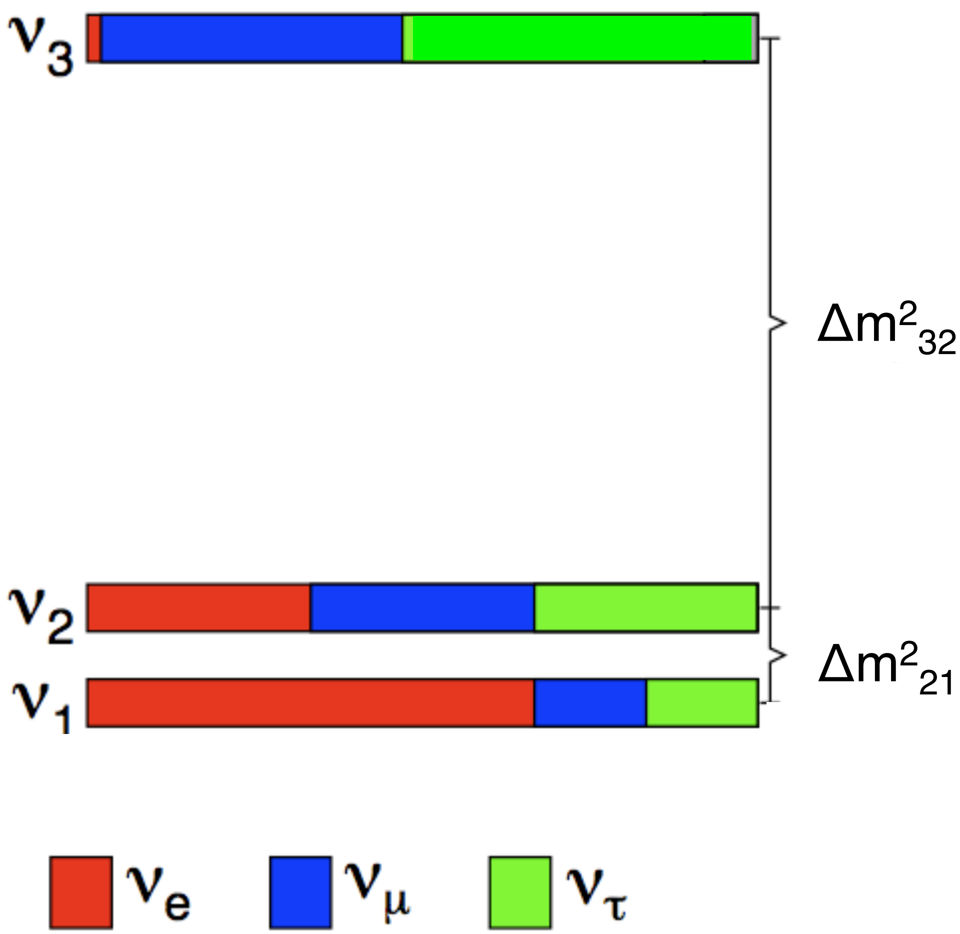
- Precision measurements provide a valuable constraints on neutrino oscillation model
- Open Questions:
  - What are the masses of the neutrinos?
  - What is the nature of neutrino mass?
  - Which neutrino is most massive?
  - Why is lepton mixing much larger than quark mixing?
  - Is there an underlying 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!

THE MINOS EXPERIMENT

- Long-baseline neutrino oscillation experiment
  - Neutrinos from NuMI beam line
    - L/E ~ 500 km/GeV
      - atmospheric Δm^2

- Two detectors mitigate systematic effects
  - beam flux mis-modeling
  - neutrino interaction uncertainties

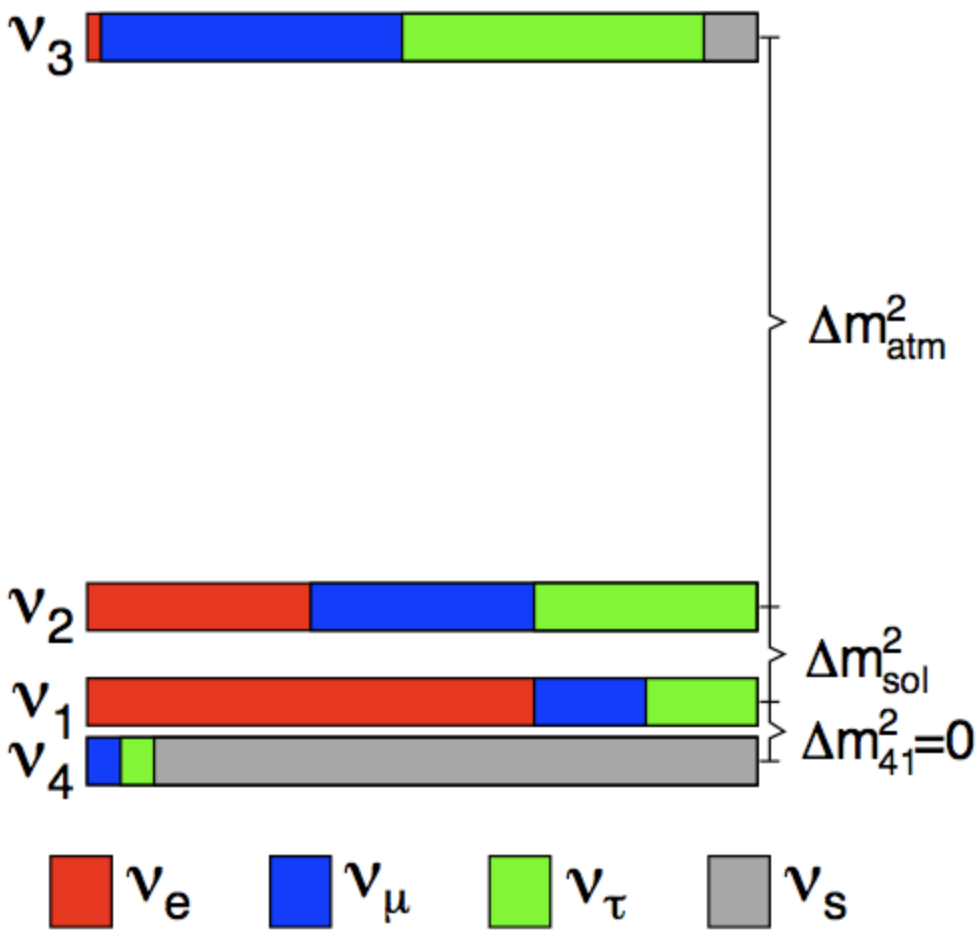
MINOS PHYSICS GOALS



- Measure ν_μ disappearance as a function of energy
  - Δm^2_{32} and $\sin^2(2\theta_{23})$
  - test oscillations vs. alternatives
  - look for differences between neutrino and antineutrinos
- Study $\nu_\mu \rightarrow \nu_e$ mixing
  - measure θ_{13}
  - δ_{CP}
  - mass hierarchy

Brand New! Combination in 3 flavor formalism

MINOS Physics Goals

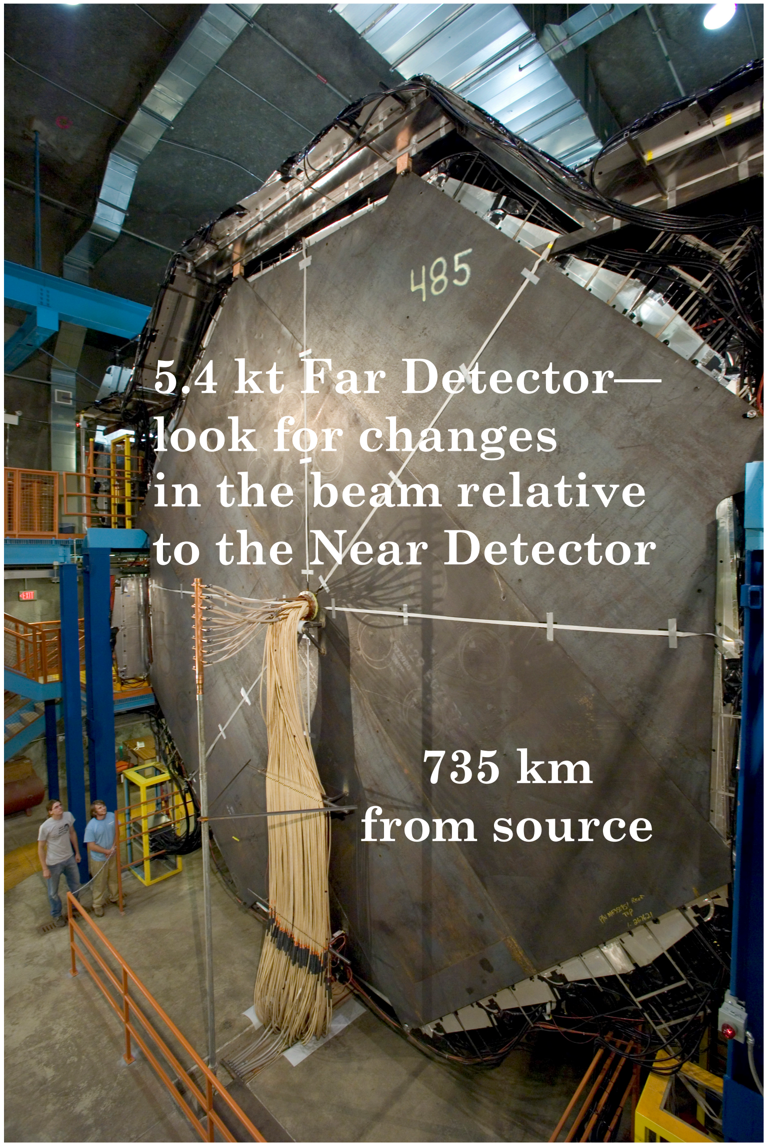


- Measure rate of Neutral Current interactions
  - probe sterile mixing

THE DETECTORS

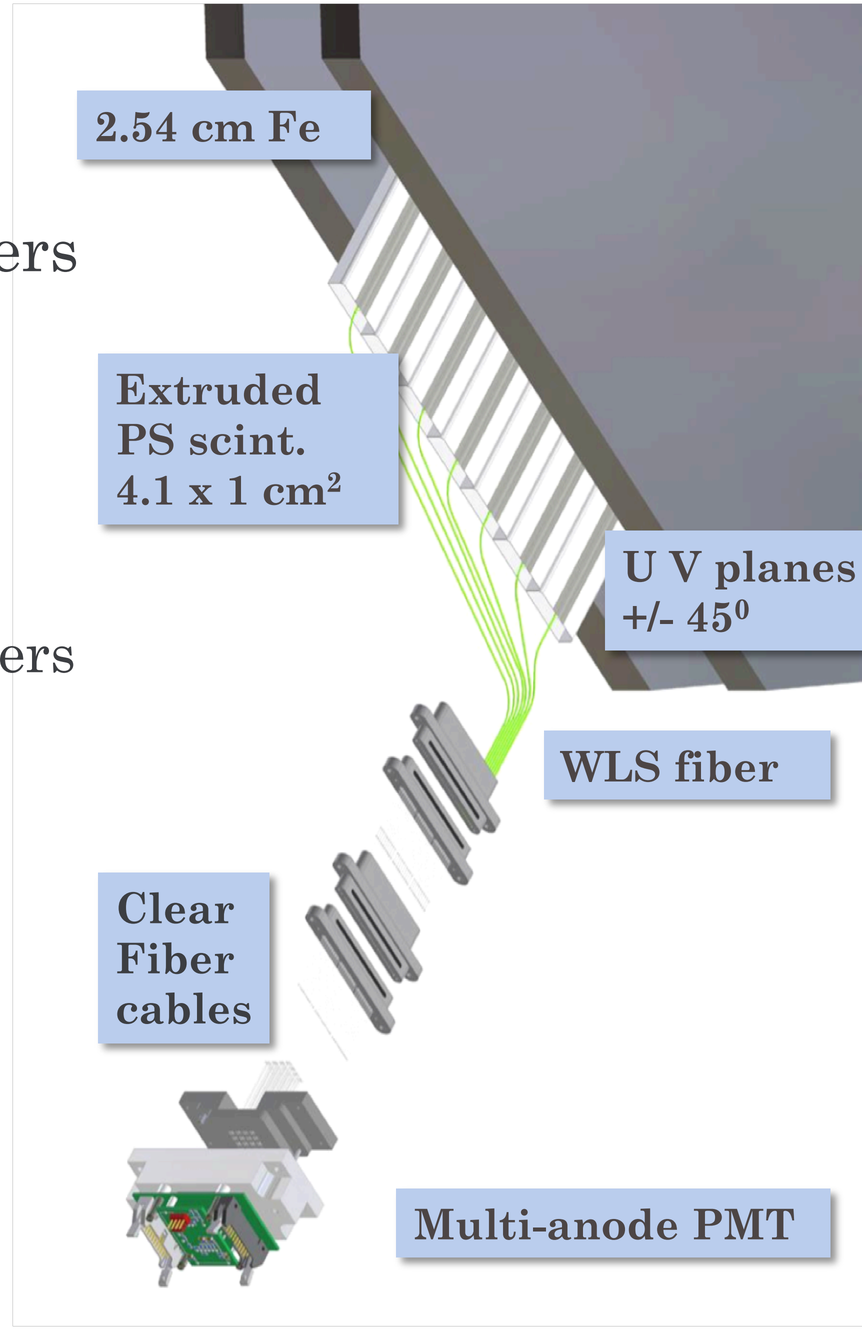
FD running since 2003

ND running since 2005

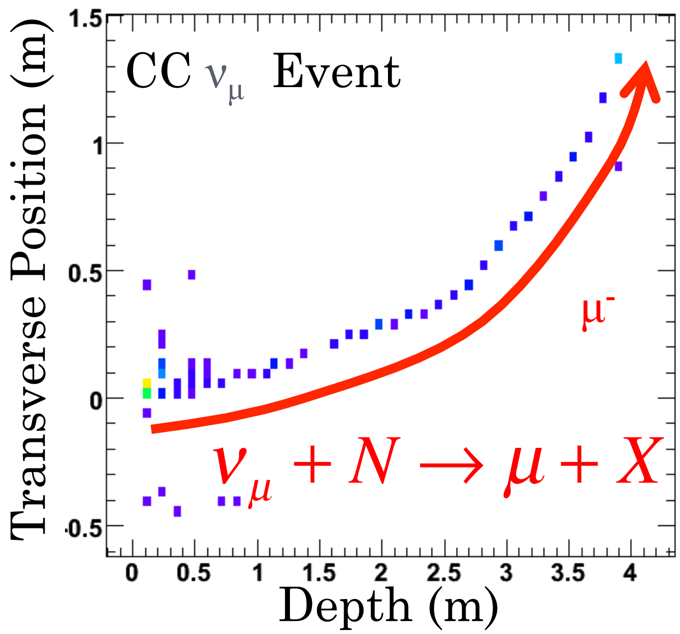


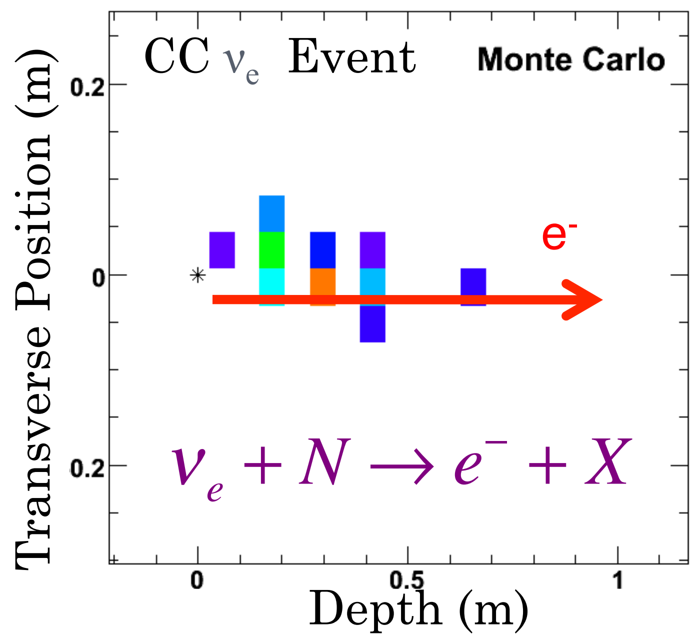
DETECTOR TECHNOLOGY

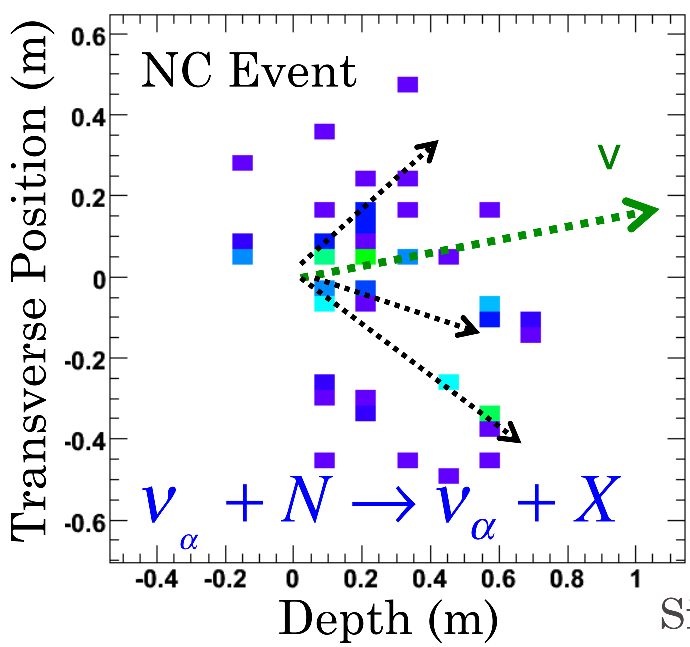
- Tracking sampling calorimeters
  - steel absorber 2.54 cm thick ($1.4\ X_0$)
  - scintillator strips 4.1 cm wide (1.1 Moliere radii)
  - 1 GeV muons penetrate 28 layers
- Magnetized
  - muon energy from range/ curvature
  - distinguish $\mu+$ from $\mu-$
- Functionally equivalent
  - same segmentation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



Events in MINOS





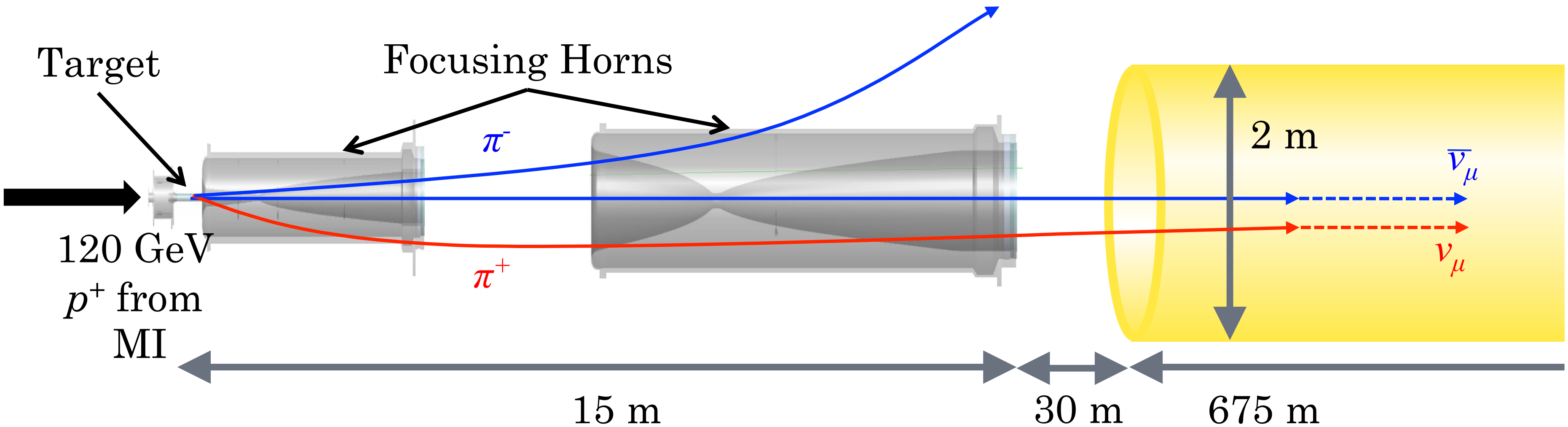


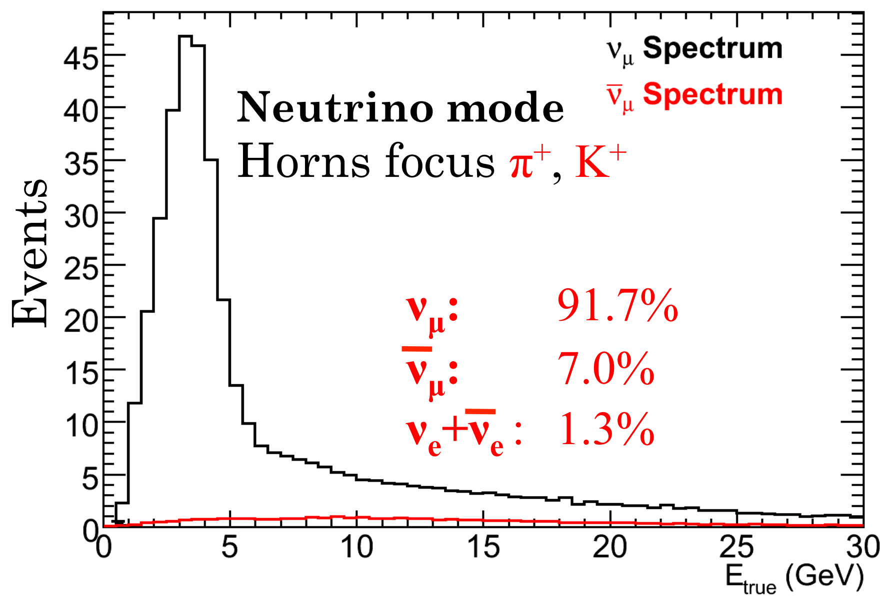
- ν_μ Charged Current events:
  - energy from sum of muon energy (range or curvature) and shower energy
- NC or ν_e:
  - energy from calorimetric response

Simulated Events

Making a neutrino beam

Making a Neutrino Beam





- **Production:** bombard graphite target with 120 GeV p^+
- **Focusing:** 2 magnetic focusing horns
  - sign selected hadrons
- **Decay:** 2 m diameter pipe
- **Result**: wide band neutrino beam

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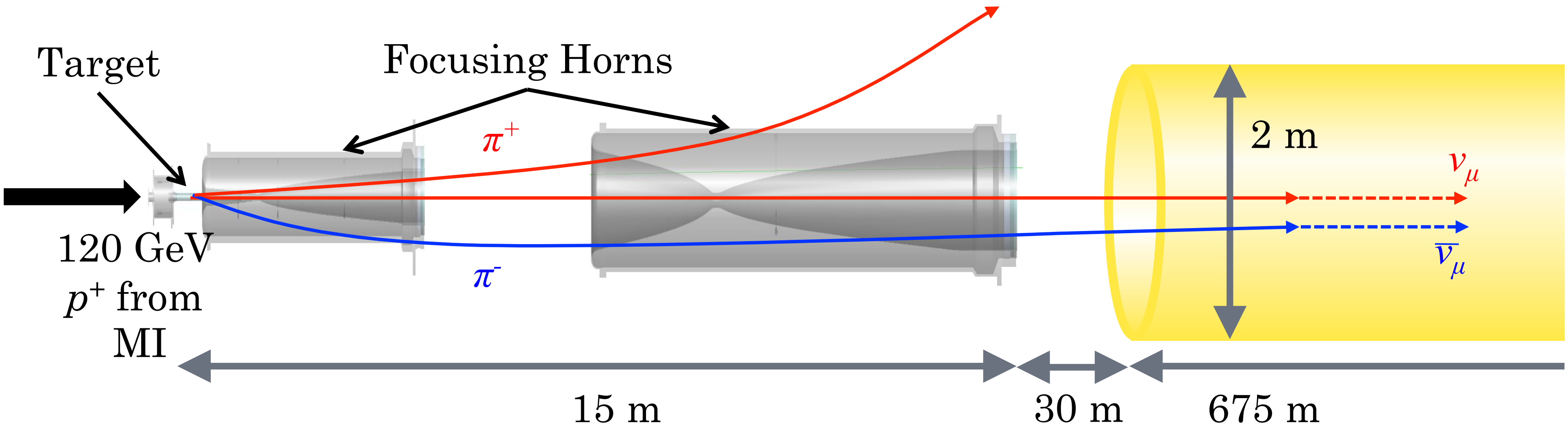
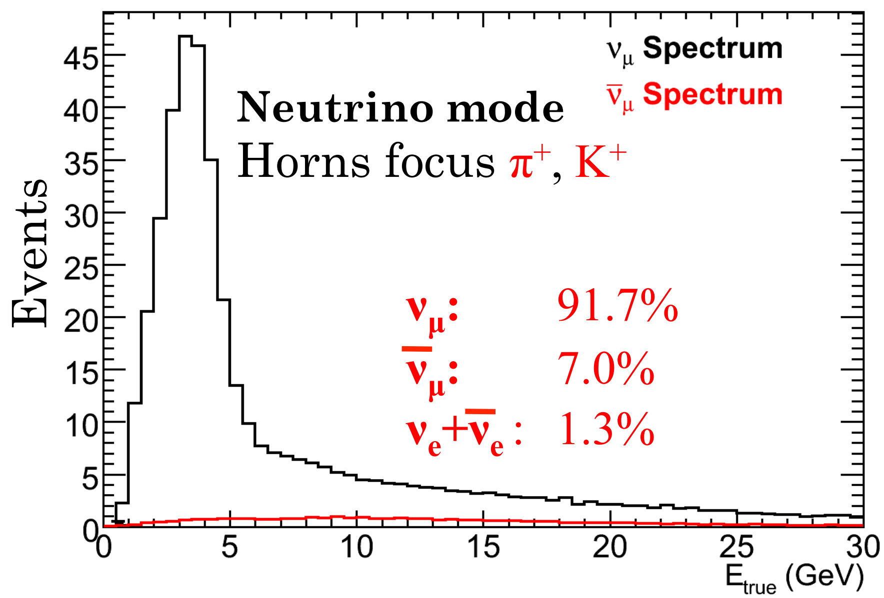
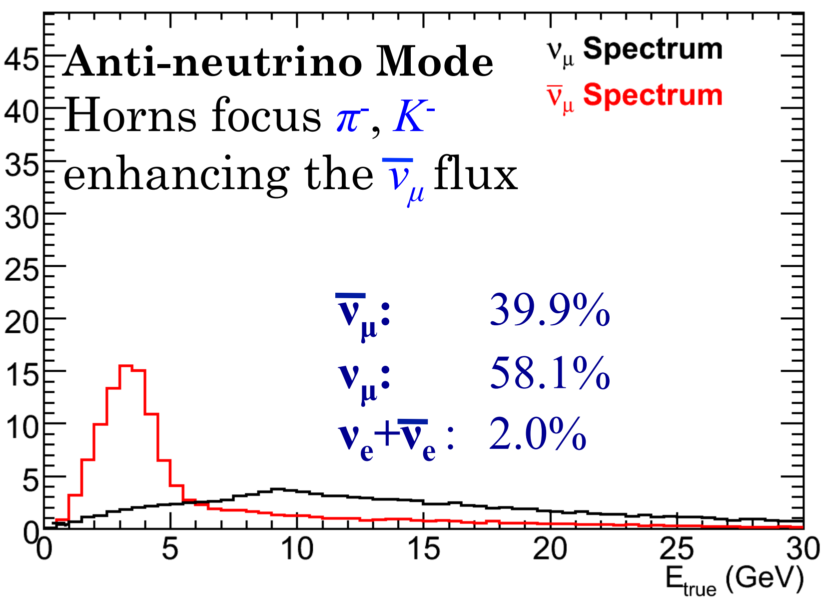
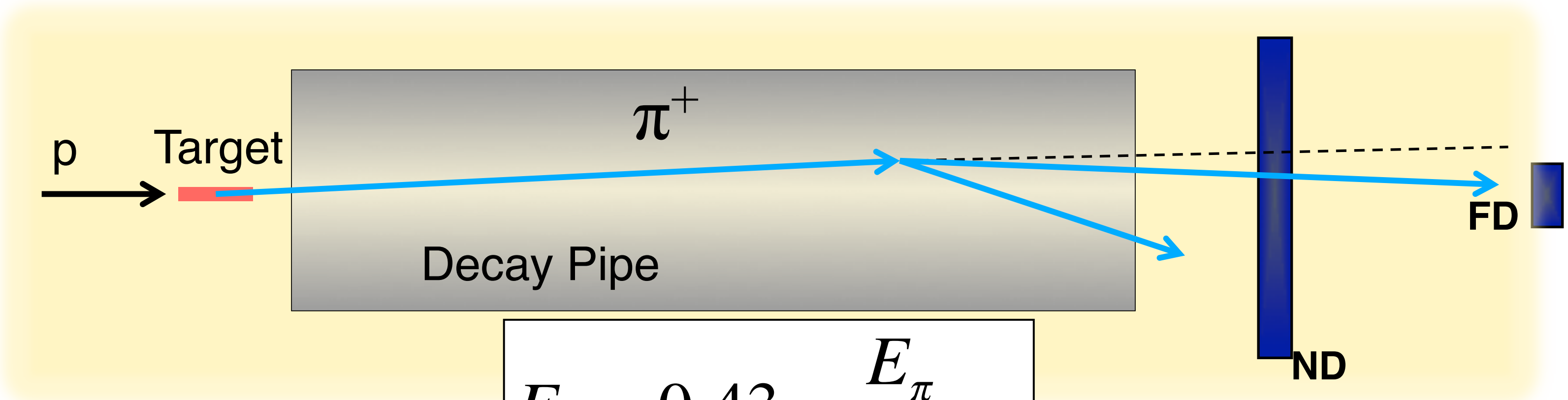
Making a Neutrino Beam







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

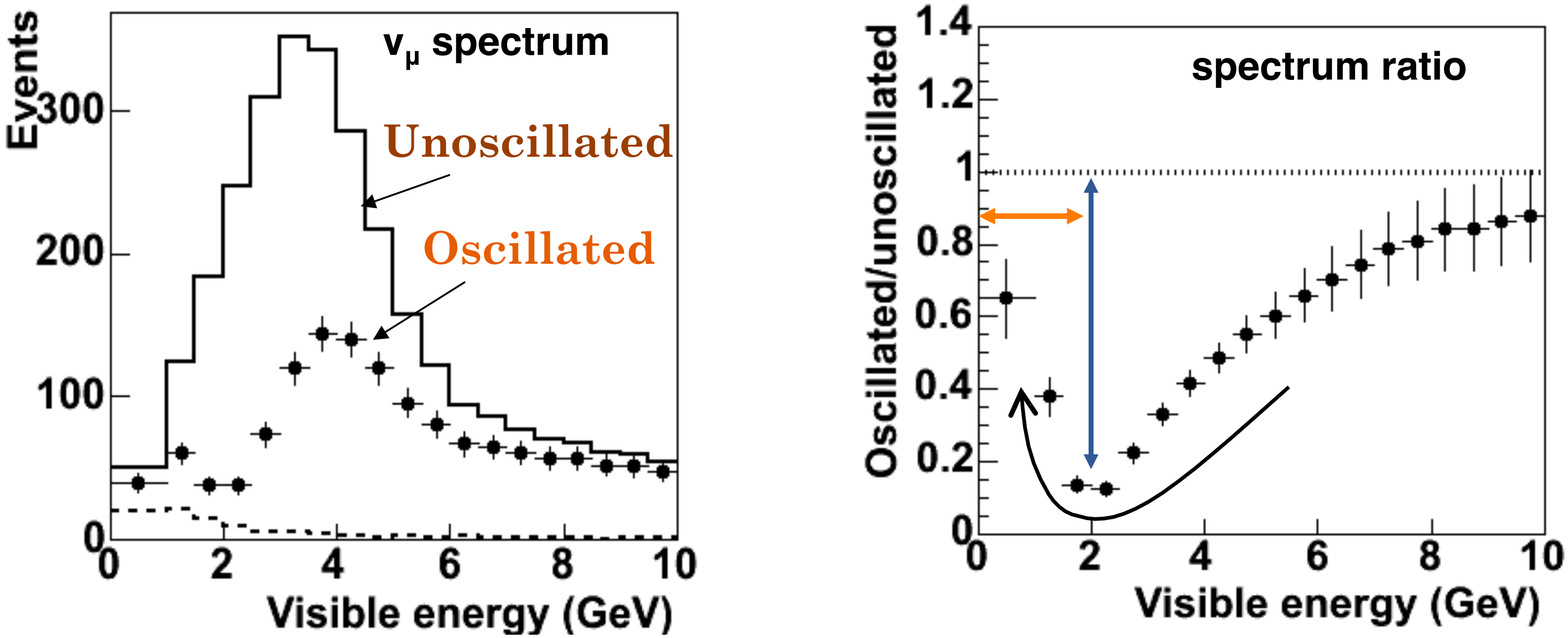
Three Flavor Analysis

2 Flavor Muon Neutrino Disappearance

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

Monte Carlo

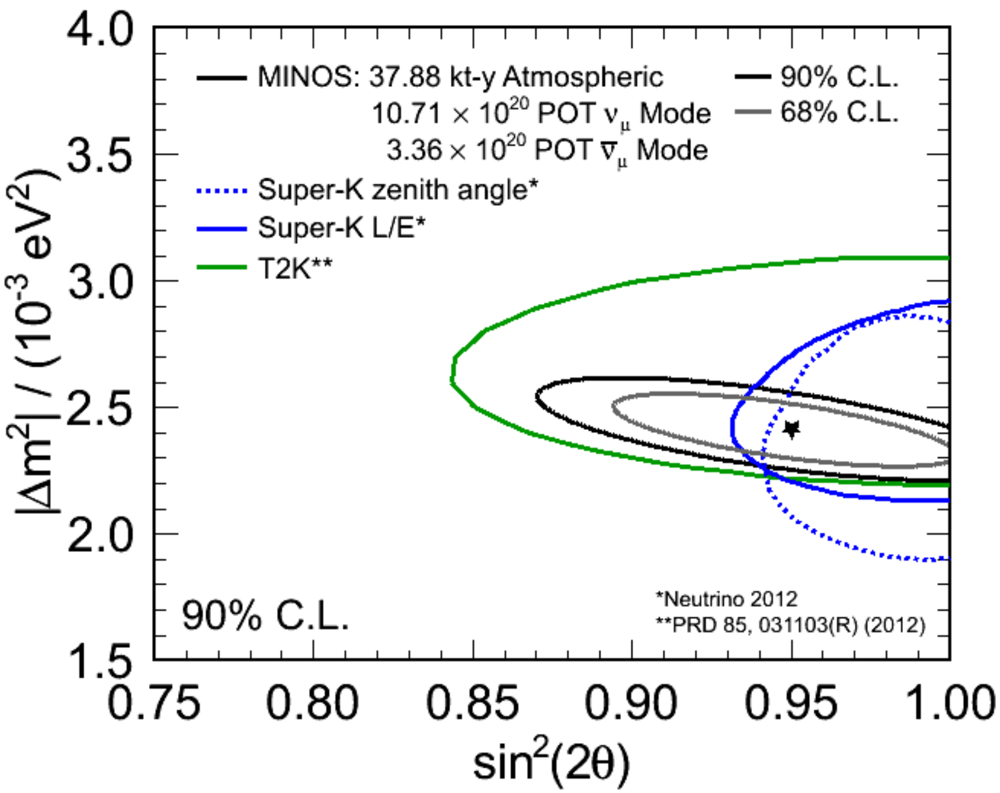
(Input parameters: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.35\times10^{-3}$ eV^2)



- Deficit of muon neutrino charged current interactions in
  - 10.71×10^{21} POT neutrino mode
  - 3.36×10^{20} POT antineutrino mode
  - 37.88 kton years of atmospheric data

PRL 110:251801 (2013)

2 Flavor Oscillation Results



- Combined MINOS neutrino oscillation parameters:

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

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

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

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

Extending to 3 Flavors

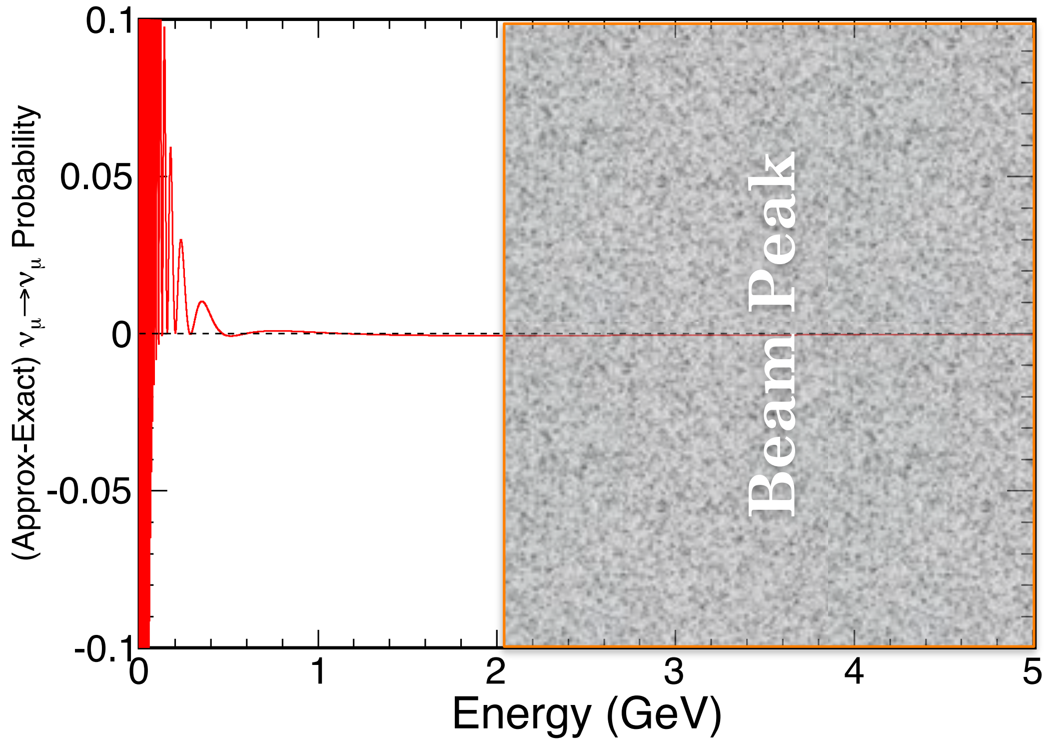
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2\left(2\theta_{\mu\mu}\right)\sin^2(1.27\Delta m^2_{\mu\mu} L / E) + \mathcal{O}\left(\Delta m^2_\odot \frac{L}{E}\right)^2$$

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

depends on θ_{13}, θ_{23} octant, mass hierarchy, δ_{CP}

(and solar mixing parameters)

Beam Events show small differences in beam peak



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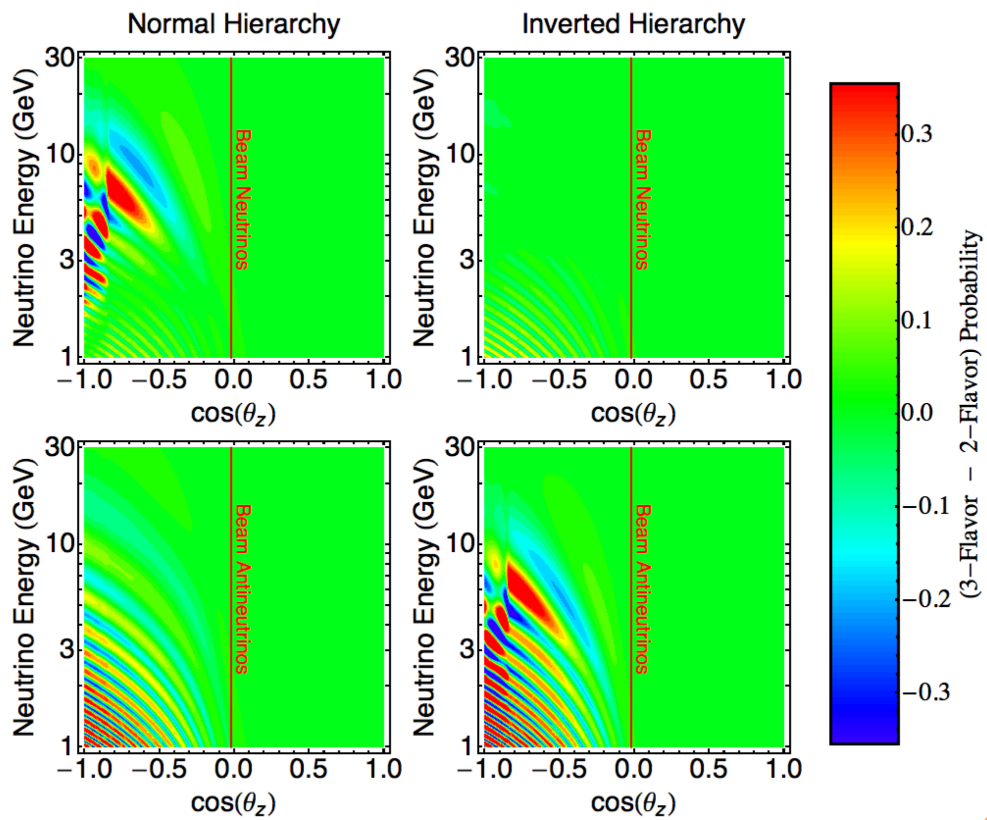
depends on θ_{13}, θ_{23} octant, mass hierarchy, δ_{CP}

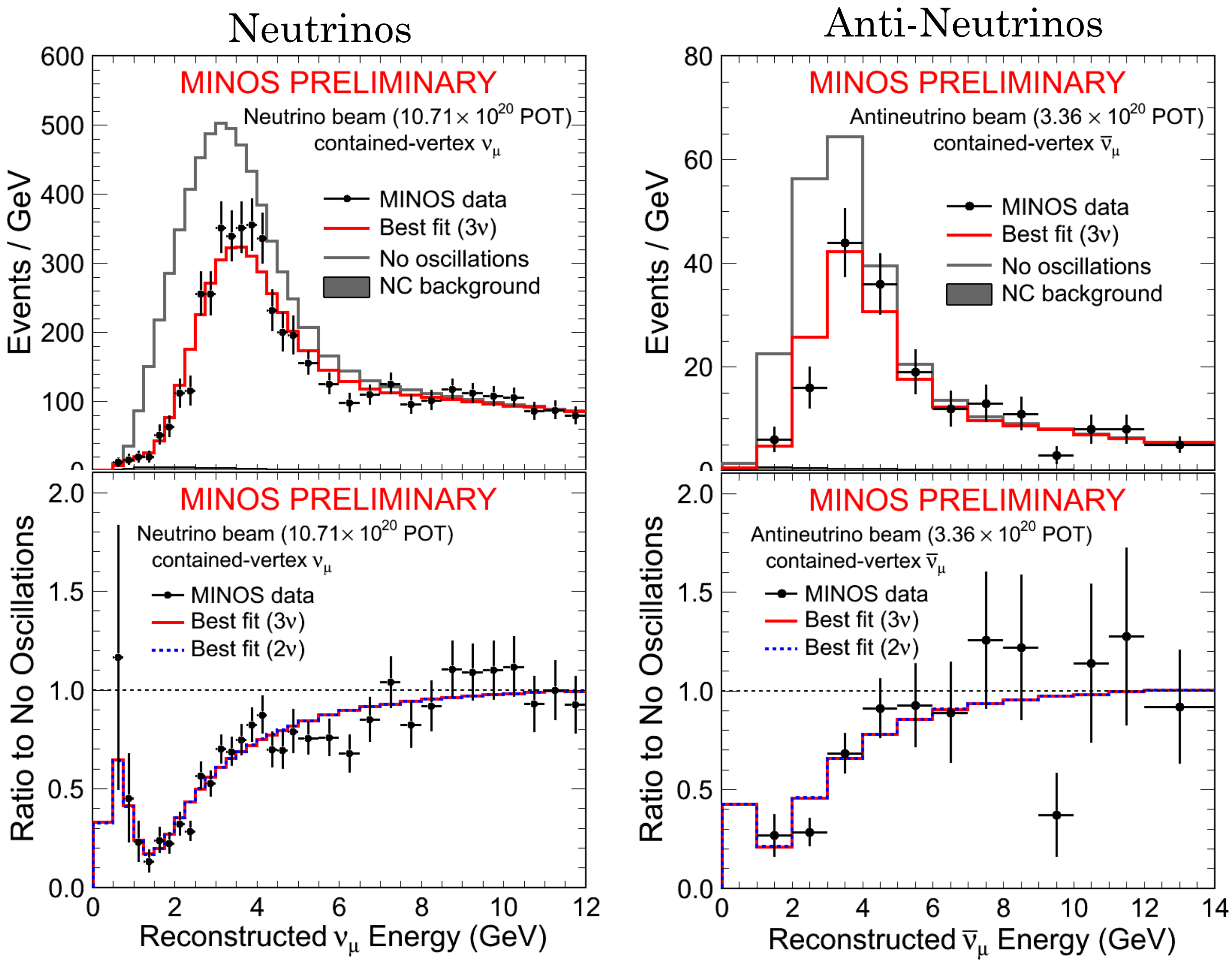
(and solar mixing parameters)

- Matter effects give rise to larger differences in multi-gev, upward atmospheric events
- Effect is seen in neutrinos or antineutrinos, depending on hierarchy
- MINOS first to probe effect with event-by-event charge separation



Far Detector Beam Samples

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



Far Detector Atmospheric Samples

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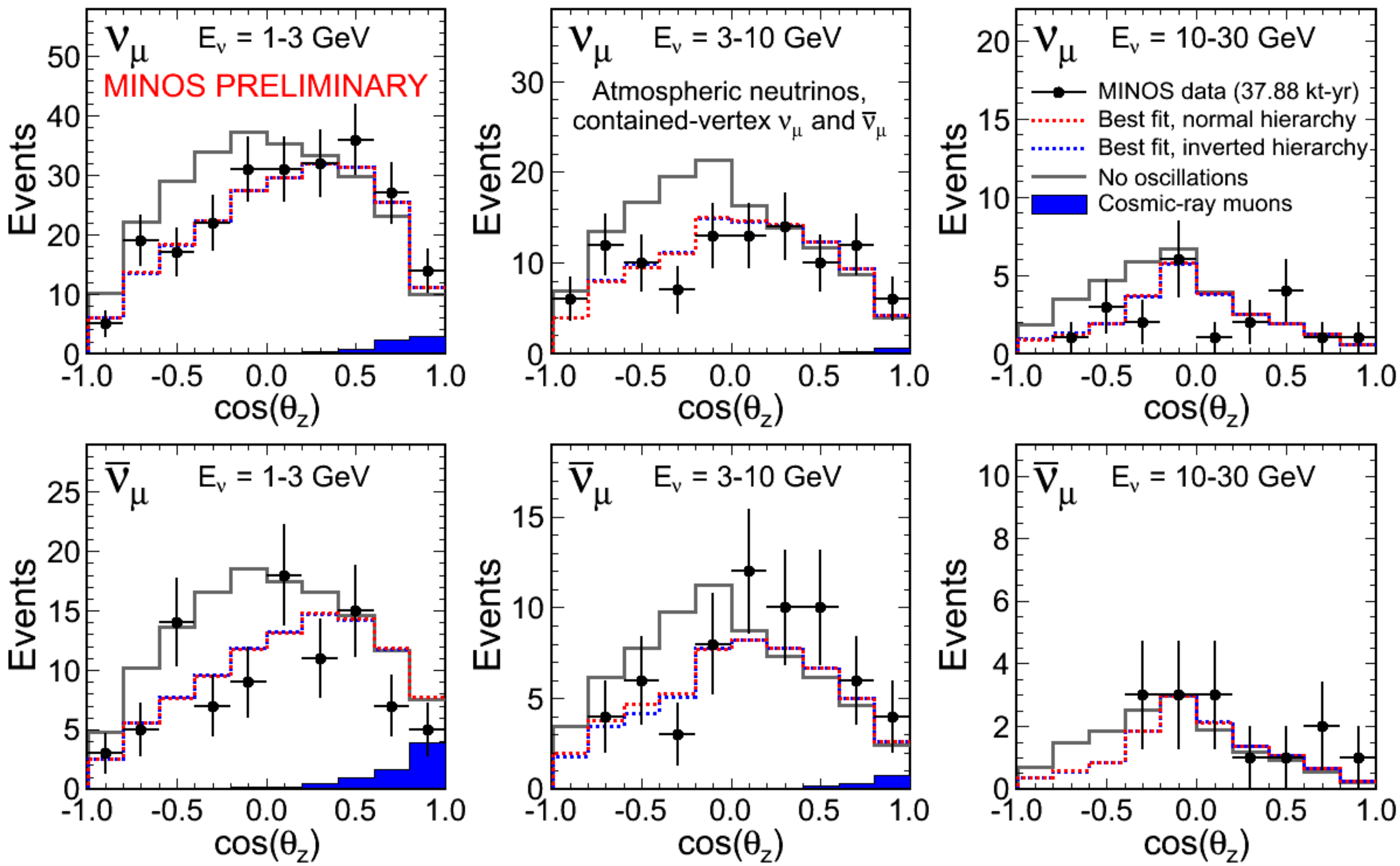


- Contained muon neutrino events shown
- Partially contained and shower events also included in fit

ELECTRON NEUTRINO APPEARANCE

- A few percent of the missing ν_μ could change into ν_e
- Including subdominant mode enhances sensitivity to 3 flavor effects

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

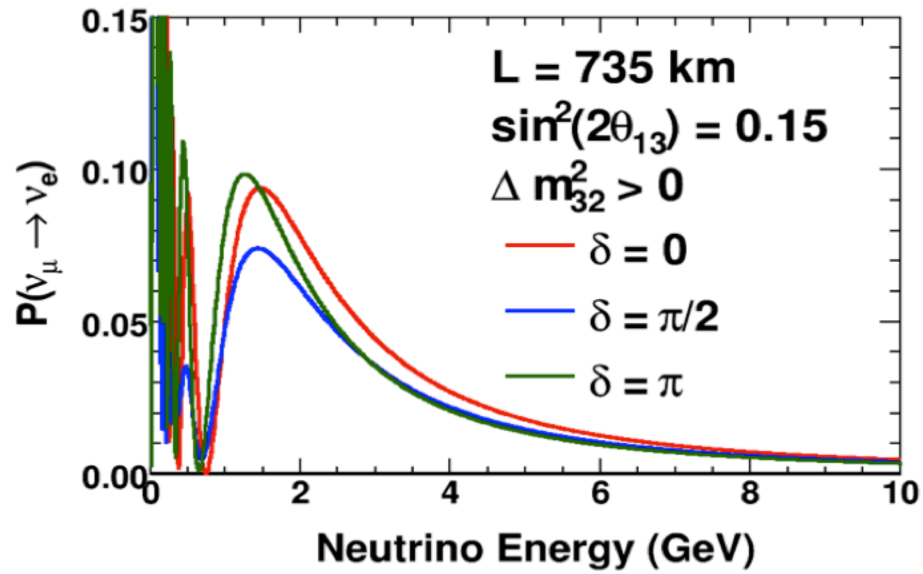
$$P_{atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

"Solar" Term
<1% in MINOS

Interference Term
- for neutrinos
+ for antineutrinos

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

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



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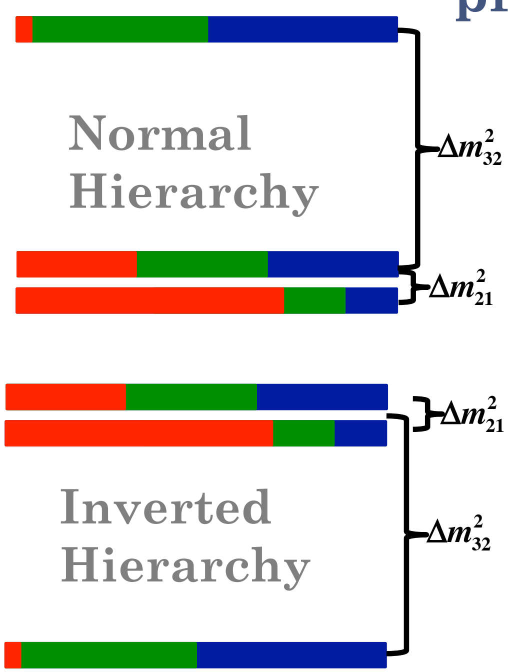
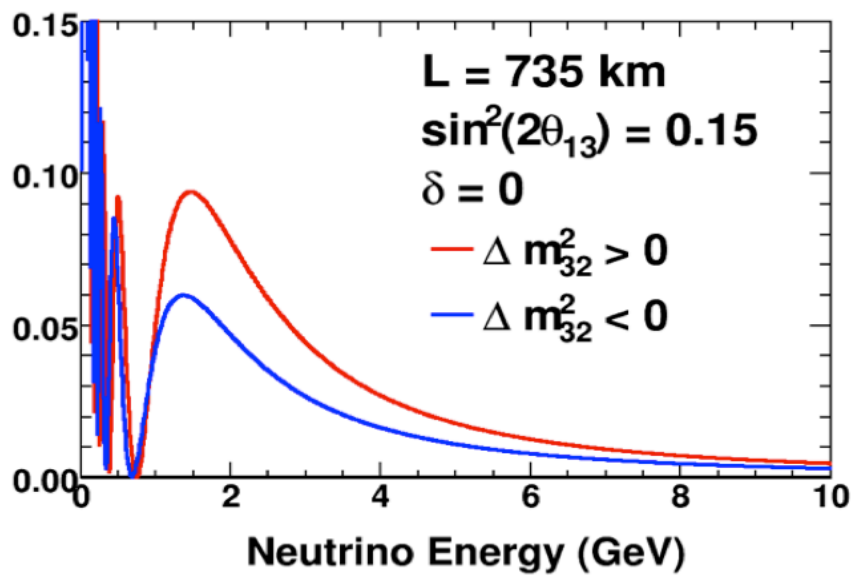
In matter, ν_e + e CC scattering modifies oscillation probability ~30% in MINOS





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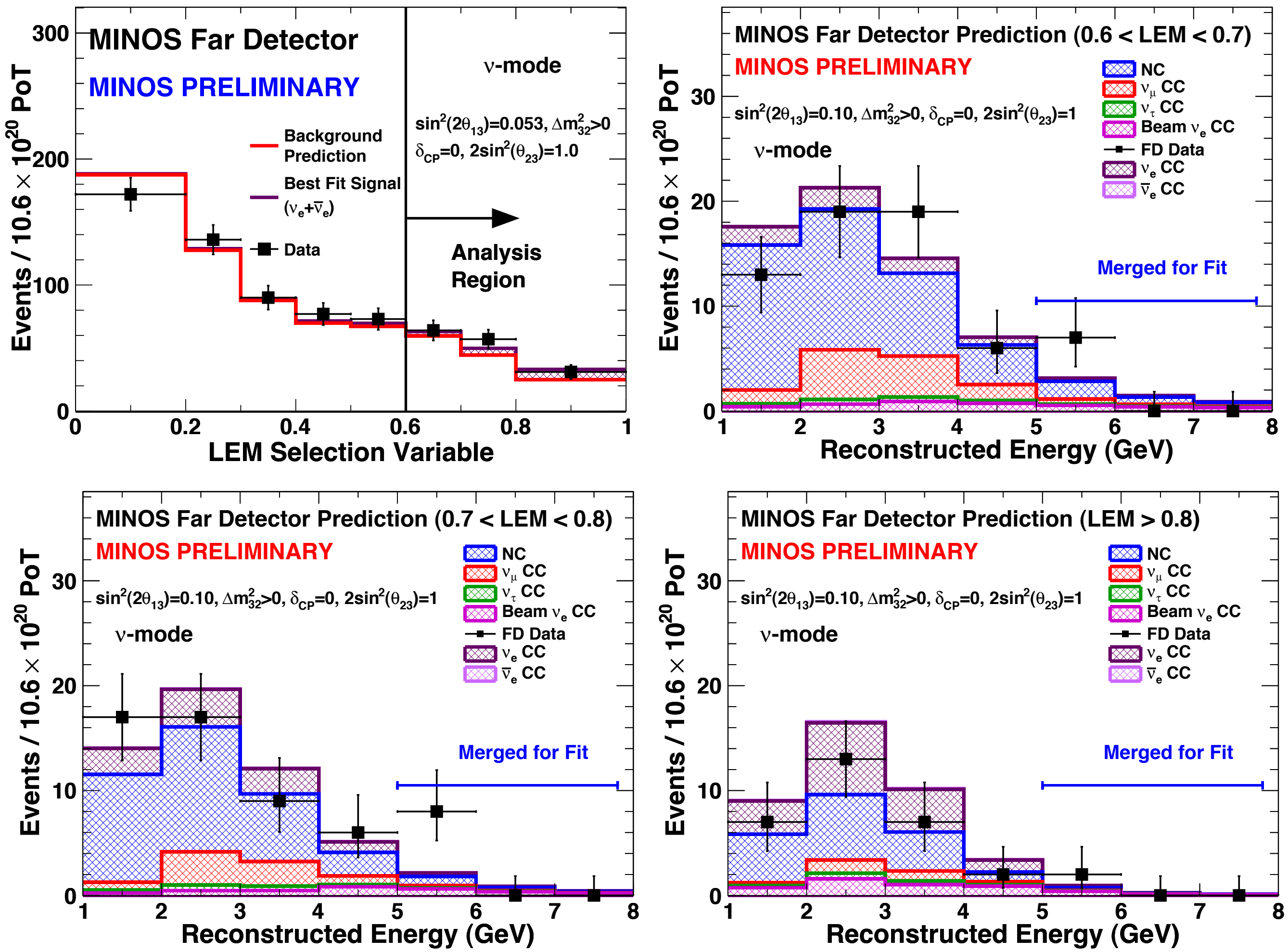
Electron Neutrino Appearance: FHC Beam

In Signal Enhanced Region:

- If θ_{13}=0: 69.1 BG Events
- If $\sin^2(2\theta_{13})$=0.1: +26.0 Events

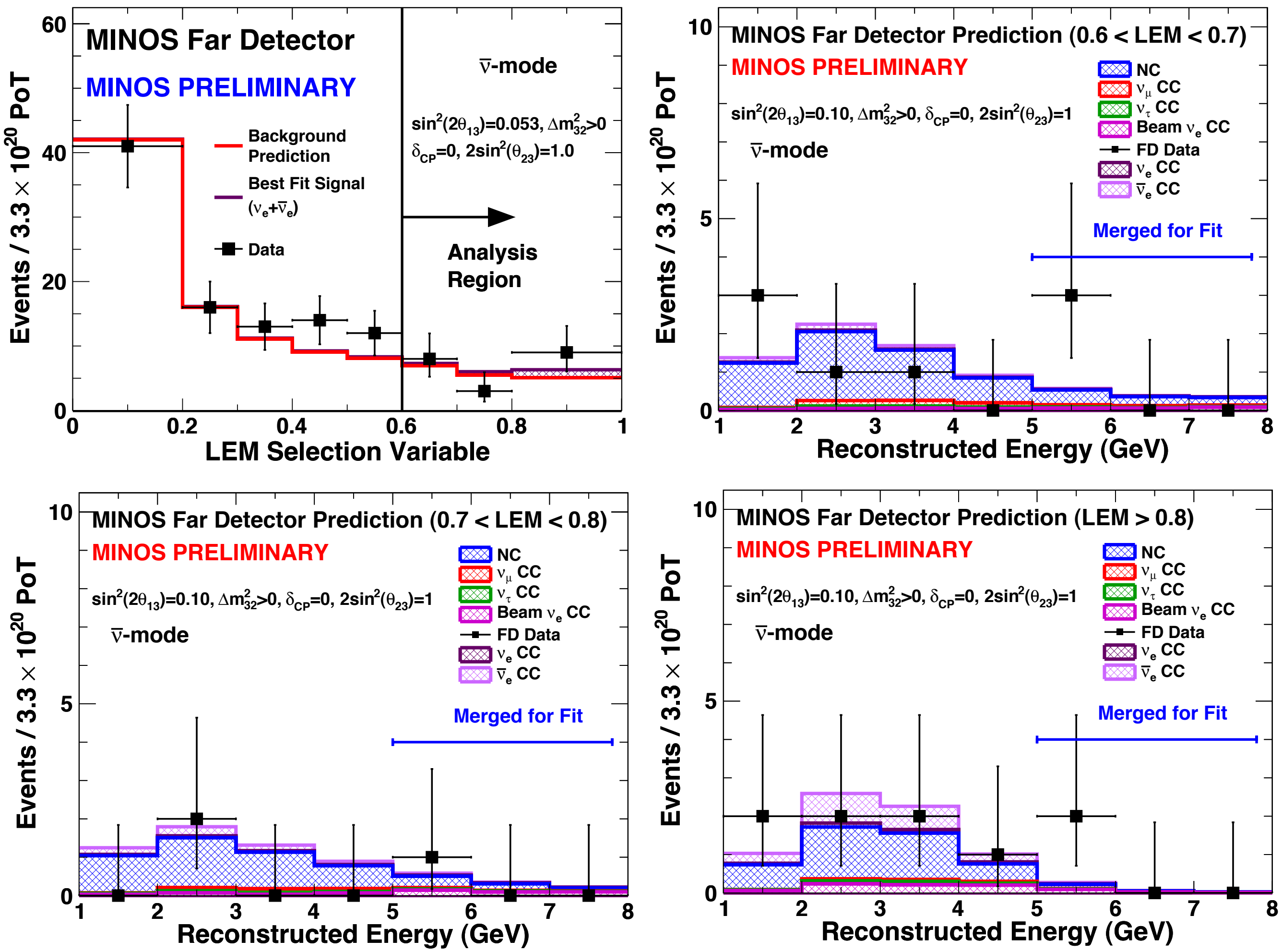
- Observe: 88 Events



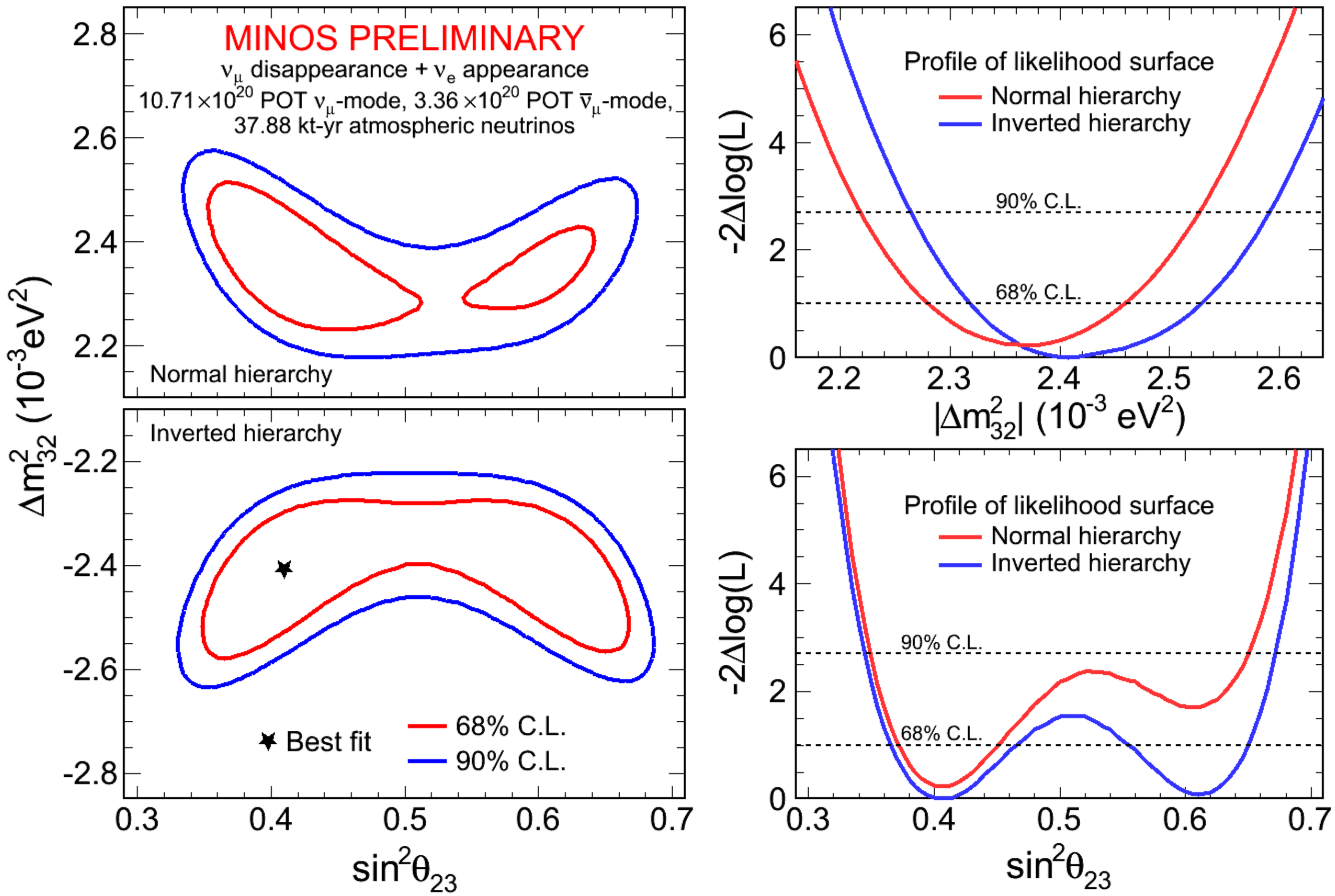
Electron Neutrino Appearance: RHC Beam

In Signal Enhanced Region:

- If θ_{13}=0: 10.5 BG Events
- If $\sin^2(2\theta_{13})$=0.1: +3.1 Events
- Observe: 12 Events



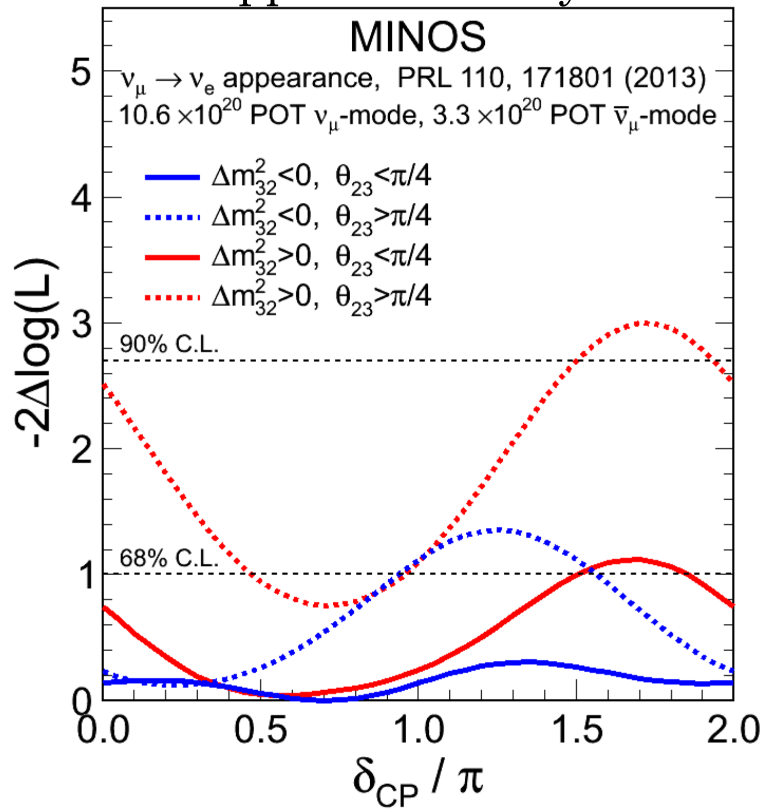
PUTTING IT ALL TOGETHER



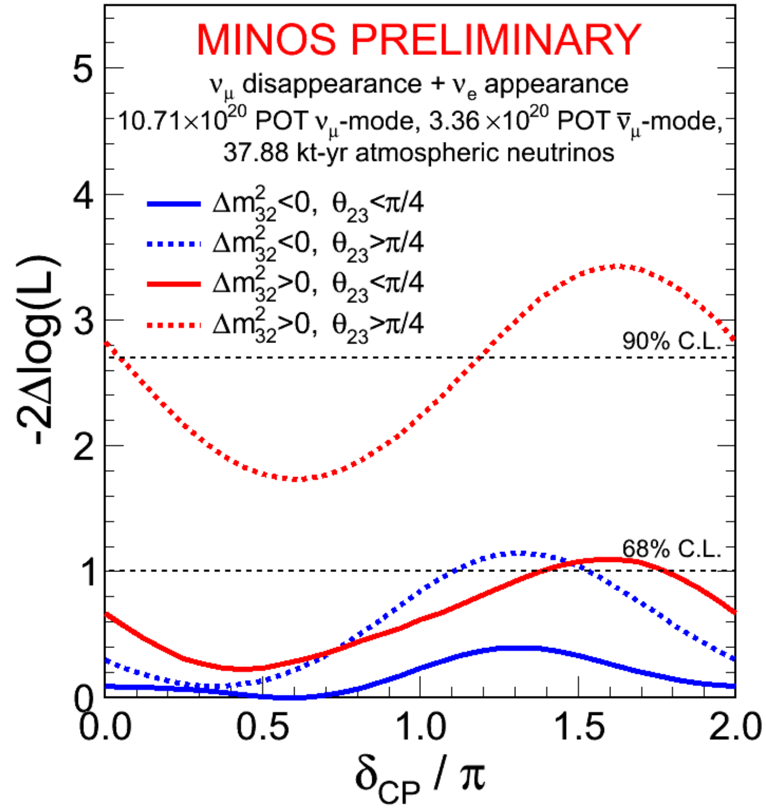
- Solar mixing parameters fixed
- θ_{13} fit as nuisance parameter, constrained by reactor results
- δ_{CP}, θ_{23}, Δm^2 unconstrained
- major systematic uncertainties included as nuisance parameters

Delta Dependence

Appearance Only



Appearance+Disappearance



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

Results

Hierarchy, Octant	Best fit oscillation parameters 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: $-2\Delta\log L = 0.23$

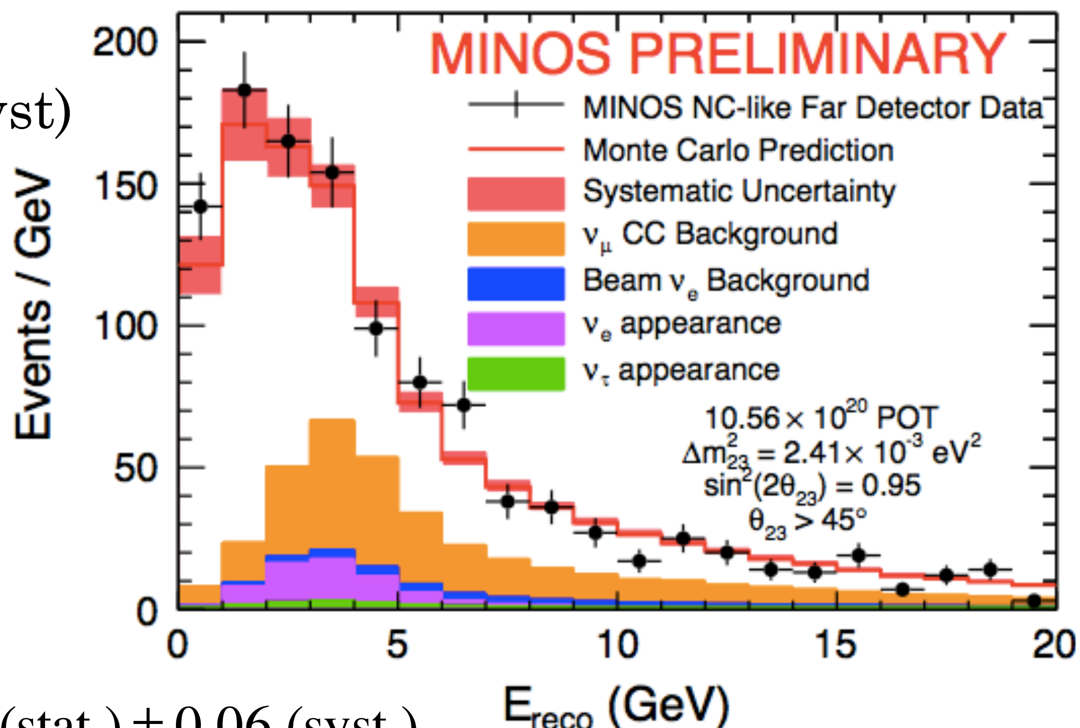
Preference for lower octant: $-2\Delta\log L = 0.09$

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

Sterile Neutrino Mixing

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



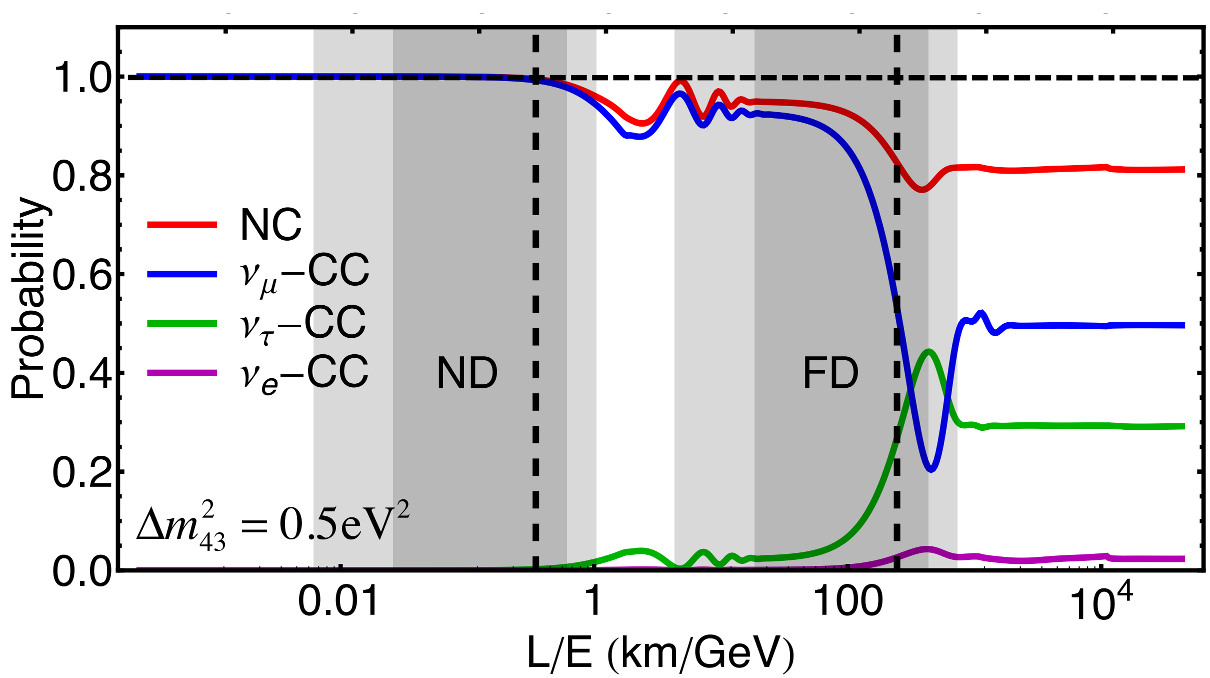
$$R = \frac{N_{data} - BG}{S_{NC}}$$

$0-200$ GeV: 1.05 ± 0.05 (stat.) ± 0.06 (syst.)

$0-3$ GeV: 1.09 ± 0.06 (stat.) ± 0.08 (syst.)

4 FLAVOR OSCILLATIONS

- Mixing with steriles also causes anomalous disappearance of muon neutrinos

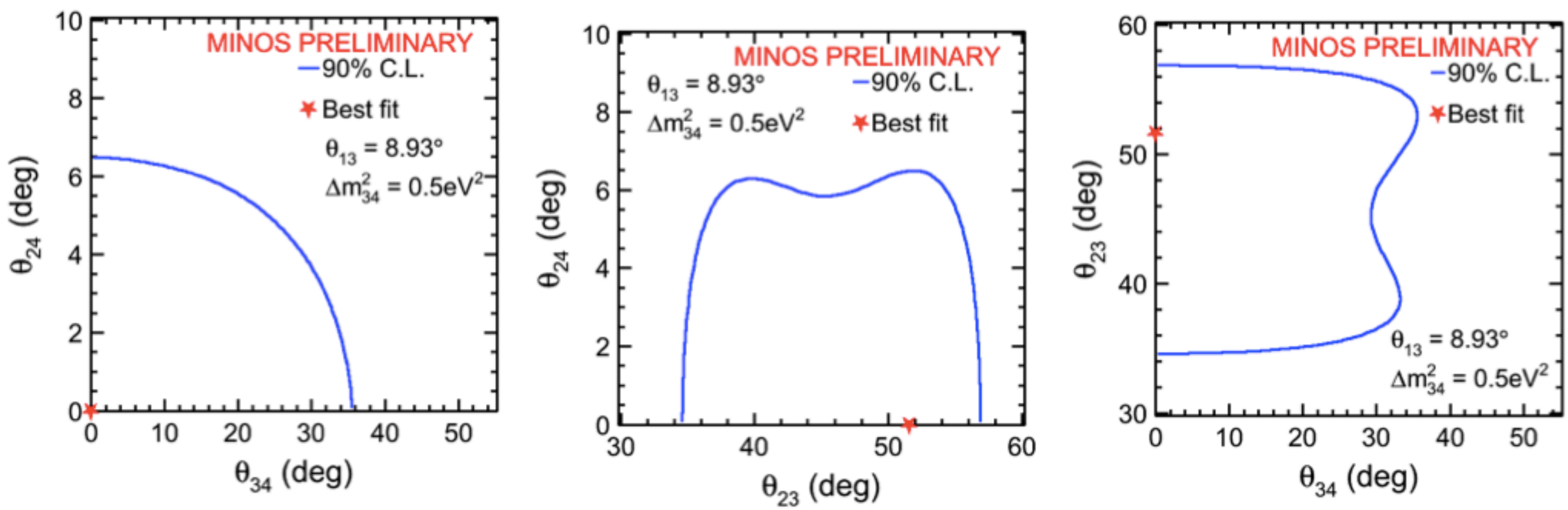


- Three regimes:
  - small Δm^2: wiggles in FD at high energies
  - medium Δm^2: rapid FD wiggles average out
  - large Δm^2: oscillations occur in ND

Tricky

Just Right

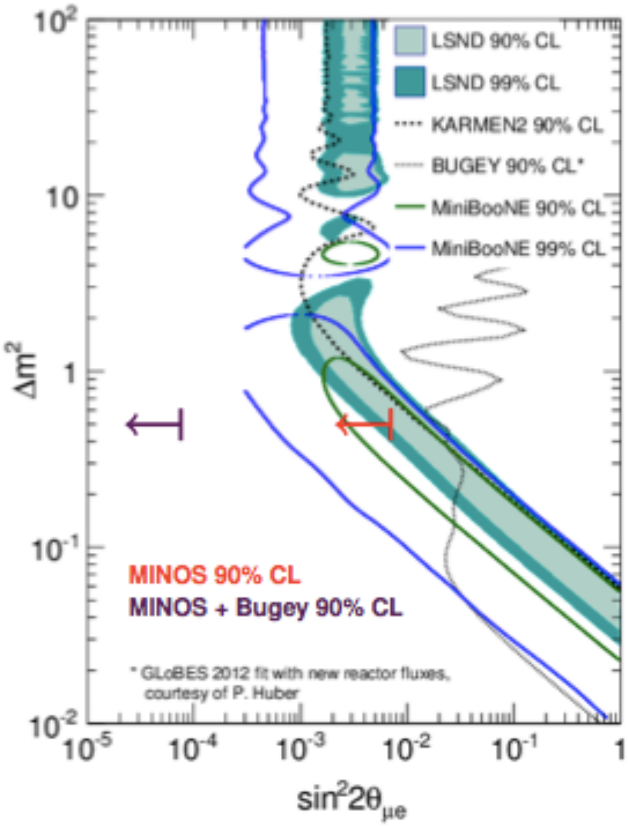
LIMITS ON THE ANGLES



- slight preference to upper θ_{23} octant
- $\theta_{34} < 24^o$ at 90% C.L.
- $\theta_{24} < 5^o$ at 90% C.L.

Comparison to MiniBooNE

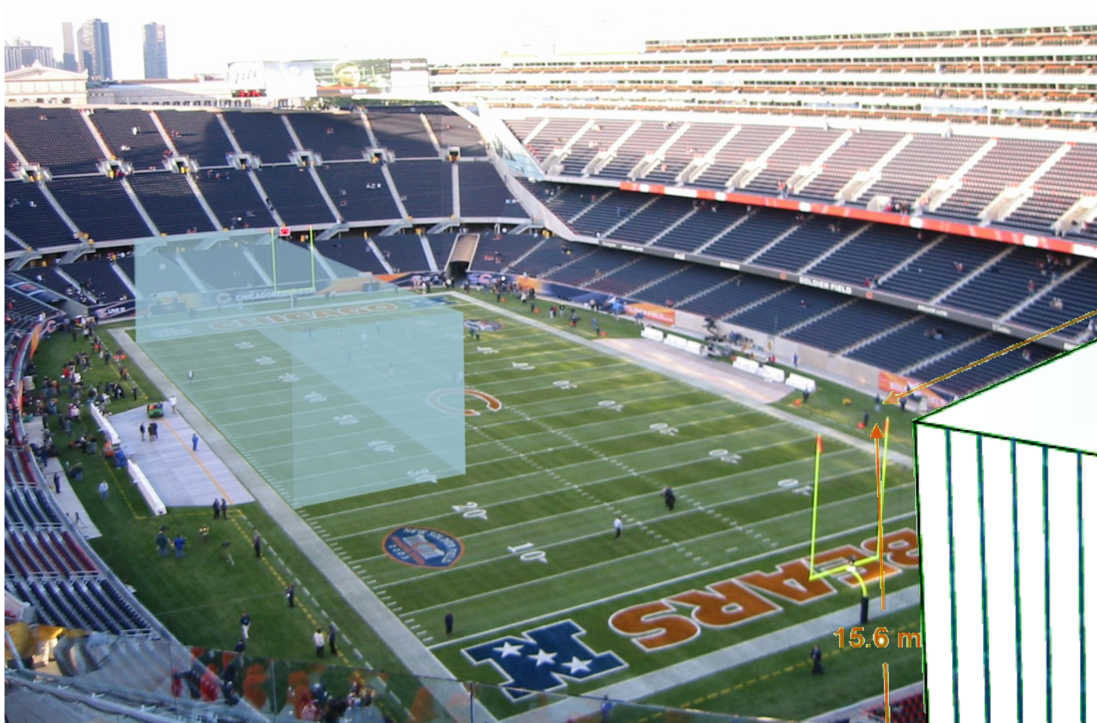
- Our limit on θ_{24} can be combined with Bugey limit on θ_{14} for comparison with MiniBooNE/LSND
- Stay tuned for the extension to higher and lower mass splittings
- MINOS+ will continue to pursue this analysis mode

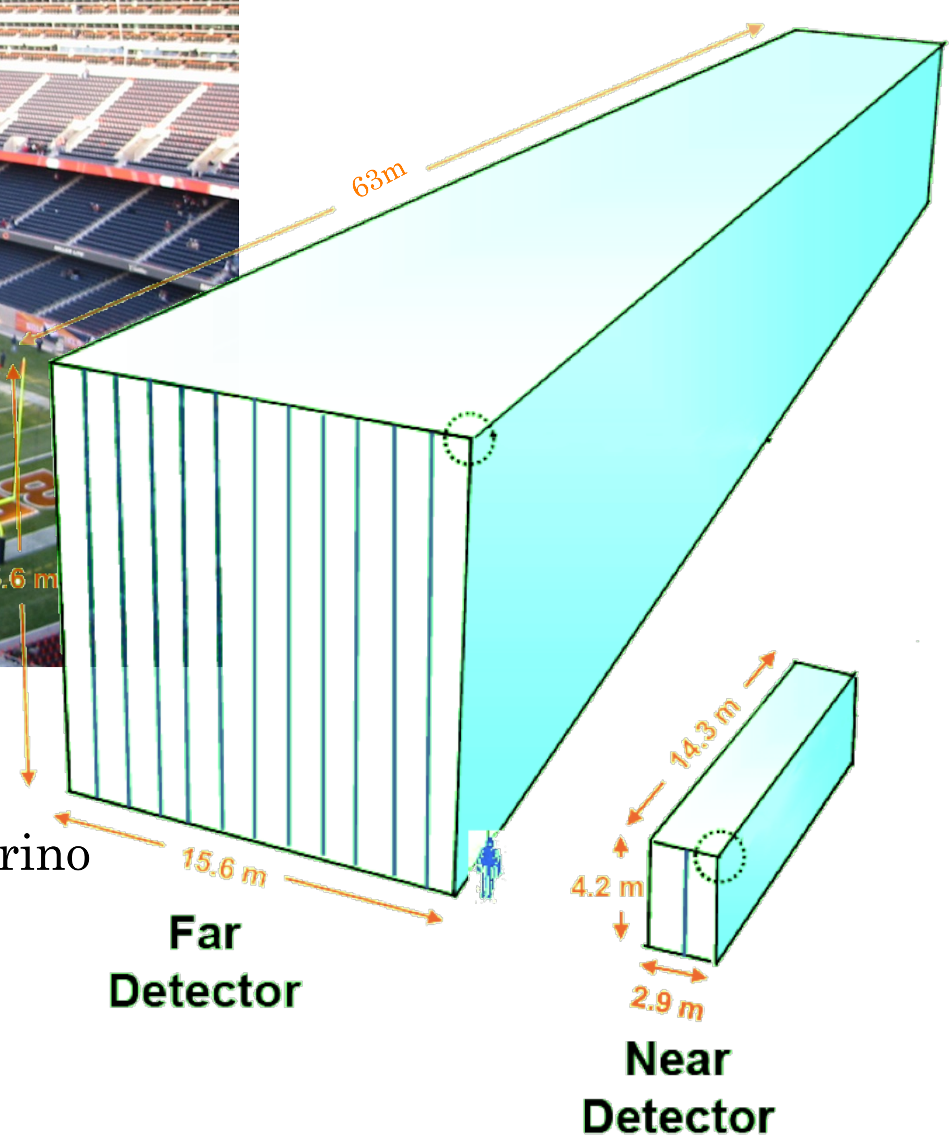


$\sim \sin^2(2\theta_{14})\sin^2\theta_{24}$

NOvA

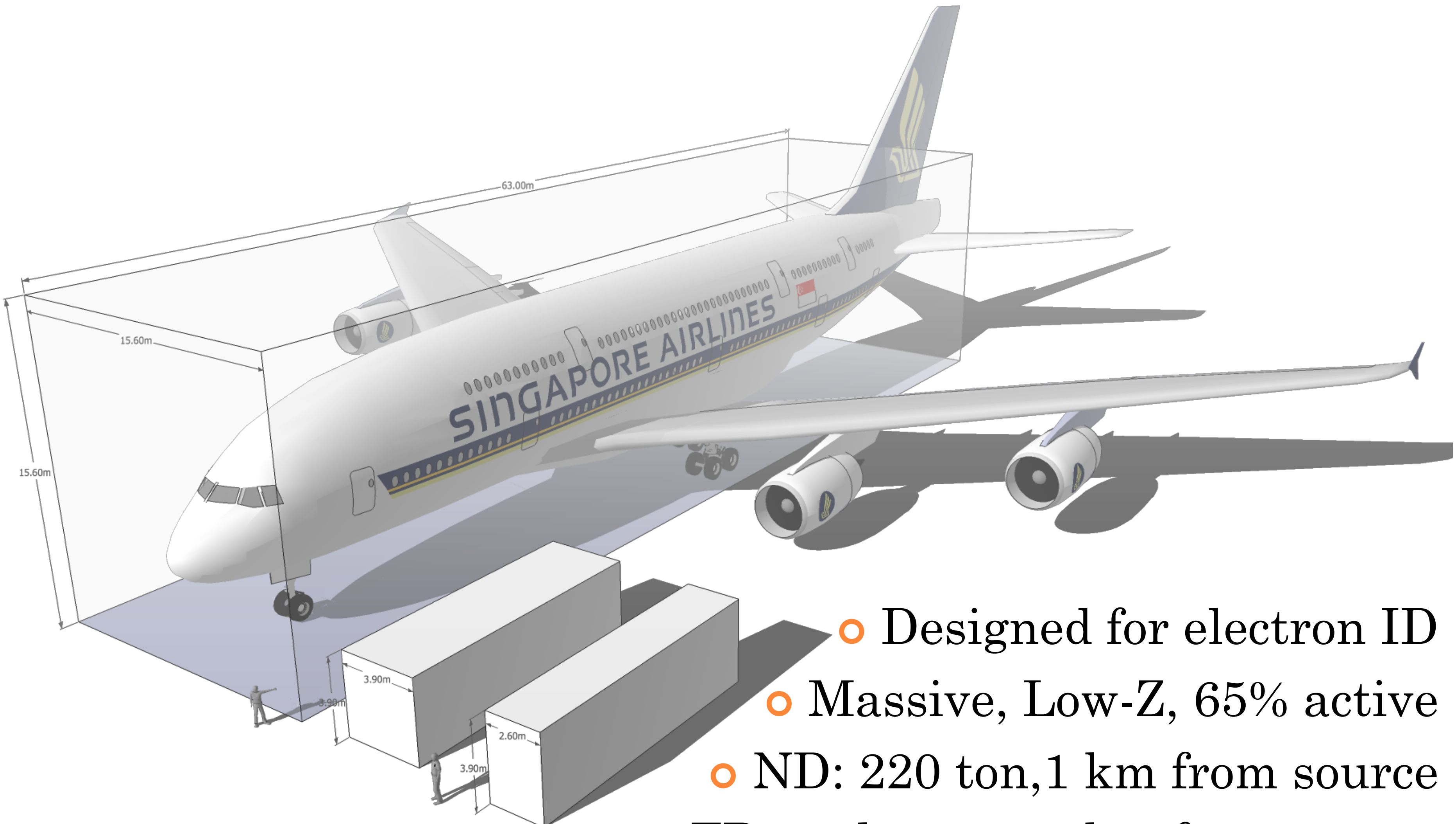
THE NOvA EXPERIMENT





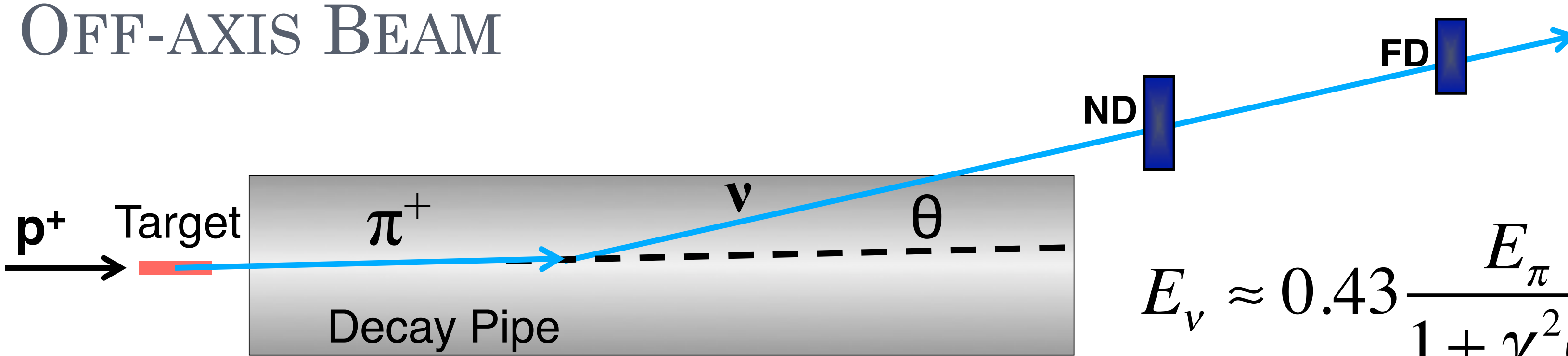
- Study electron neutrino/antineutrino appearance
  - mass hierarchy, delta CP, octant
- Higher precision muon neutrino disappearance
- Exotics
  - monopoles, dark matter, supernova, etc.

The NOvA Detectors



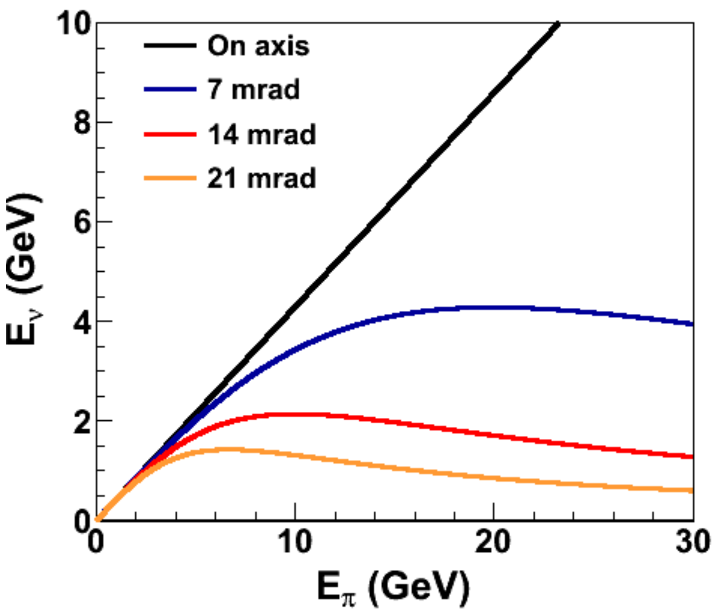
- Designed for electron ID
- Massive, Low-Z, 65% active
- ND: 220 ton,1 km from source
- FD: 15 kton, 810 km from source

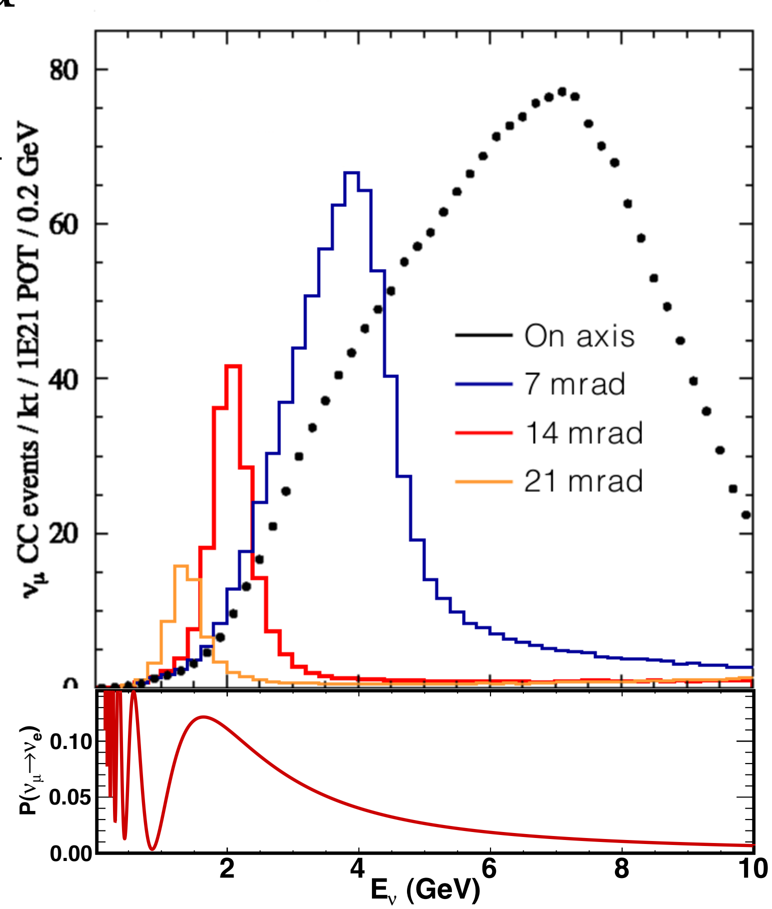
Off-axis Beam



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

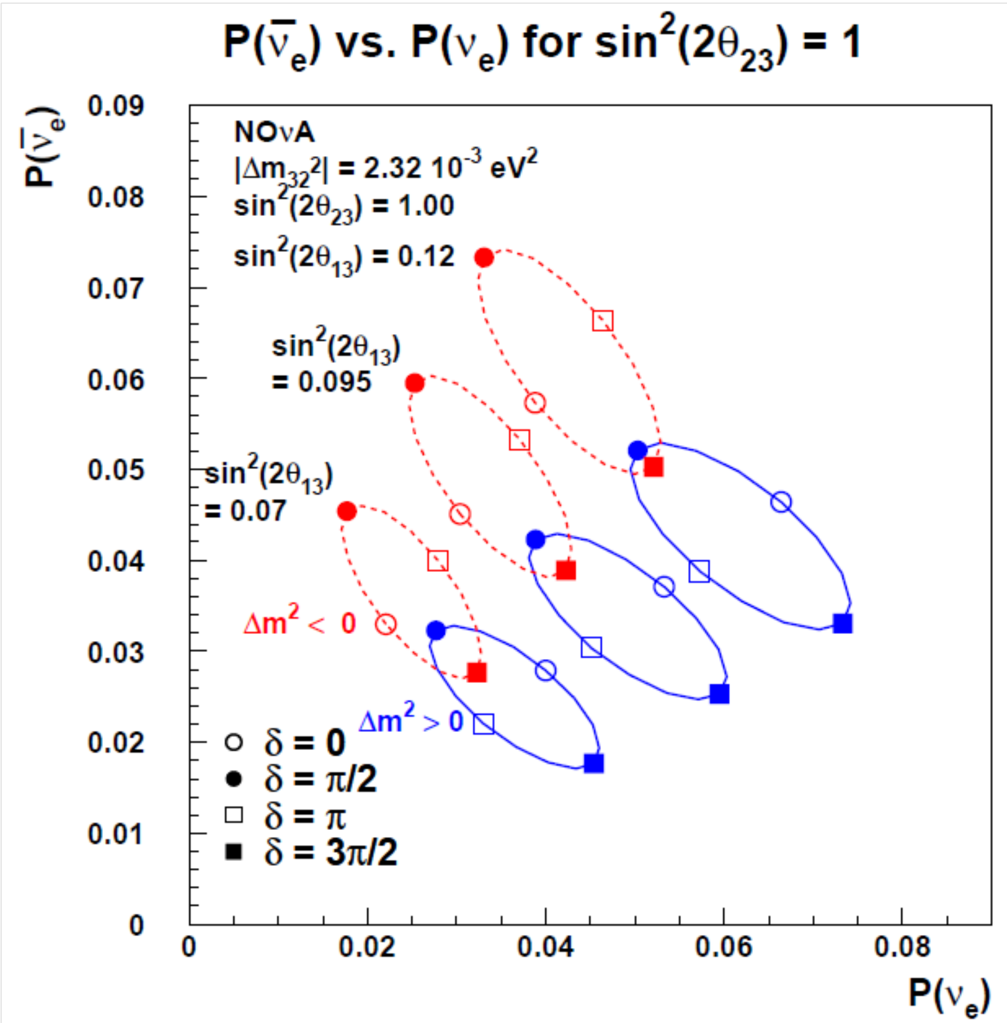
- 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events





How its done

- Compare oscillation probability measured with neutrinos and antineutrinos

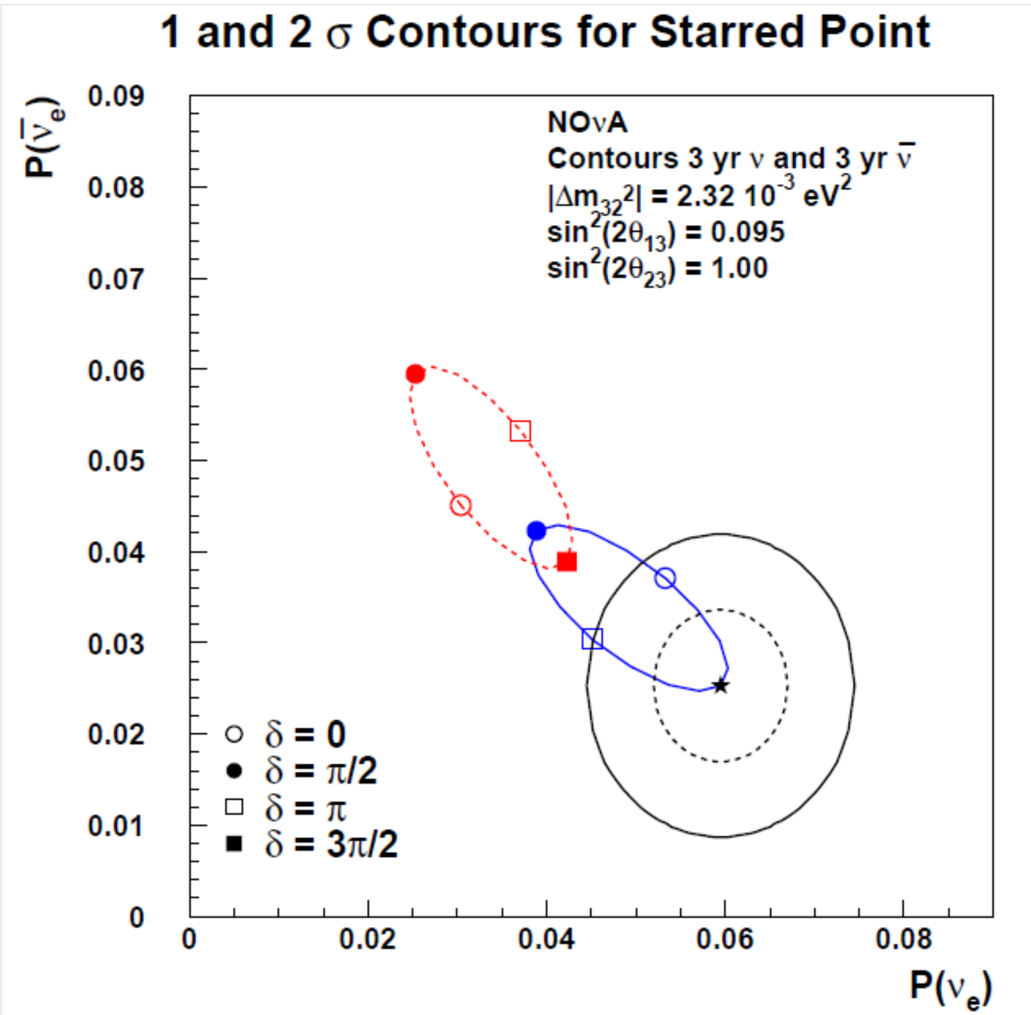


Events ($\sin^2(2\theta_{13})=0.095$)	ν	anti-ν
NC	19	10
ν_μ CC	5	<1
beam ν_e	8	5
Tot. BG	32	15
Signal	68	32

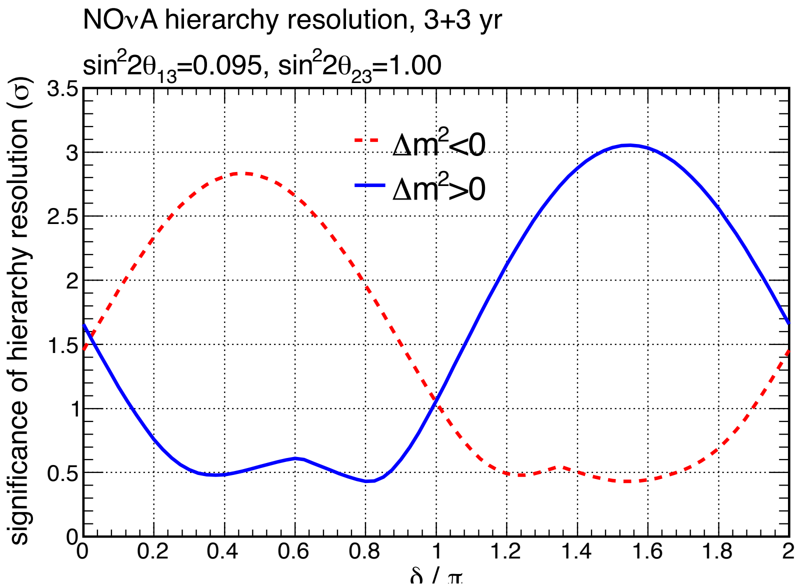
"Representative" event counts from 3 years neutrinos+3 years antineutrinos

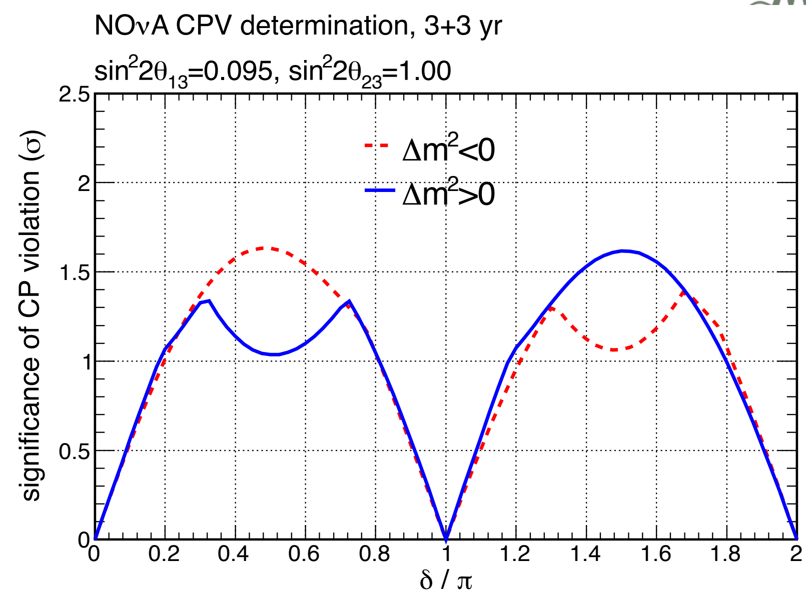
How its done

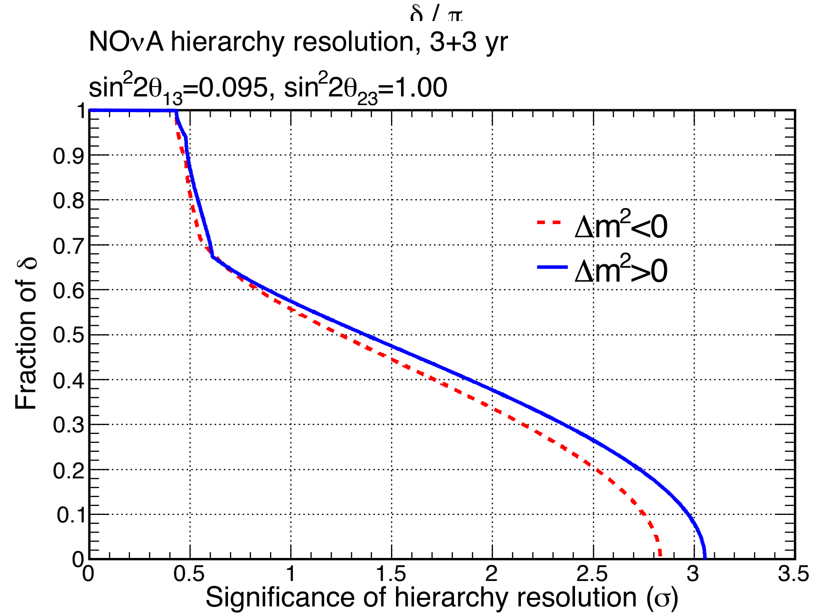
- Compare oscillation probability measured with neutrinos and antineutrinos

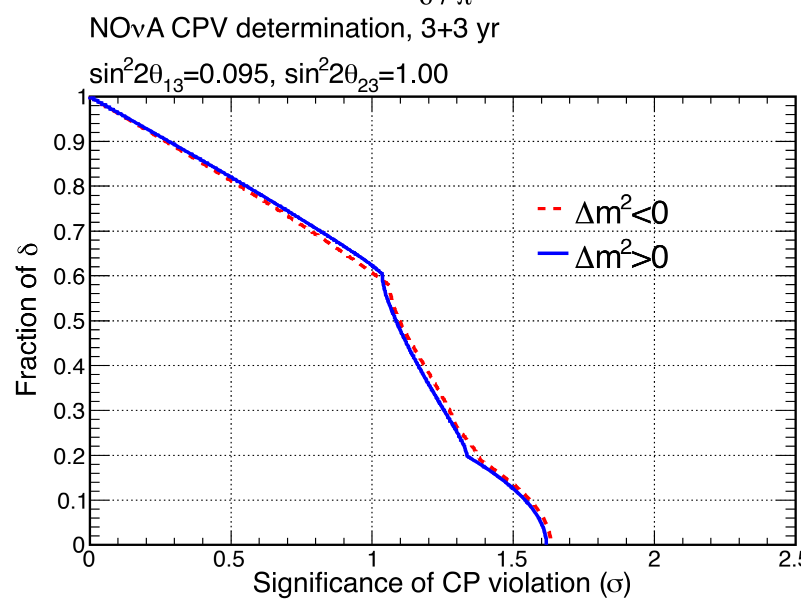


Mass Hierarchy & Delta CP



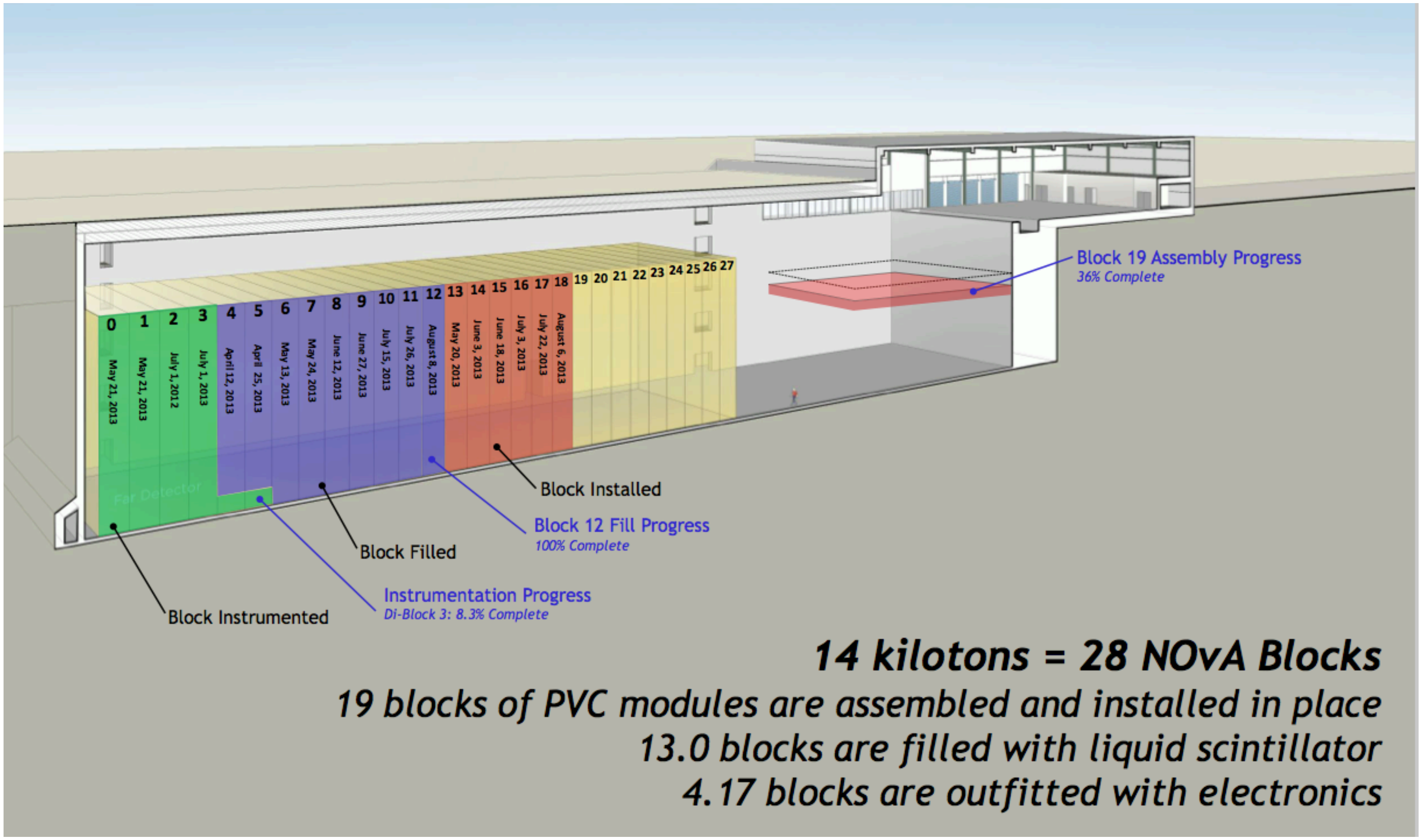




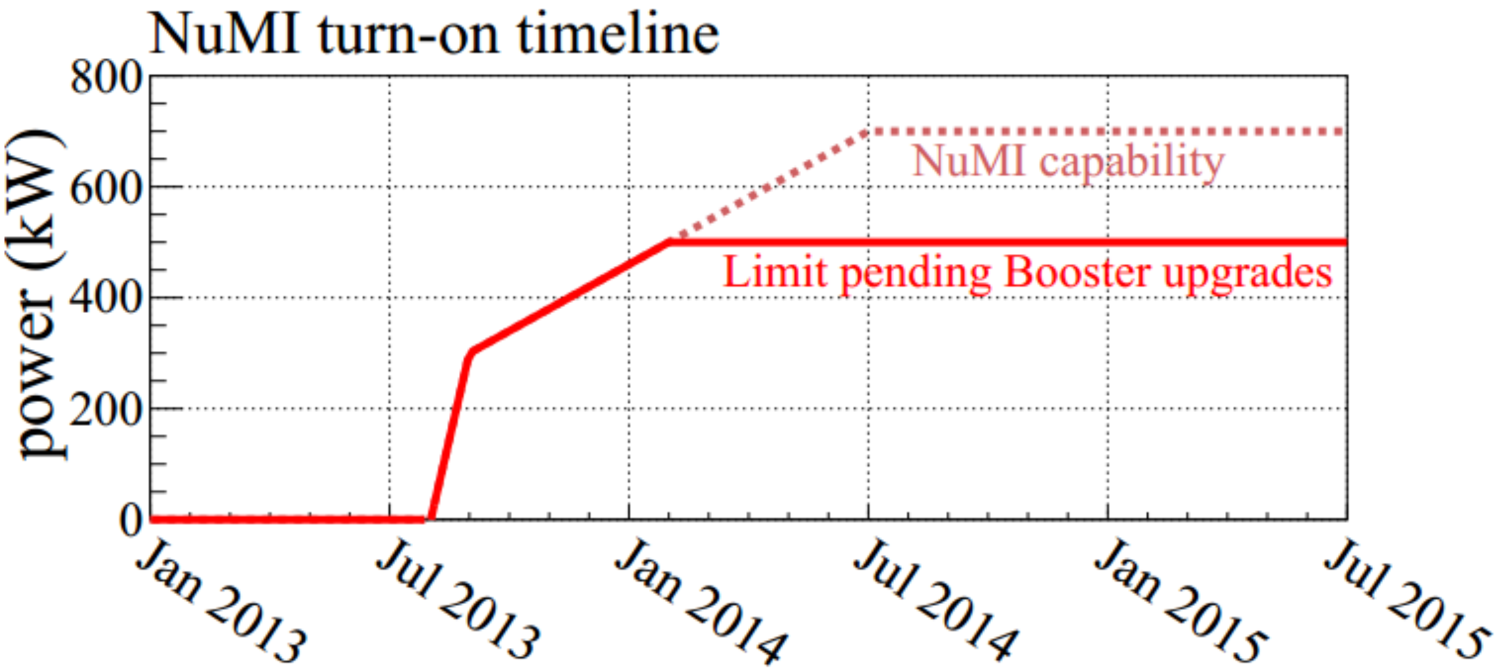


NOvA+T2K—shorter baseline helps when hierarchy/CP effects conspire to cancel each other out in NOvA

DETECTOR STATUS



BEAM STATUS

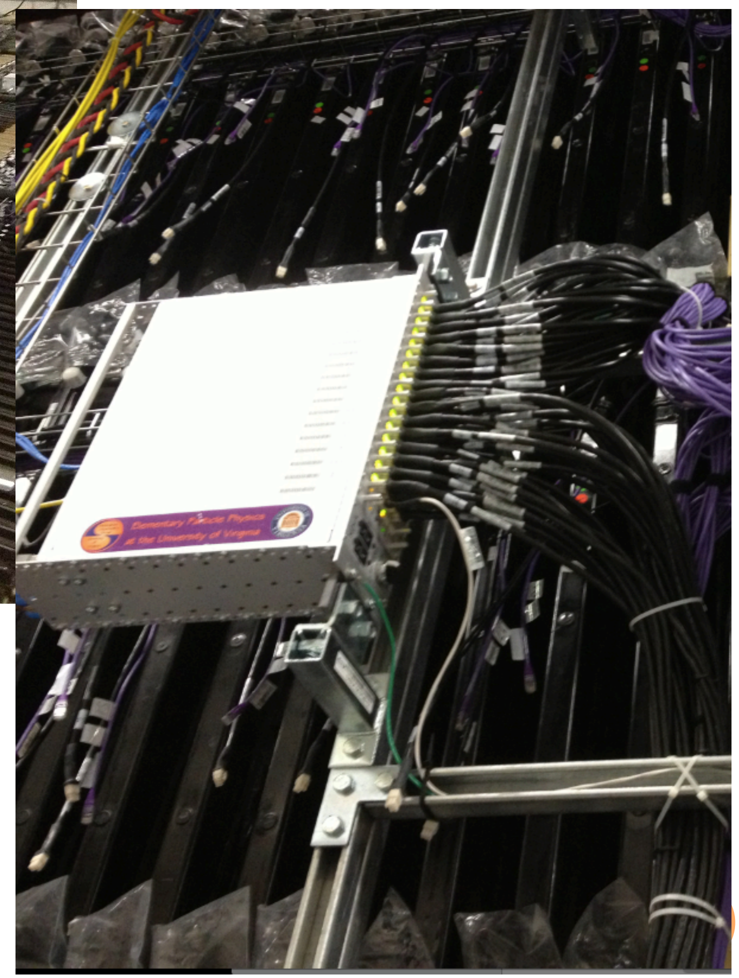


- Beam Commissioning started
  - corrosion in MI beam pipe, repairs underway
- Routine beam operation expected in September
- First year power expected to be 500 kW
  - Limited by Booster until RF upgrades completed

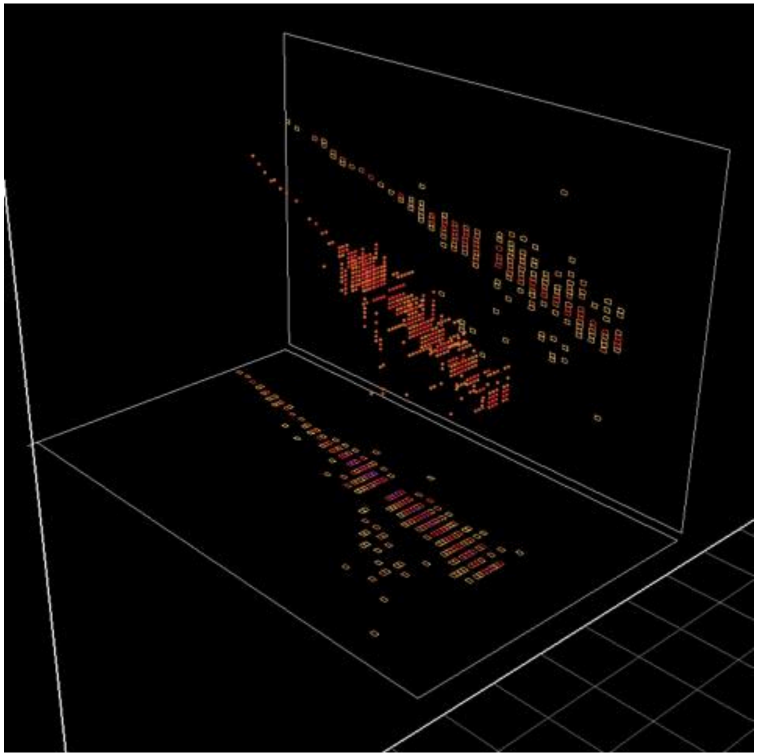
Detector Status

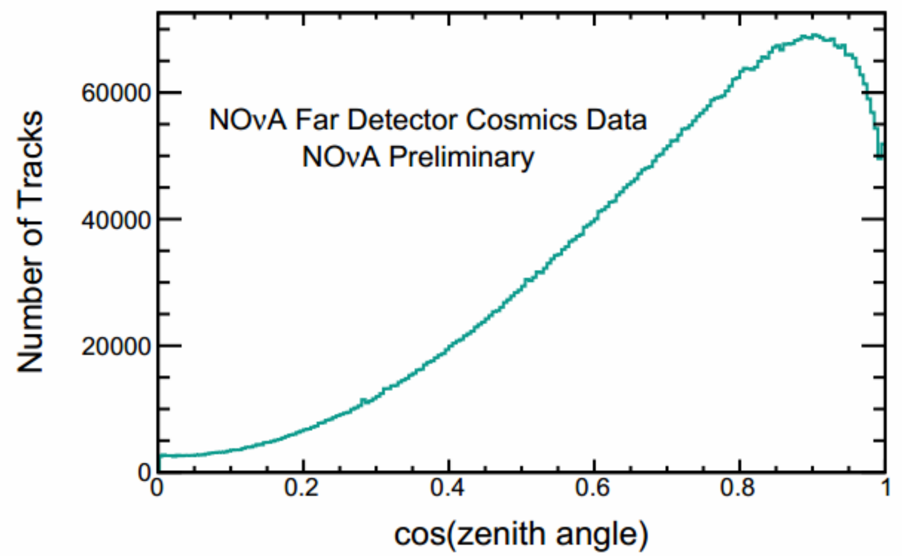
Detector Status

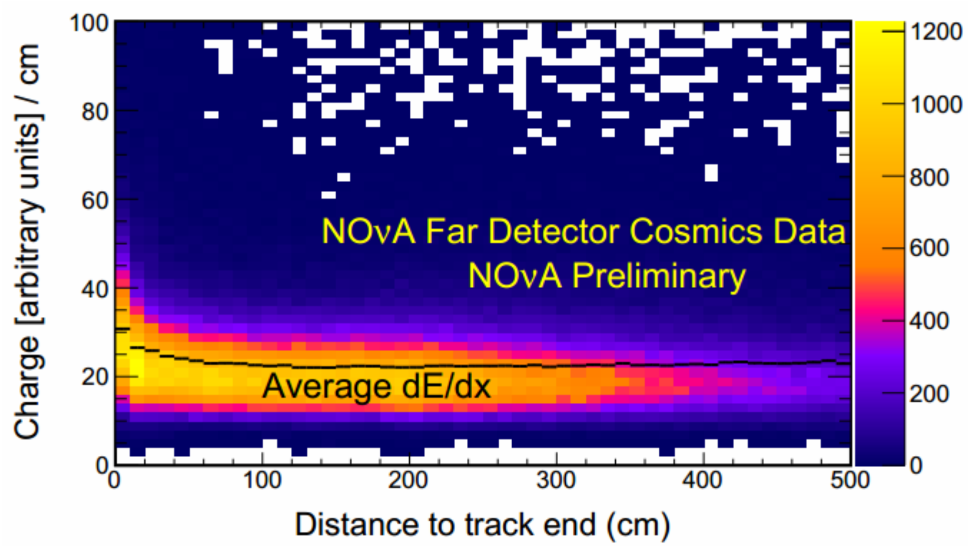
DETECTOR STATUS



Far Detector Data



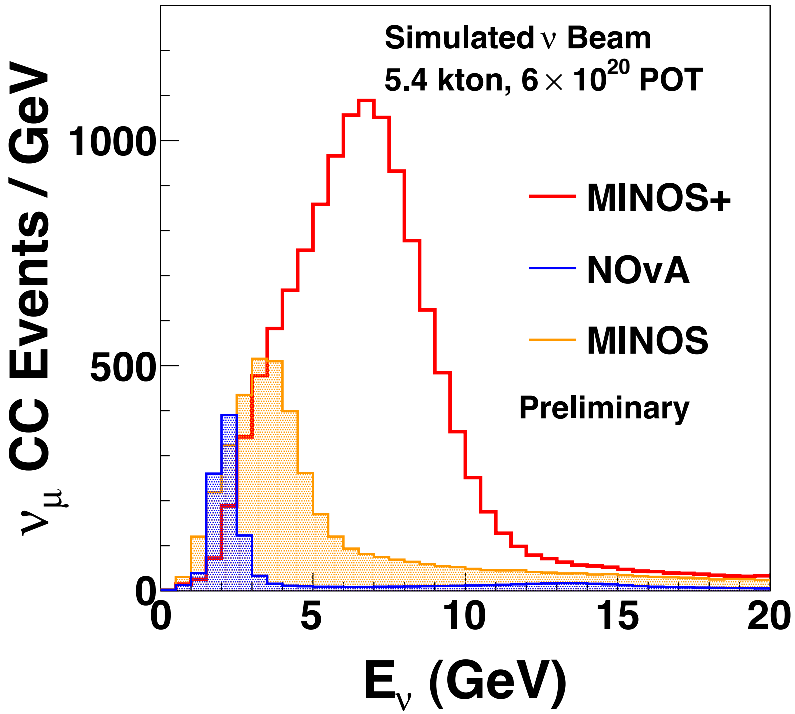


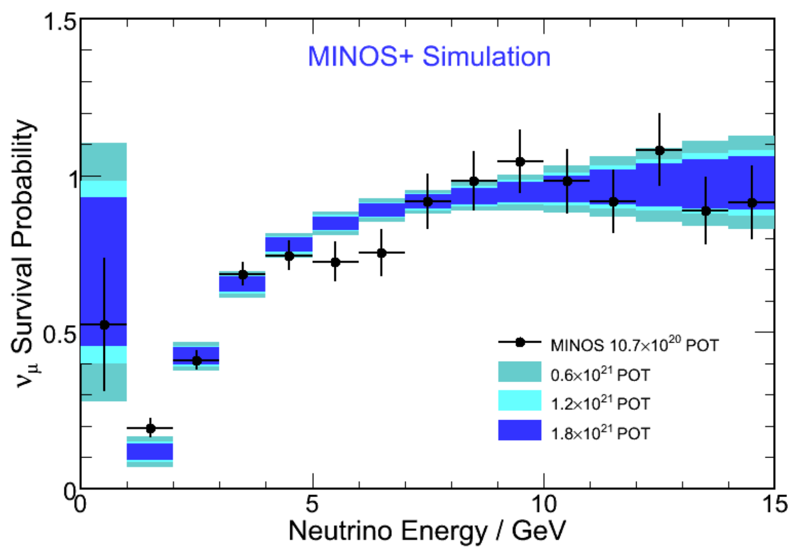


- 2 ktons instrumented
- We see cosmics!
- Reconstruction algorithms tested on cosmic ray data collected

MINOS+ AND BEYOND

MINOS+

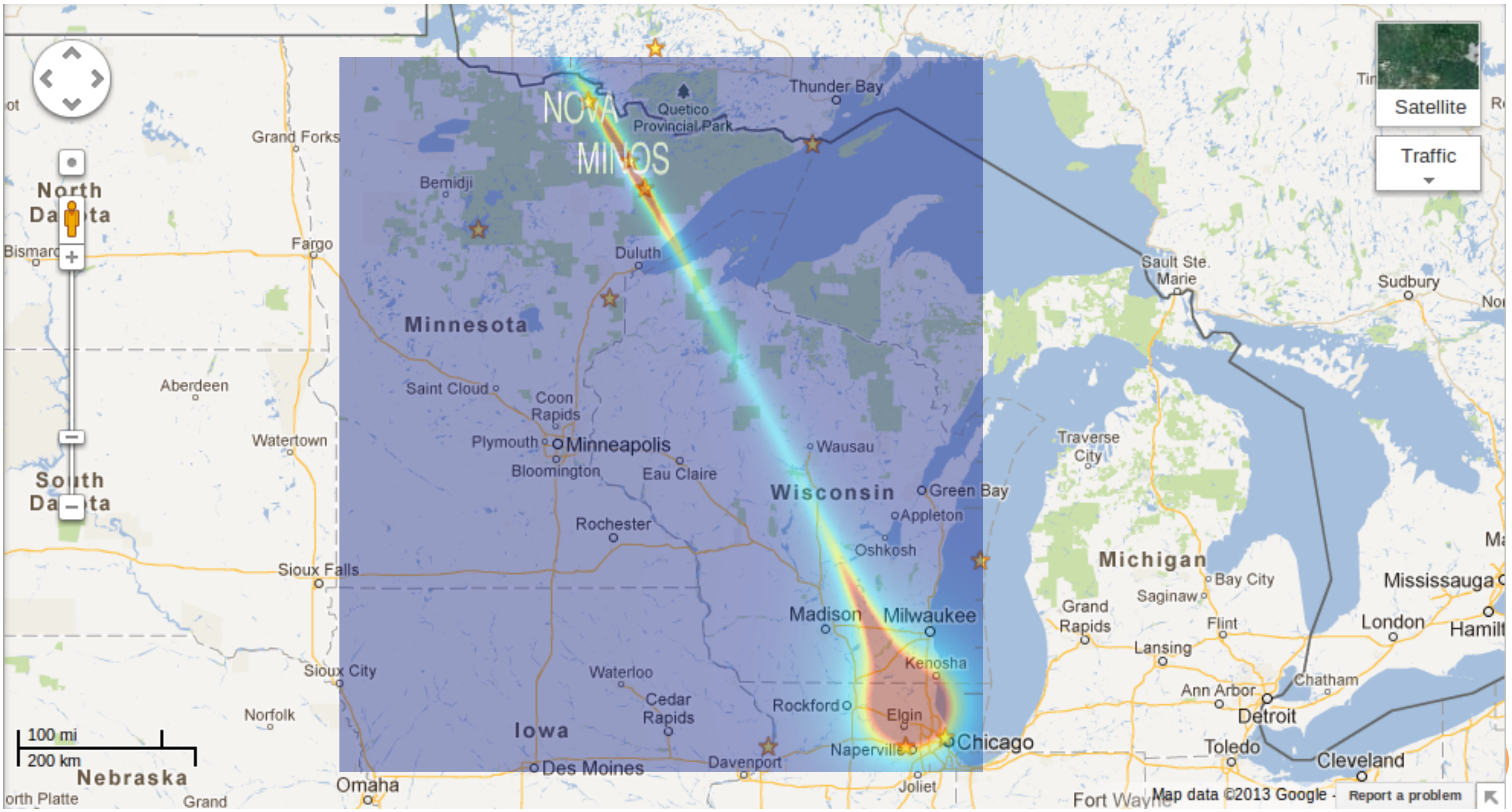




- MINOS will continue to run in the NOvA era
- ME beam peaks above the oscillation dip on axis
- But we get a lot of events!
  - ~4000 muon neutrino CC events per year expected at FD
  - ~80 tau neutrino CC events (with a lot of background)
- Unique test of oscillation paradigm with sensitivity to exotic signals

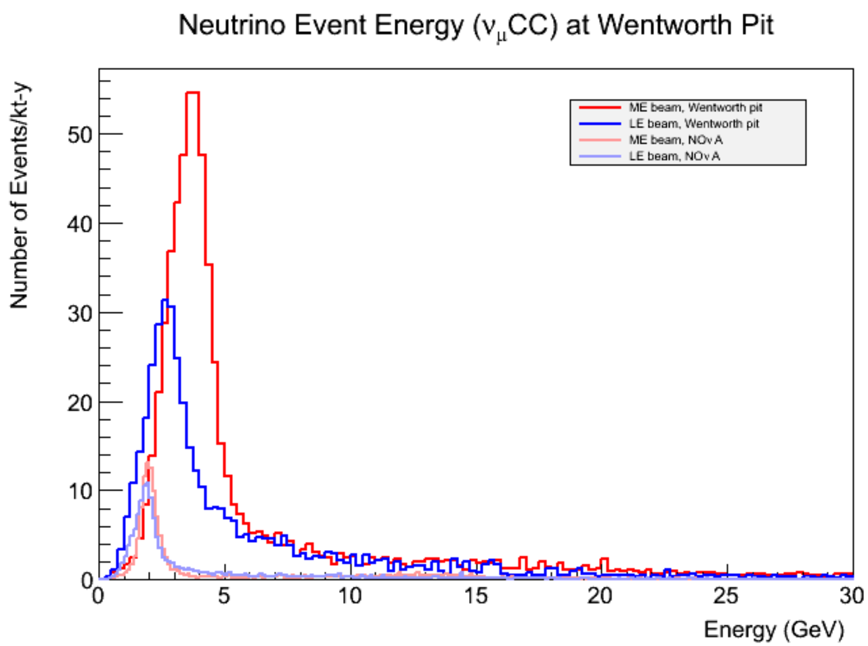
Even more NuMI

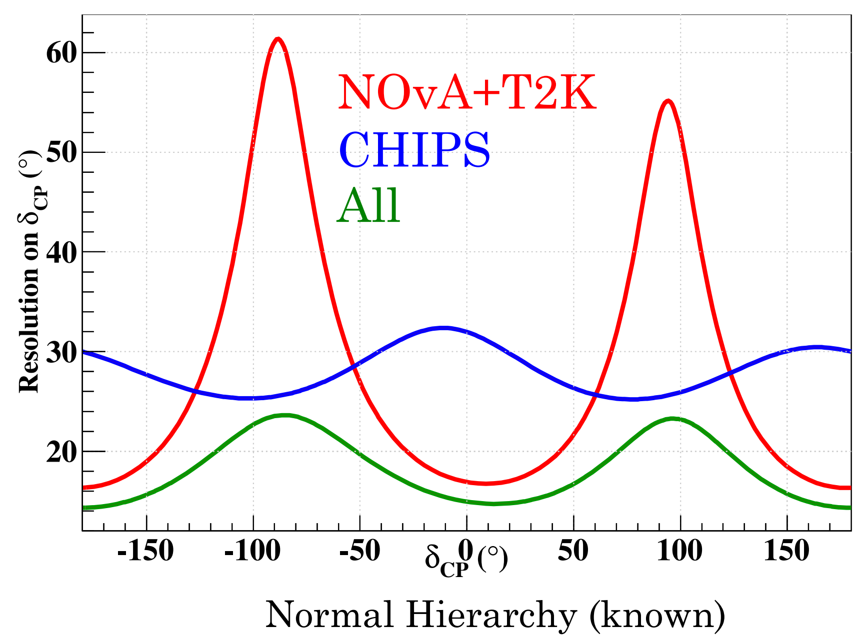
- Additional detectors in the NuMI beam can provide cost-effective, world class neutrino physics



CHIPS

- 100 kton water Cherenkov detector
  - installed in water filled mine pit
  - no need for large (expensive) structure
- Wentworth Pit is 7mrad off-axis in NuMI beam
  - an opportunity for measurements of delta CP





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CHIPS

- Deploy from industrial floating fishery platform
  - Replace nets with PVC + KEE roofing membranes
  - Idea for floating deployment developed by Madison group for LBNE WC, based on Ice Cube technology
- Reinstall in LBNE beam line once operational
- R&D plan for a 10kton proof-of-principle under development
- LOI submitted to Snowmass, FNAL PAC arXiv:1307.5918

Conclusions

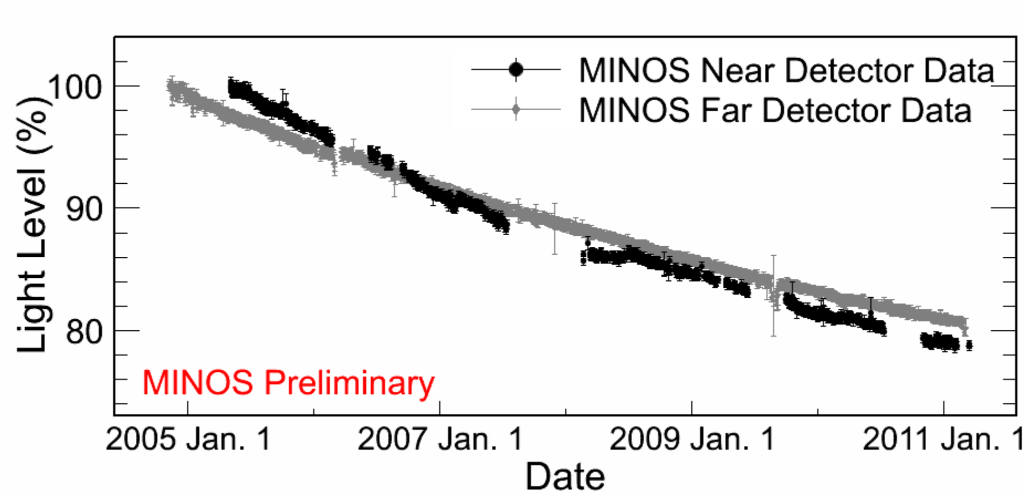
- New MINOS 3 flavor results

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

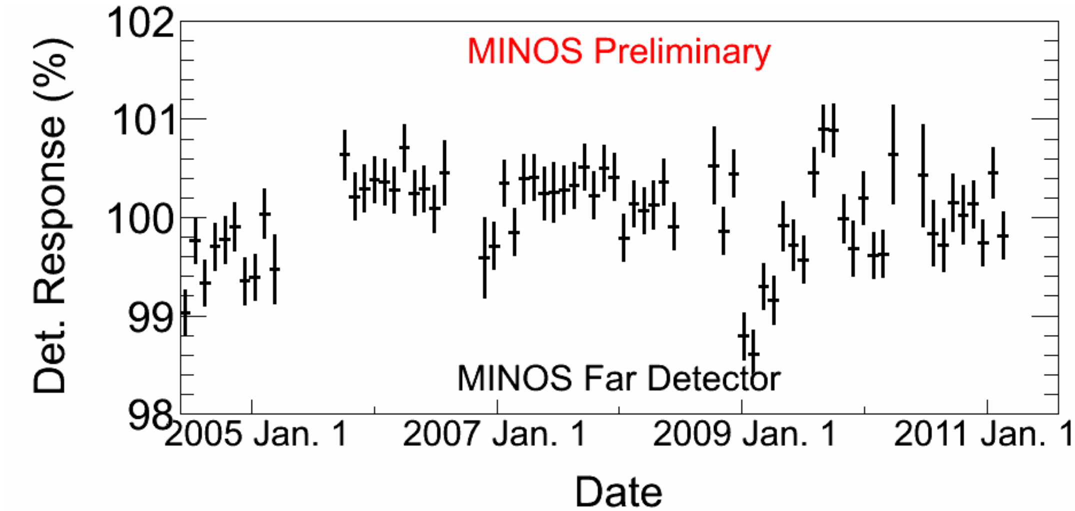
- watch for updates on sterile mixing limits
- NOvA is being built! Beam any day now…
- The NuMI beam at FNAL will continue to provide exciting physics in the years to come.

Backup Slides

Detector Stability

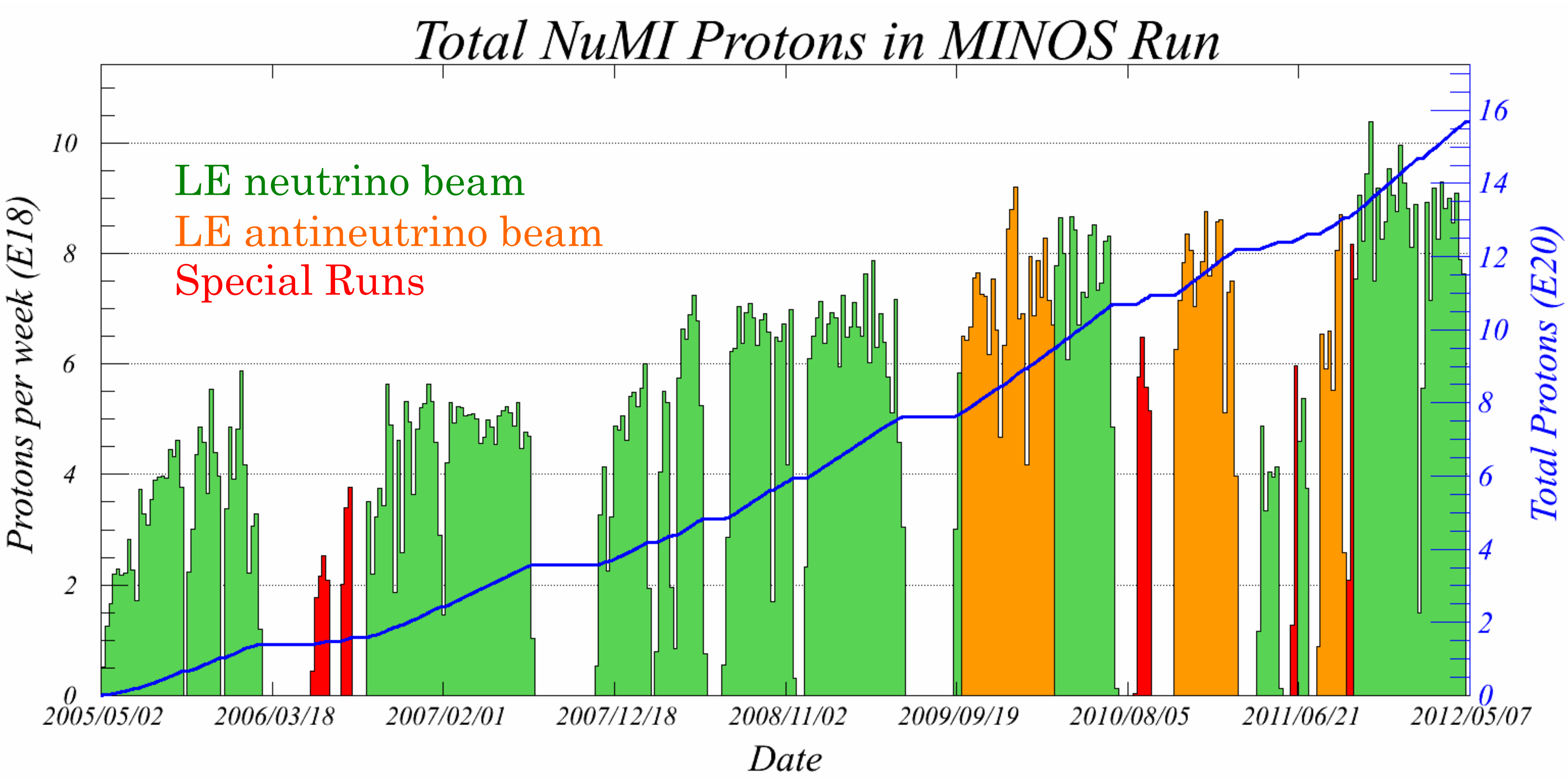


Far Detector live for 97% of Beam Exposure



	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%

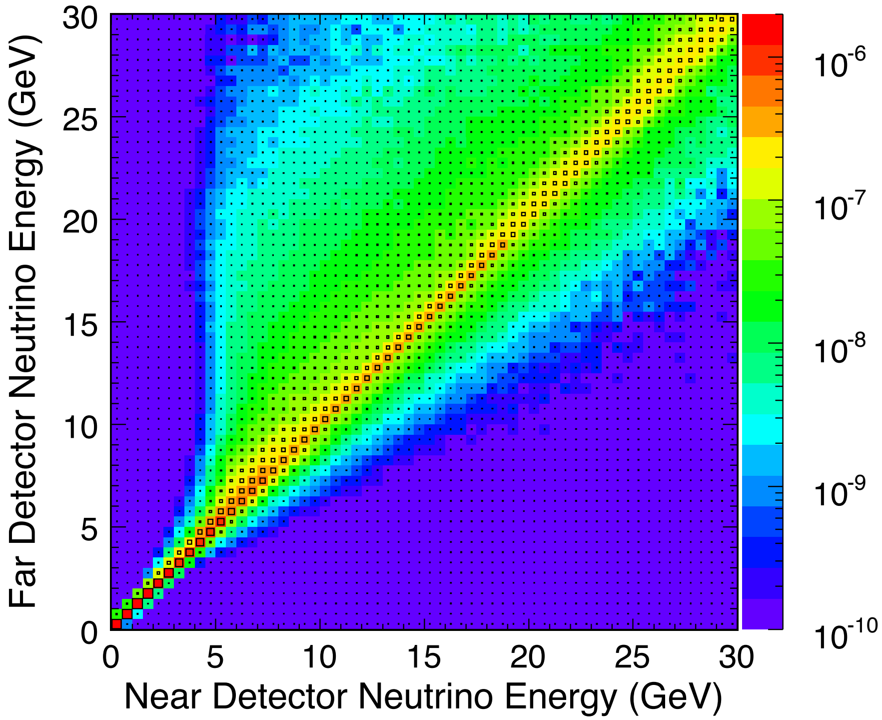
1.5 SEXTILLION POTS

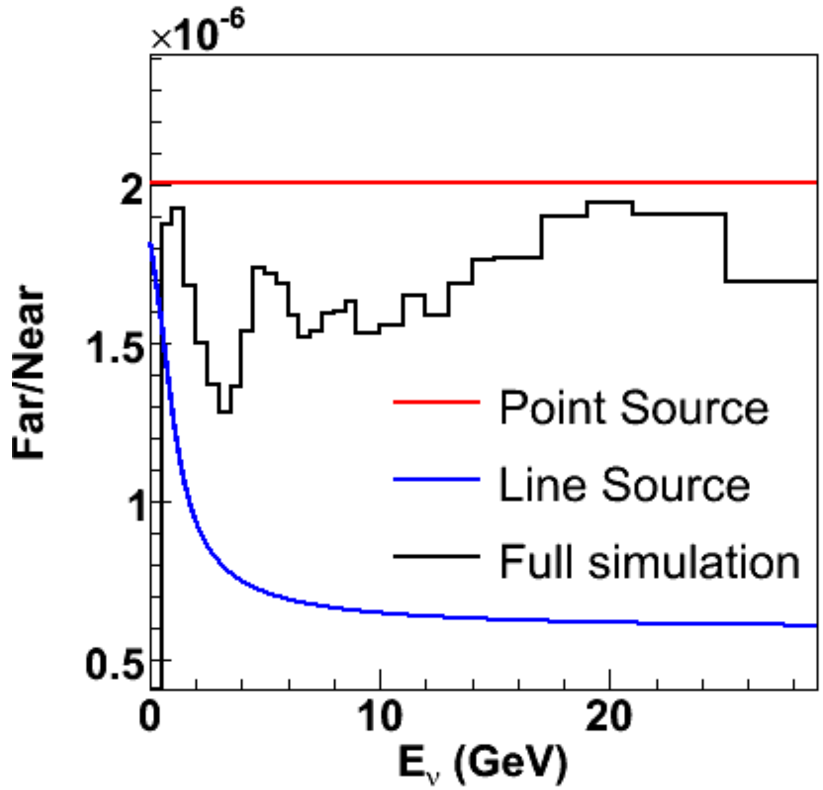


- NuMI beam shut off April 30, 2012
- Accumulated more than 15 x 10^{20} POT
  - 10.7 x 10^{20} POT in (LE) neutrino running
  - 3.36 x 10^{20} POT in antineutrino running

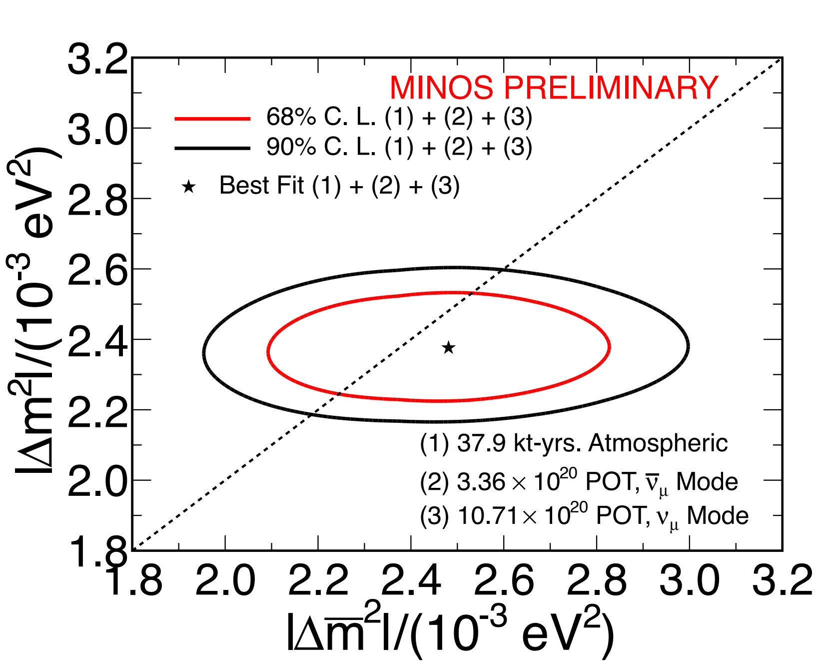
EXTRAPOLATION

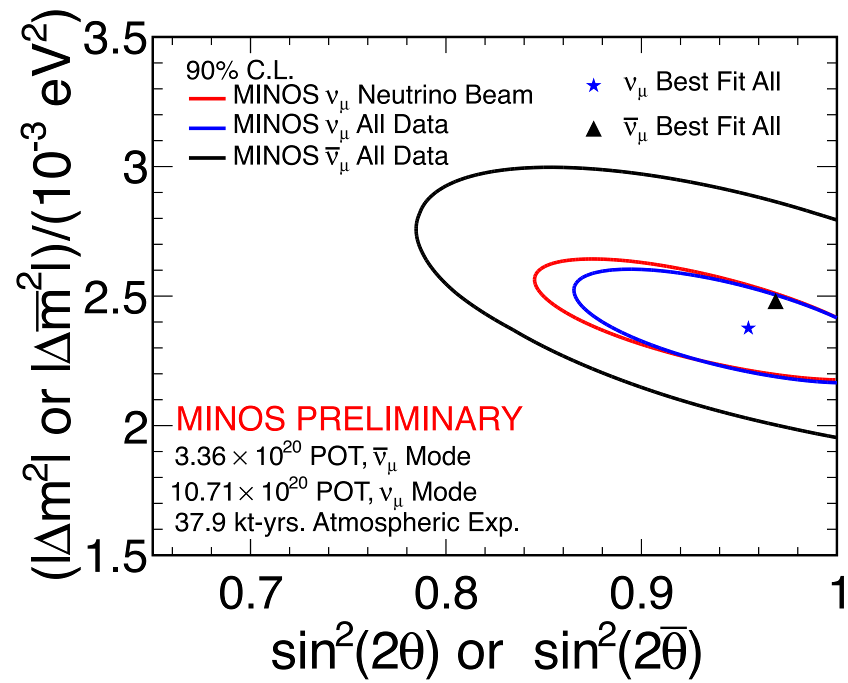
- Muon-neutrino and anti-neutrino analyses: beam matrix for FD prediction of track events
- Electron-neutrino analyses: Far to Near spectrum ratio for FD prediction of shower events





COMPARING NEUTRINOS AND ANTINEUTRINOS



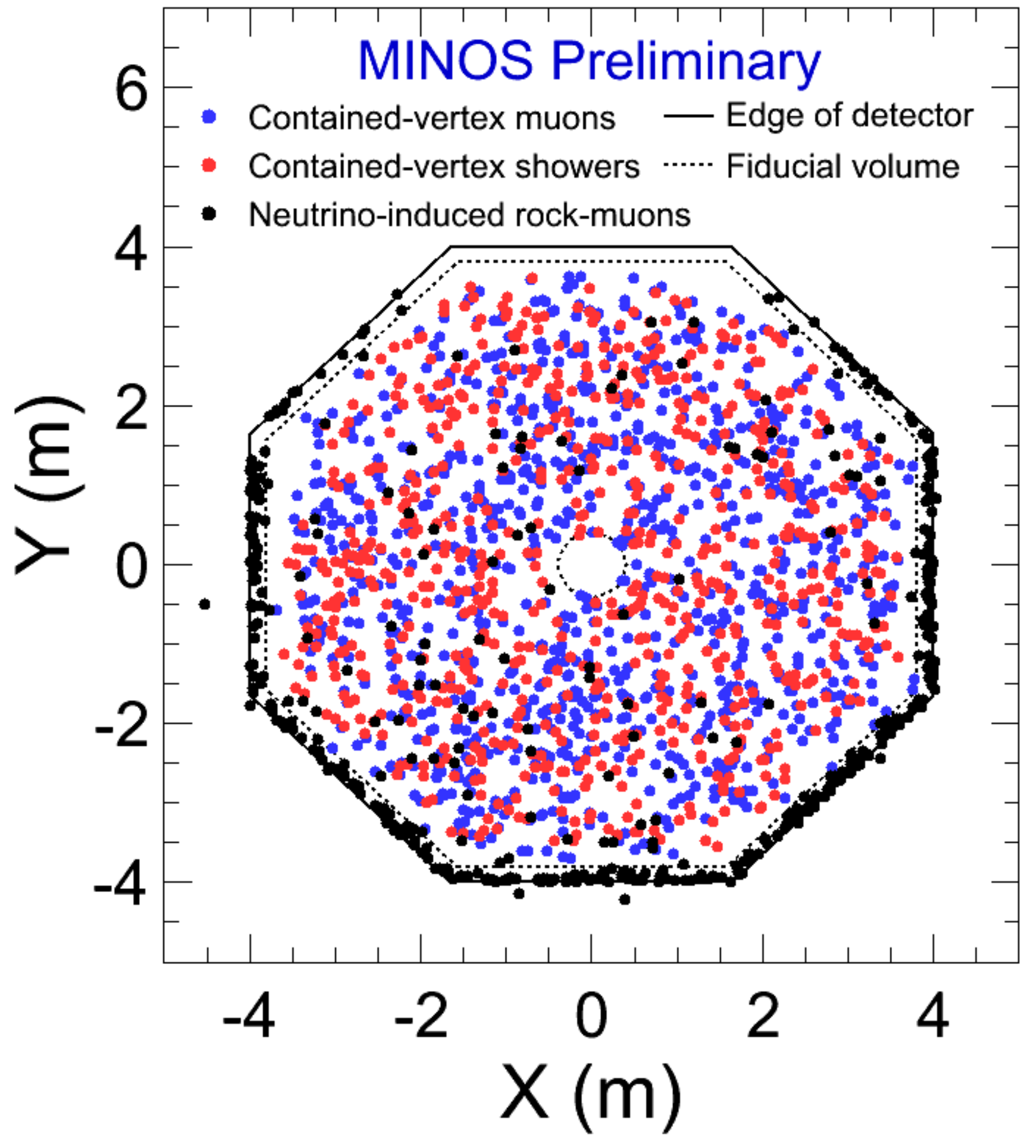


$$\left|\Delta\bar{m}^2\right| - \left|\Delta m^2\right| = 1.0^{+2.4}_{-2.8} \times 10^{-4}\,\mathrm{eV}^2$$

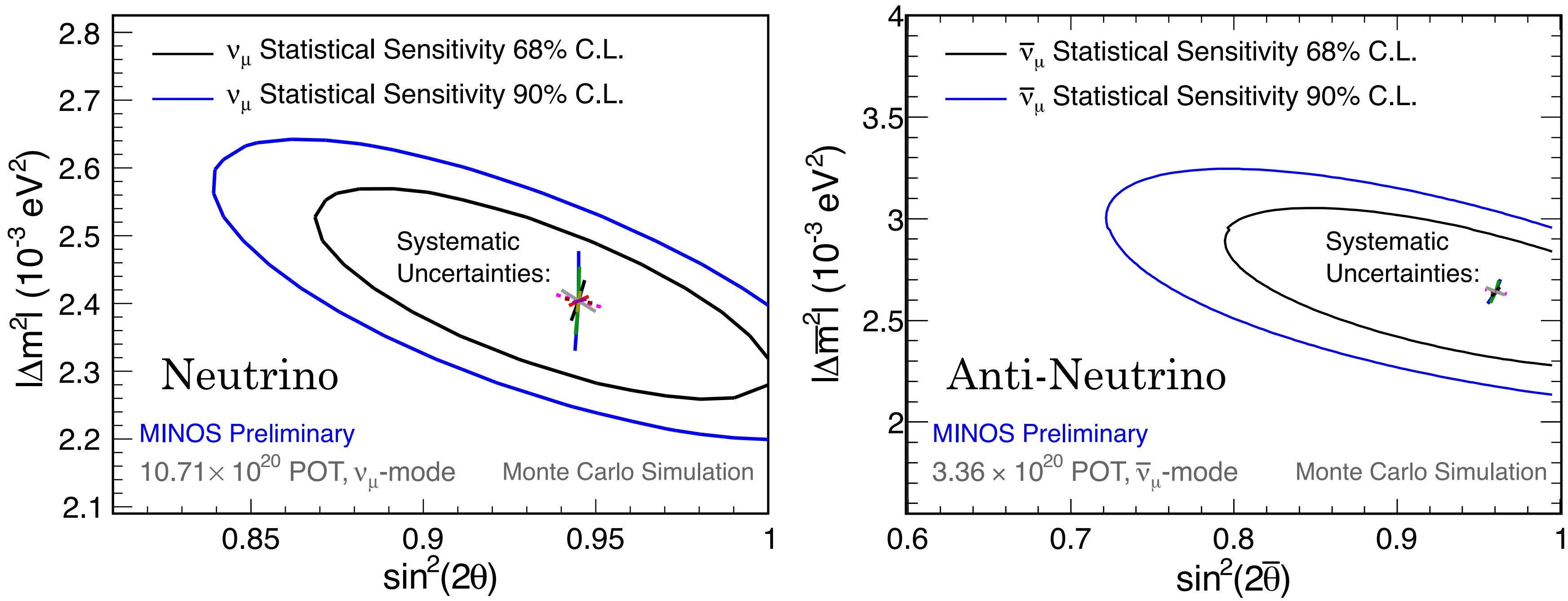
New data has resolved tension between neutrino and antineutrino results

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

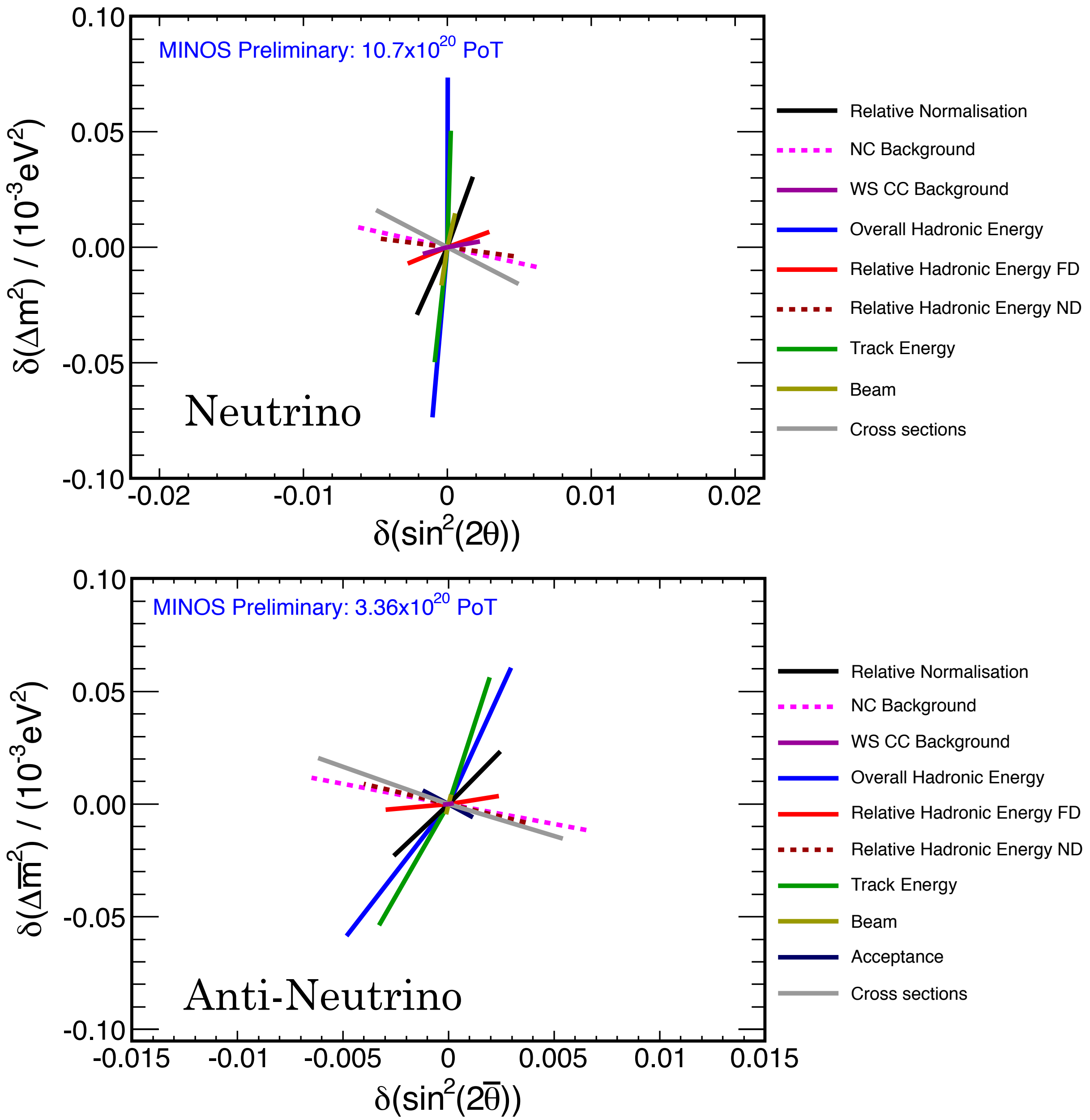


SYSTEMATICS



- 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

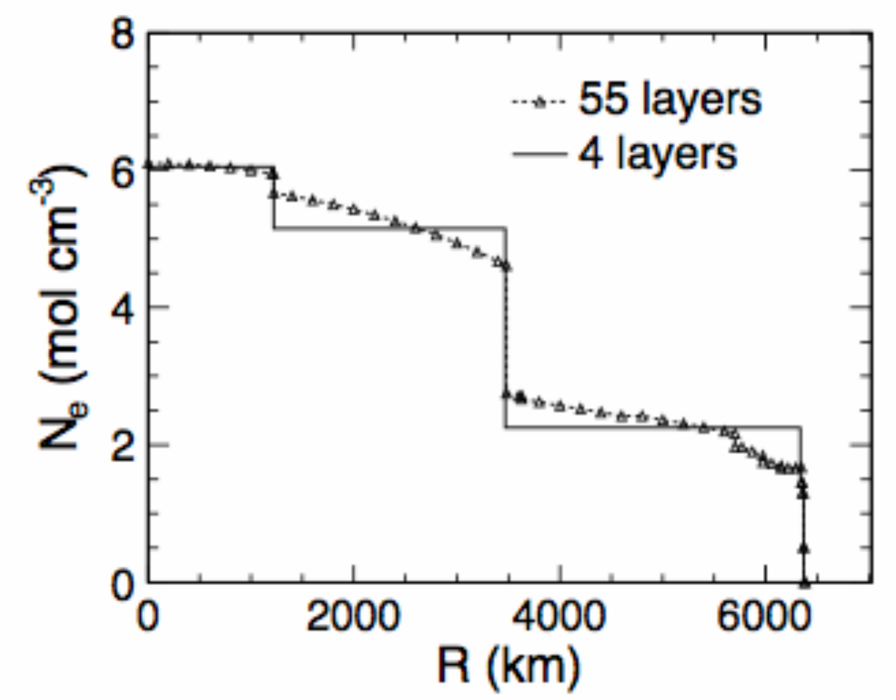


Figure 3: Comparison of the 4-layer earth density model used in this three-flavour oscillation analysis with a more precise 55-layer model based on the PREM model.

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

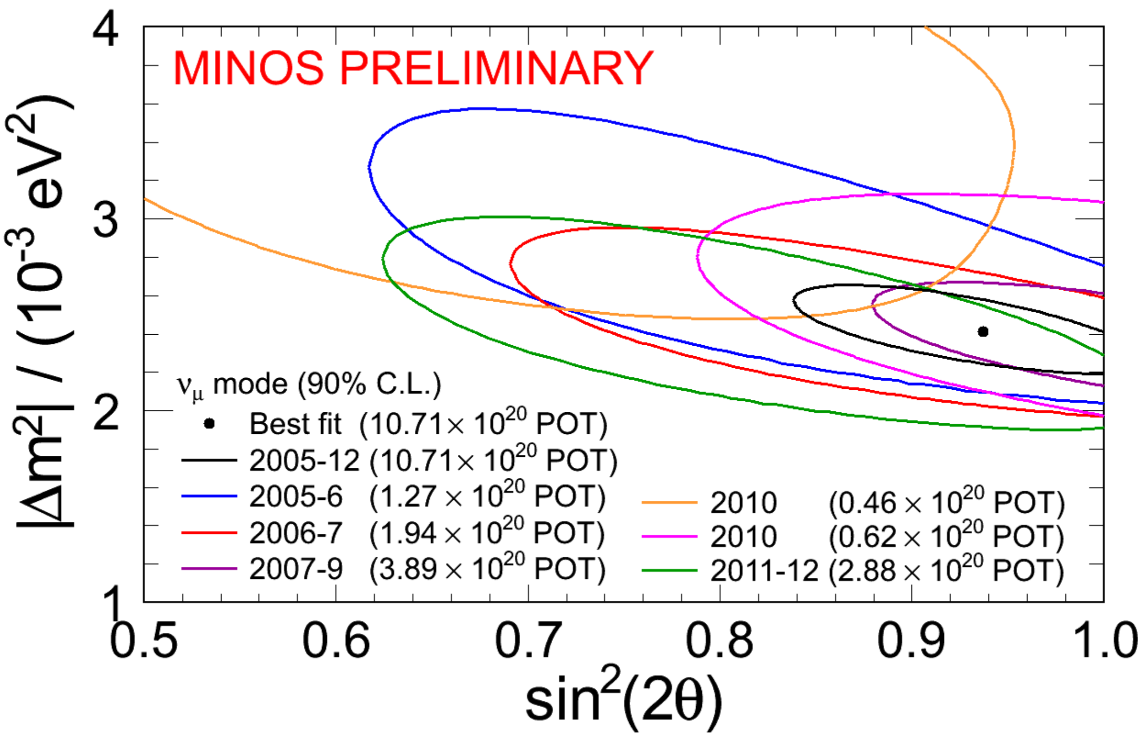
Table 1: The radius and earth density of each layer used in the four-layer earth model.

STATISTICS

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

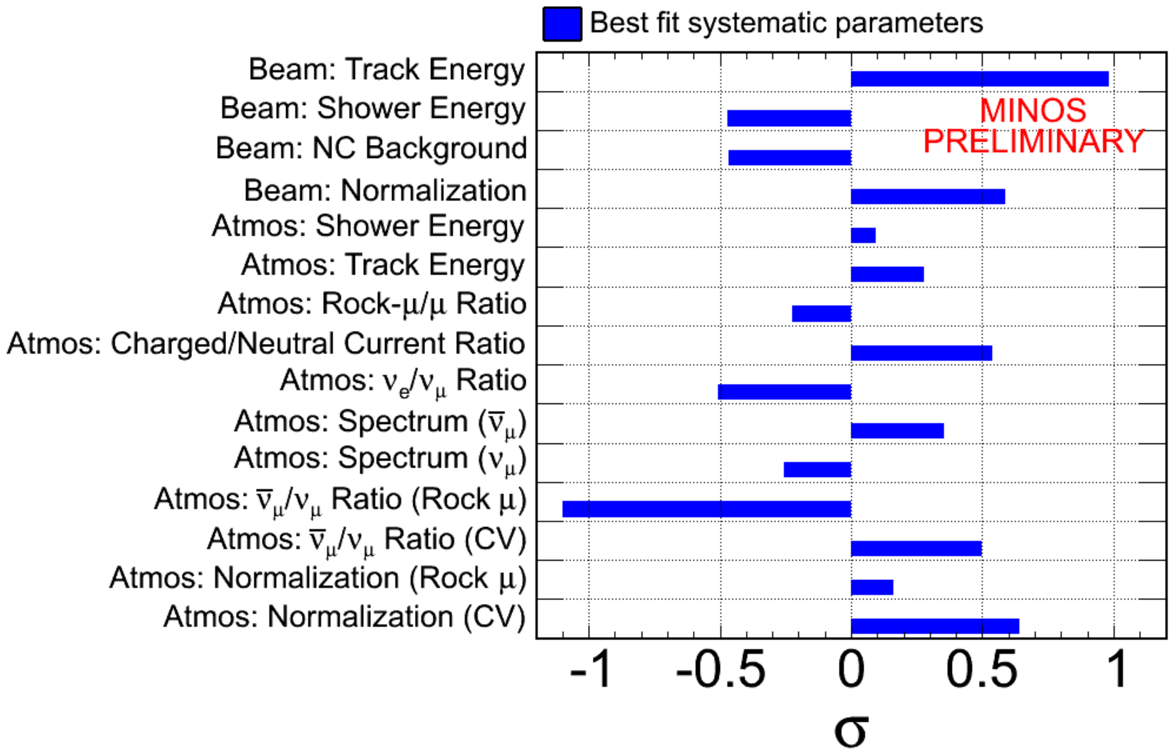
Atmospheric	No Oscillations	Observed
Contained CC	1100	905
Rock Vertex	570	466
Showers	727	701

Contour Evolution



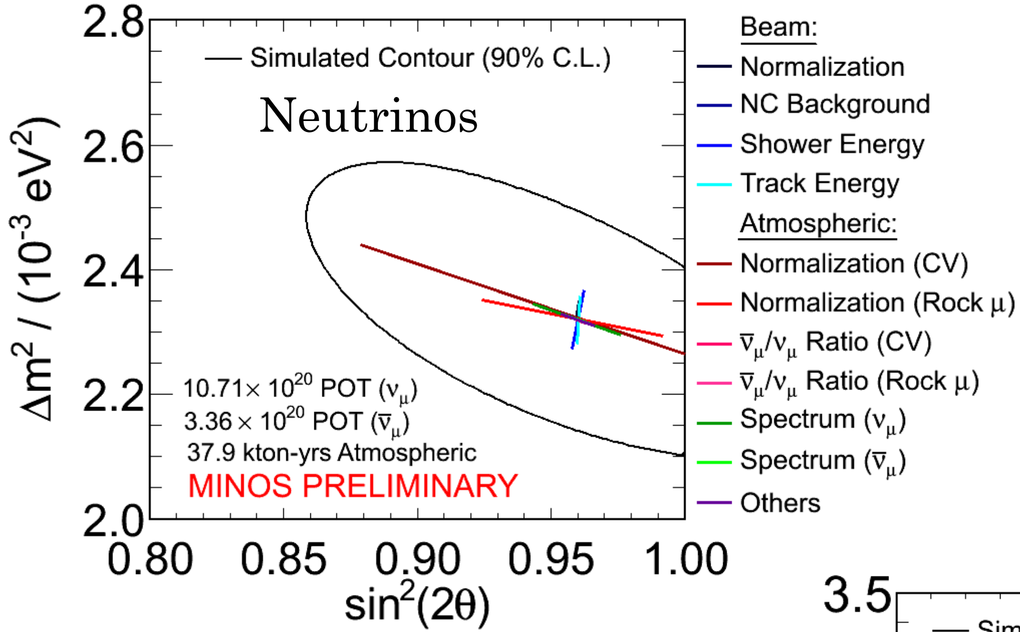
Run	I	pHE	II	III	V	VI	X	All
POT ($\times 10^{20}$)	1.27	0.15	1.94	3.89	0.46	0.62	2.88	10.71
Events	317	119	509	1034	113	154	648	2894
Δm^2 ($\times 10^{-3}$ eV^2)	2.62	2.52	2.38	2.37	3.66	2.56	2.41	2.41
$\sin^2(2\theta)$	0.89	1.00	0.94	1.00	0.73	1.00	0.84	0.94

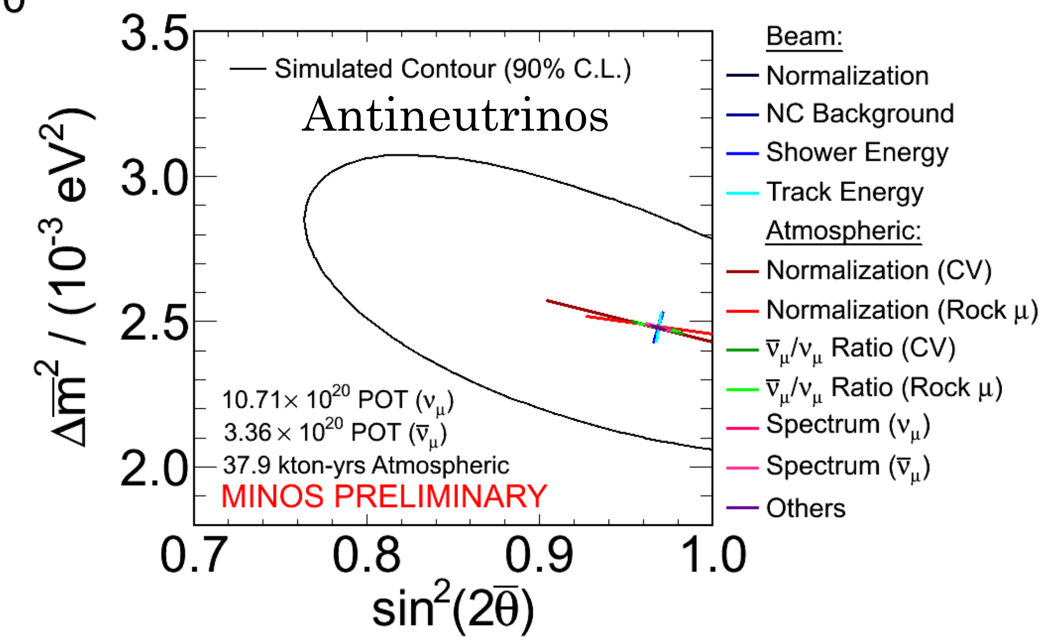
The Method



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

Combined Fit Systematics





Looking for Electron-neutrinos

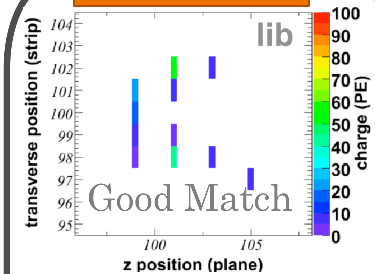
- Compare candidate events to a library of simulated signal and background events
- Discriminating variables formed using information from 50 best matches

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 #

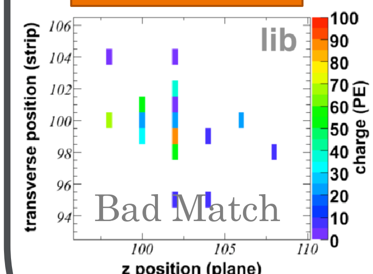


Library Event #

Library Event #

. . .

Library Event #



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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

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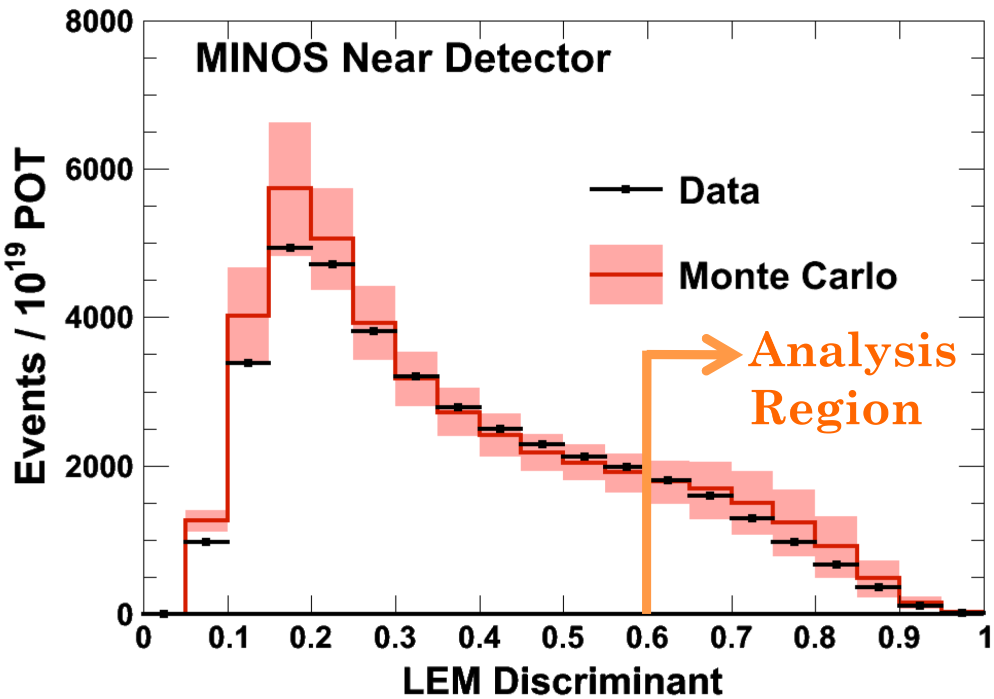
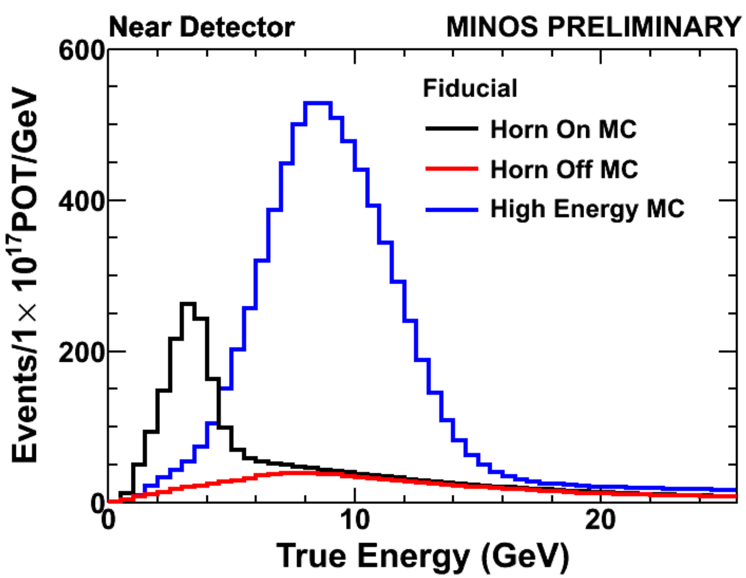
Selecting Electron Neutrinos

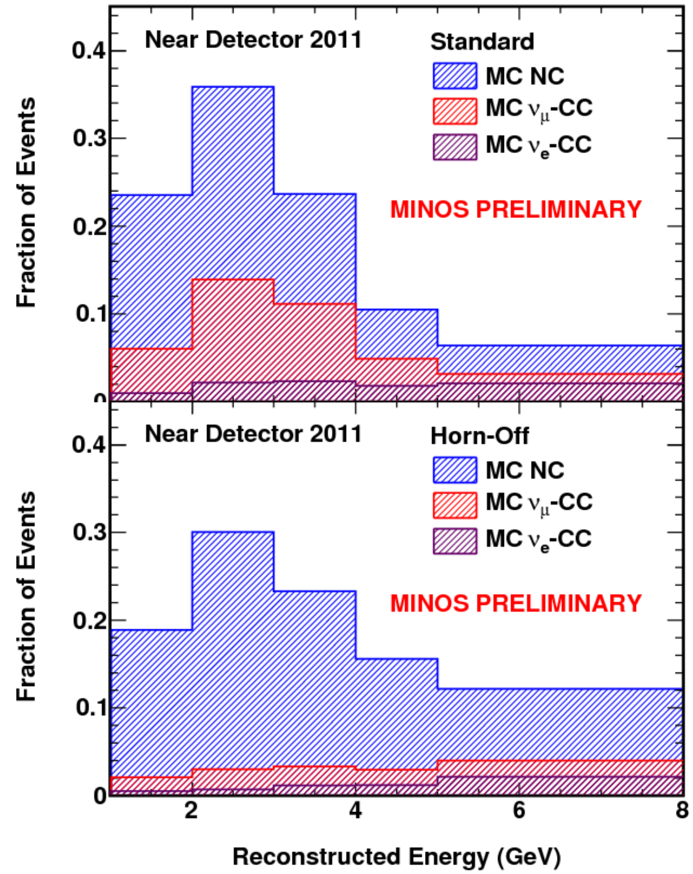
- Coarse detector granularity makes ν_e CC identification challenging
  - Compare candidate events, strip-by-strip, to a library of MC events
  - Compute discriminating variables based on truth information from library events that best match the candidate
- Apply selection to ND for background determination



Electron Neutrino Appearance

- Selected ND data comprised of NC, ν_μ CC, and beam ν_e events
- Each extrapolates to FD differently
- Use ND data in different configurations to extract relative components of background





Combined Electron Neutrino Appearance Contour

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

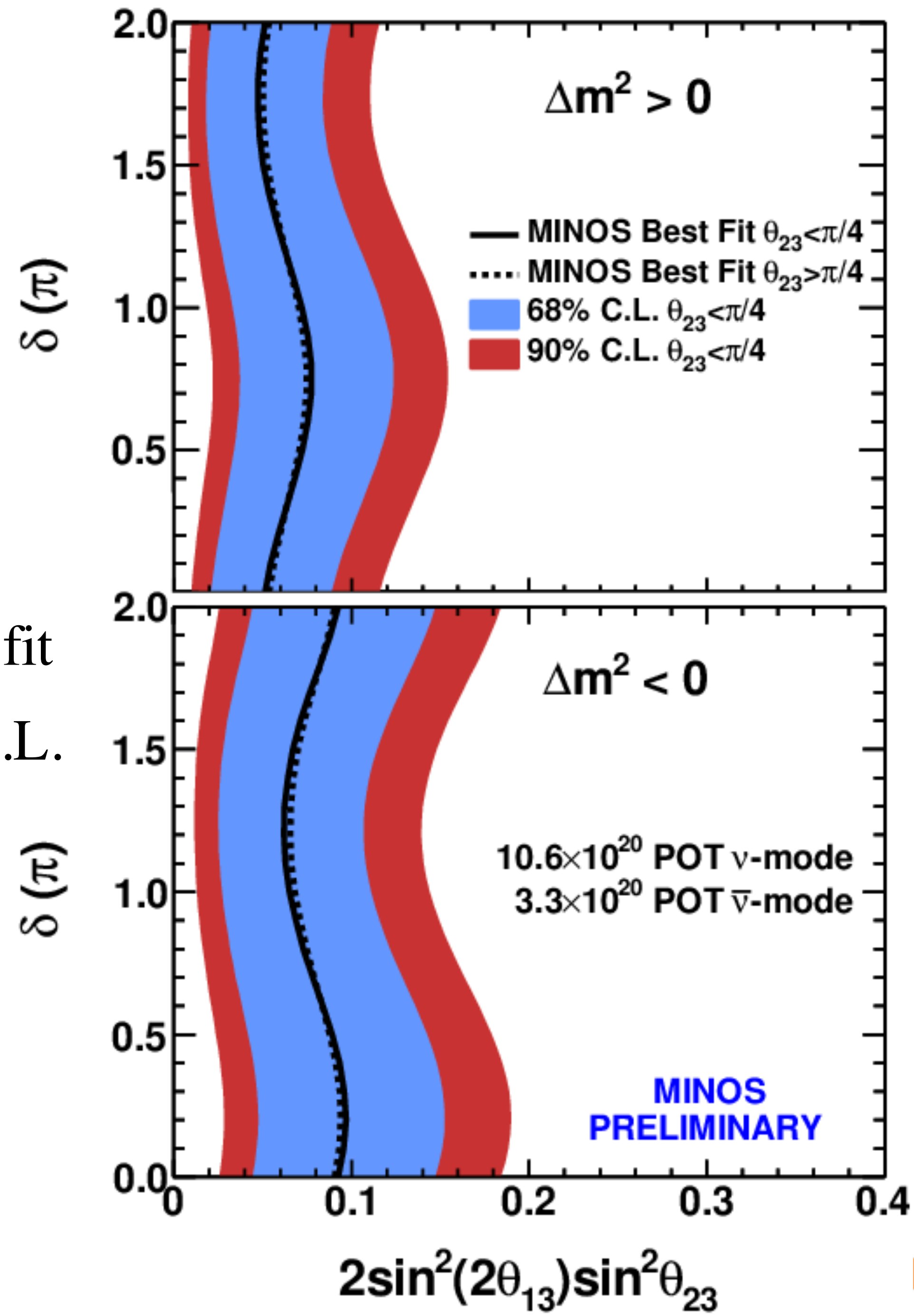
normal (inverted) hierarchy

$\sin^2(2\theta_{13}) = 0.053$ (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

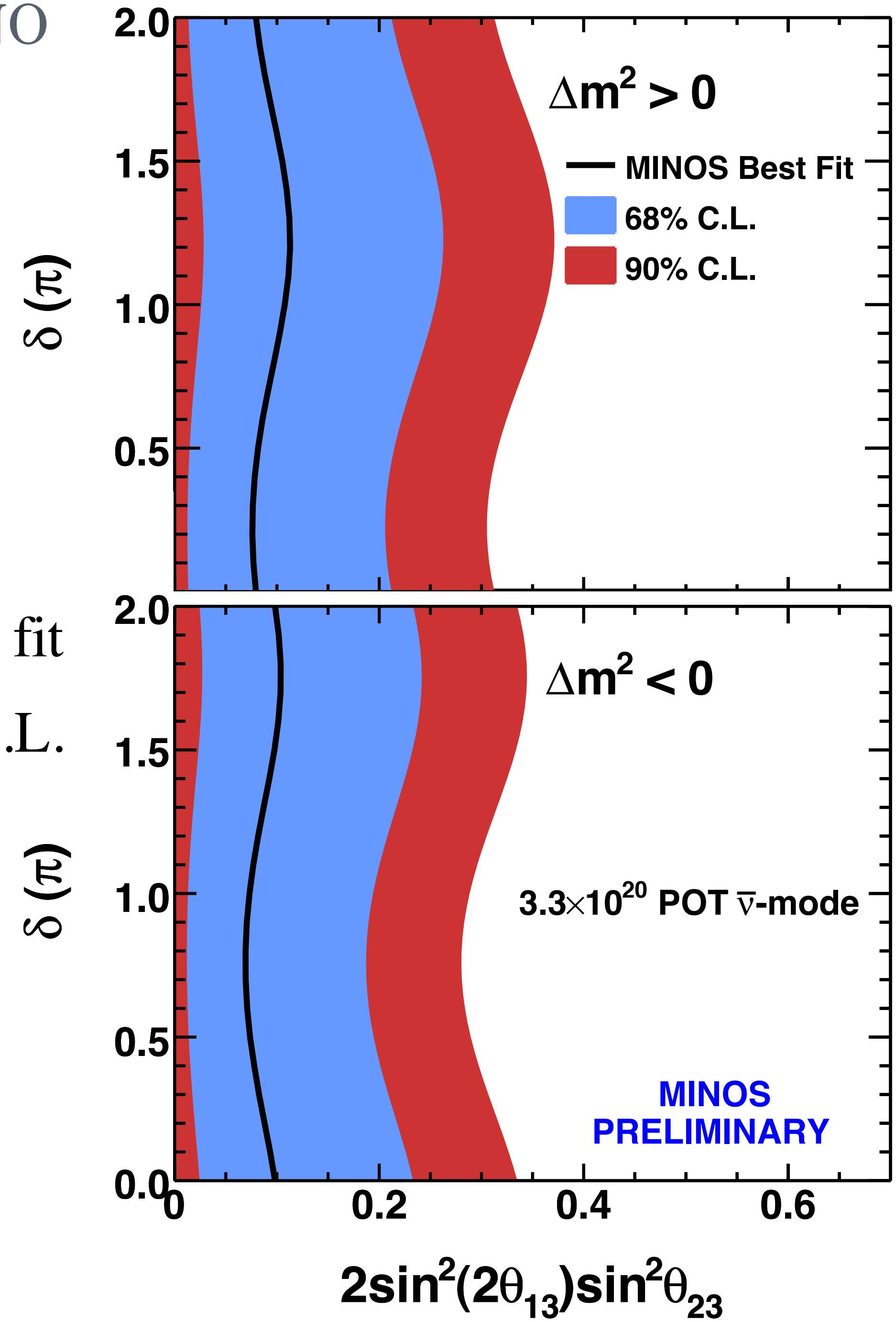
for $\delta_{CP} = 0, \sin^2(2\theta_{23}) = 1$,

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%



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Normal hierarchy

Y. Itow, Nu2012

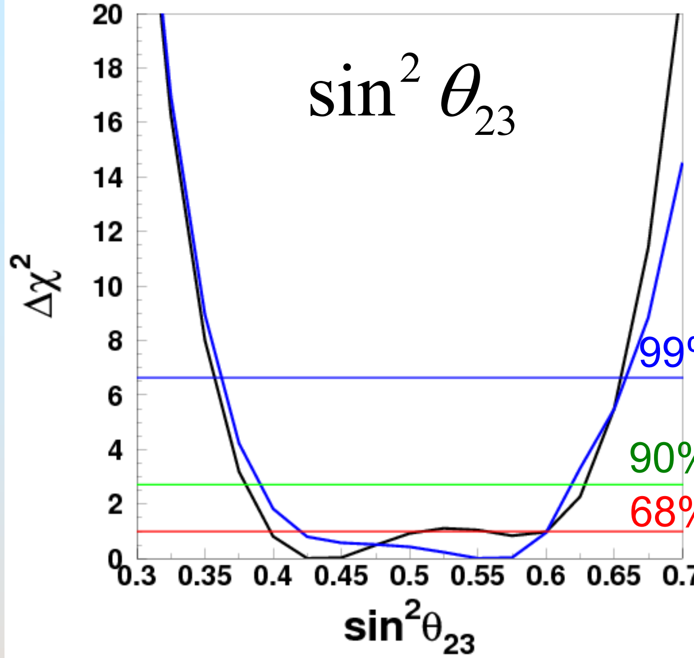
***$\sin^2\theta_{13}$ fixed to be 0.025 (reactor)**

χ^2_{min} = 556.7 / 477 dof

Δm^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

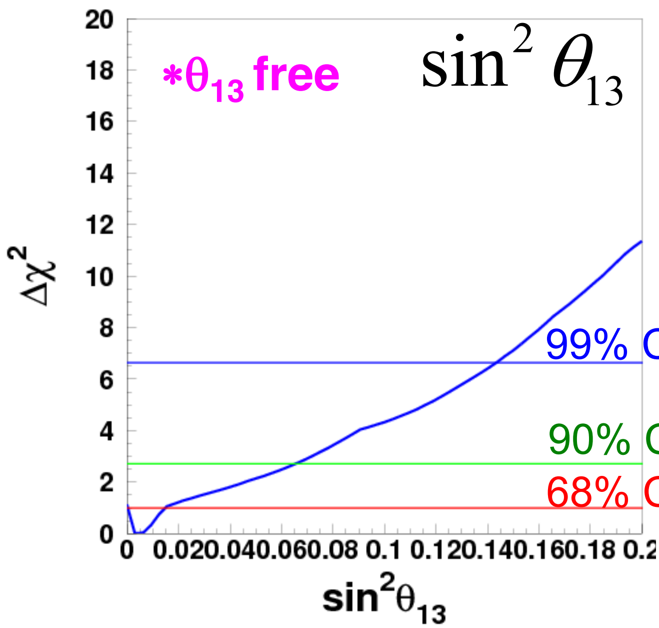
***$\sin^2\theta_{13}$ fitted**

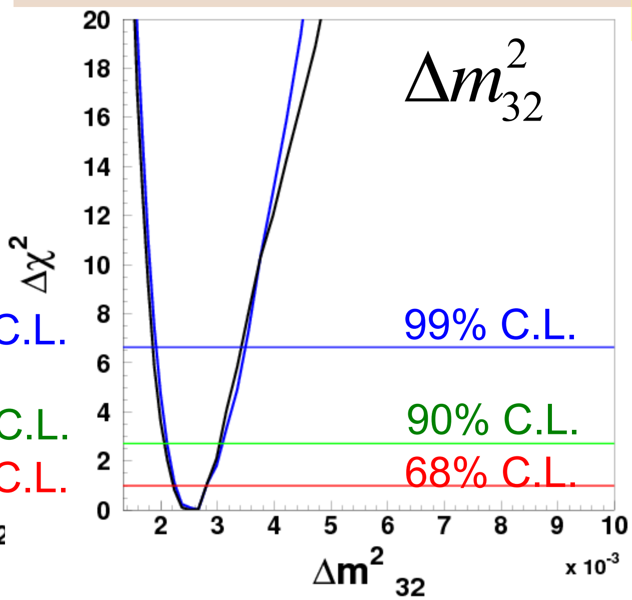
$\sin^2\theta_{13}$	0.003	0 - 0.0655

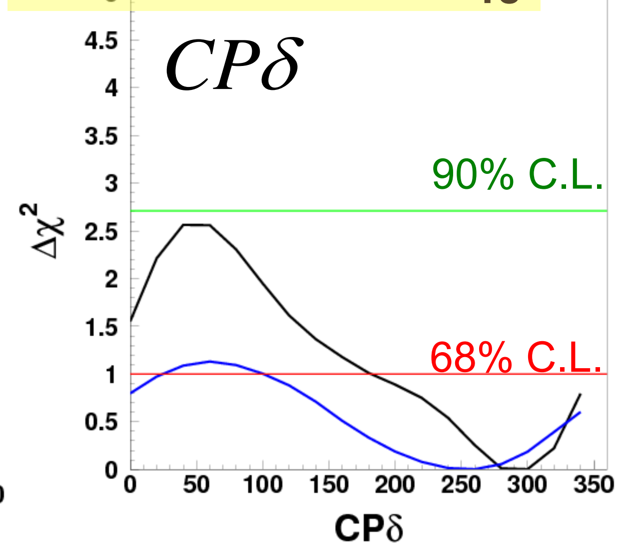


Free θ_{13}

Fixed reactor θ_{13}







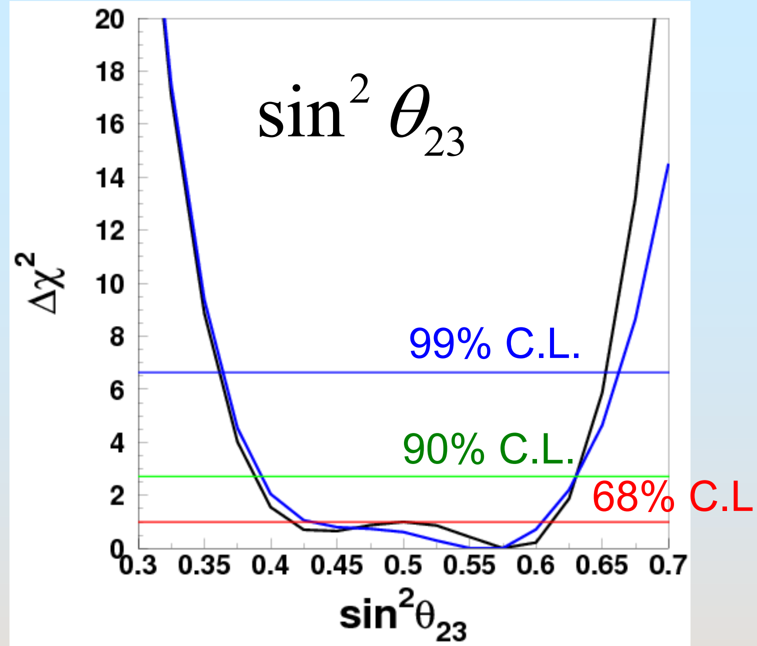
Inverted hierarchy

Y. Itow, Nu2012

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

χ^2_{min} = 555.5 / 477 dof

Δm^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
δCP	300°	All allowed at 90% C.L.

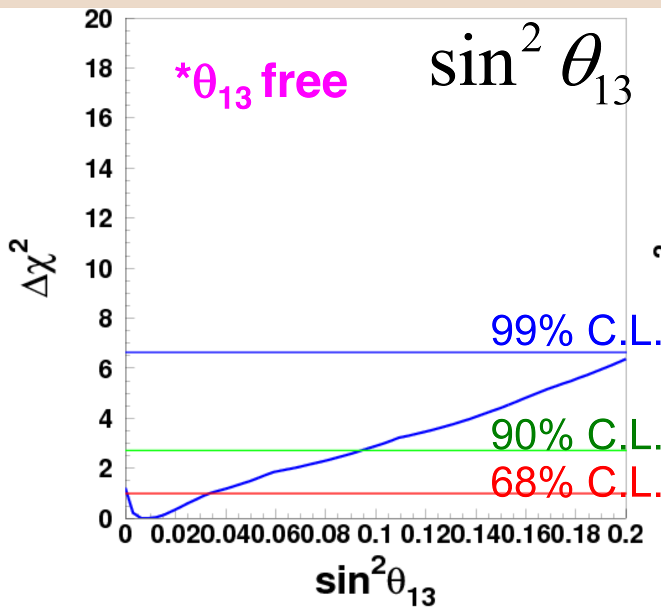


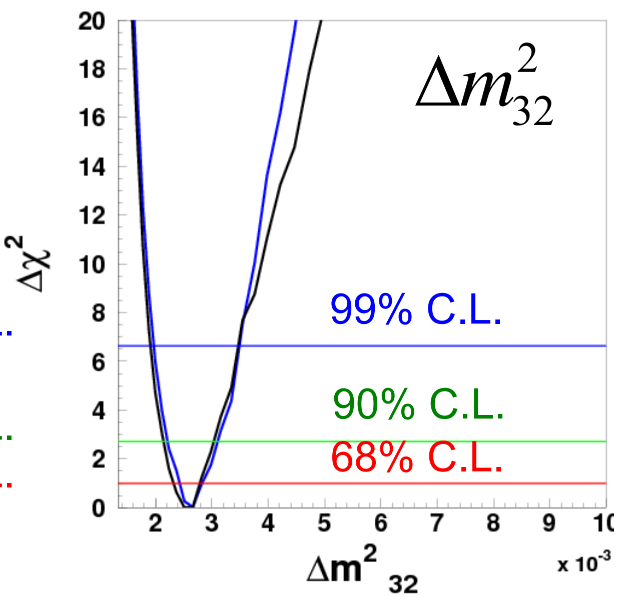
***$\sin^2\theta_{13}$ fitted**

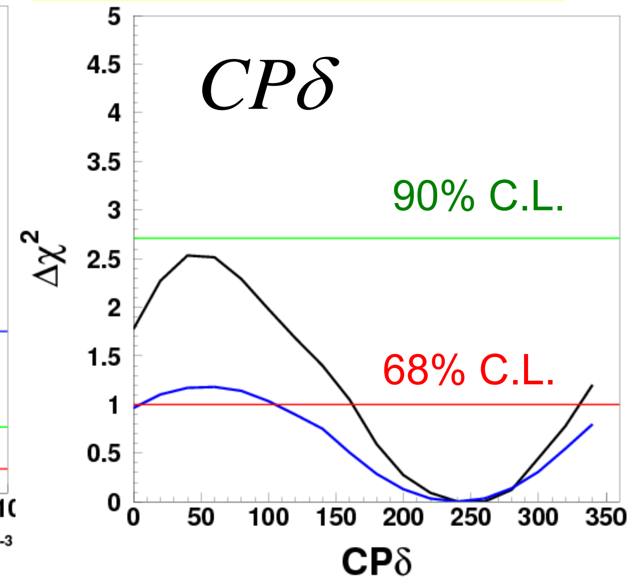
$\sin^2\theta_{13}$	0.006	0 - 0.0944

Free θ_{13}

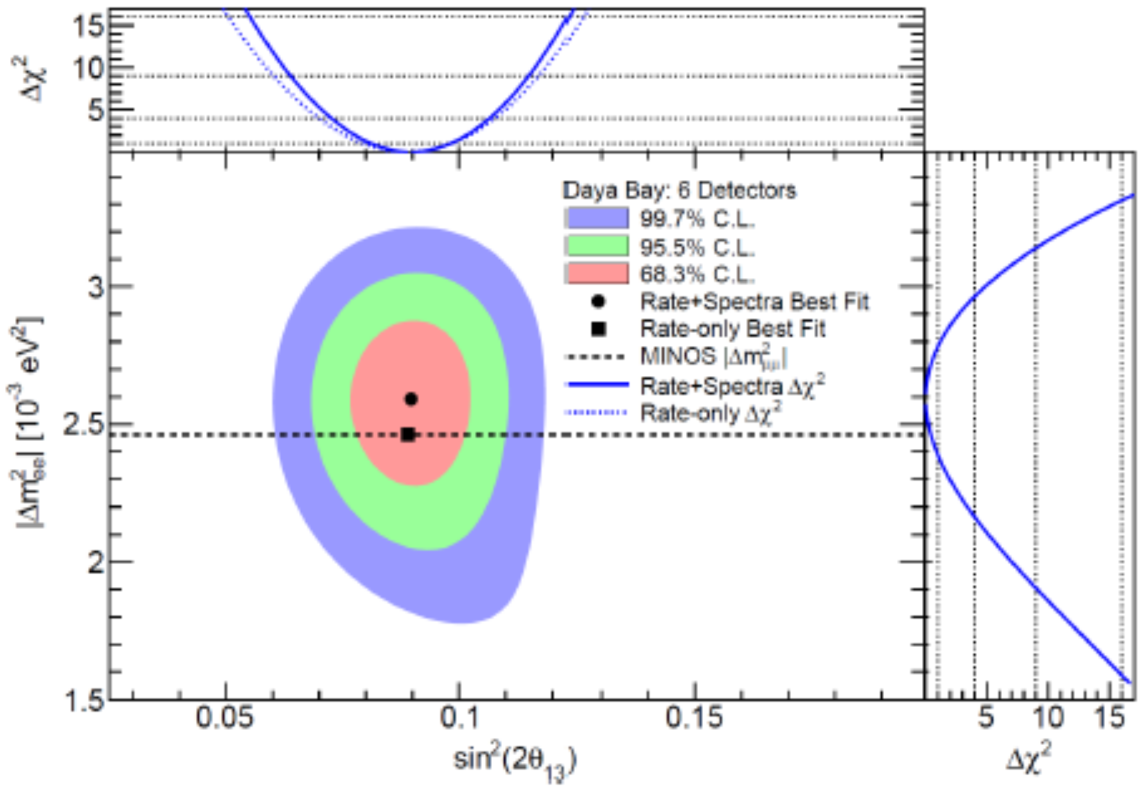
Fixed reactor θ_{13}







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)

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

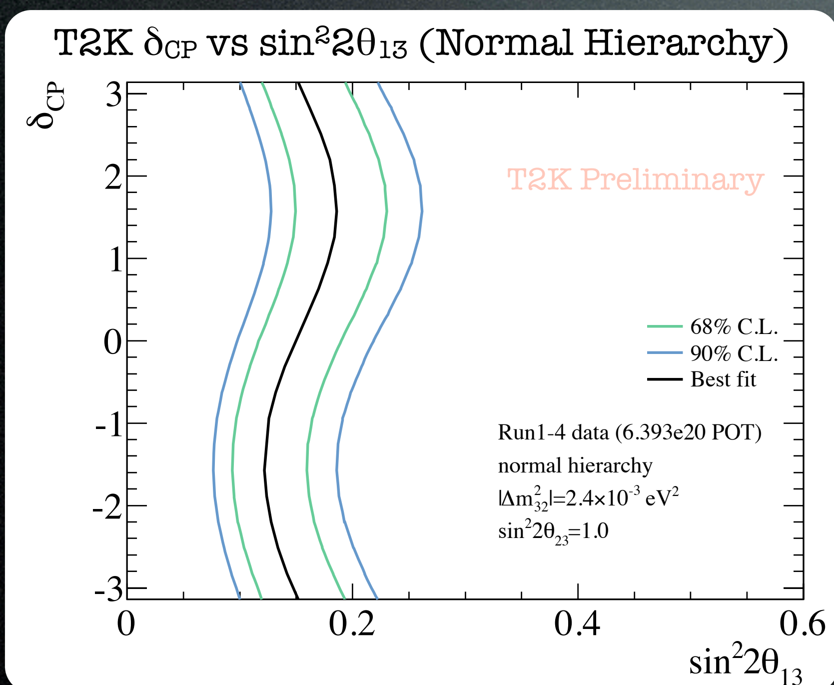
(Inverted Mass Hierarchy)

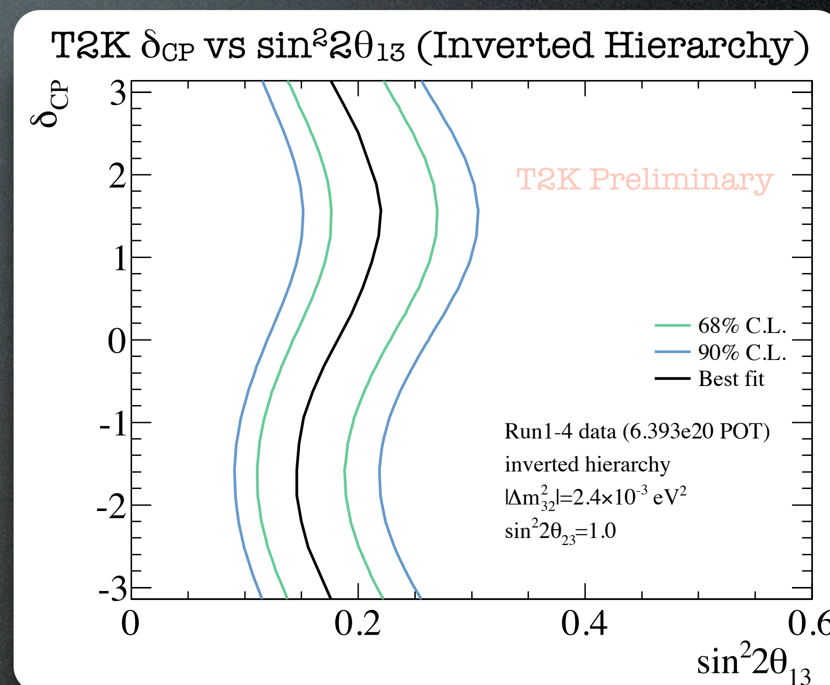
- Far vs. near relative measurement. [Absolute rate is not constrained.]
- Consistent results obtained by independent analyses, different reactor flux models.
- Result consistent with $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (eV^2)$ result from MINOS.

ν_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 θ_{13}**

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



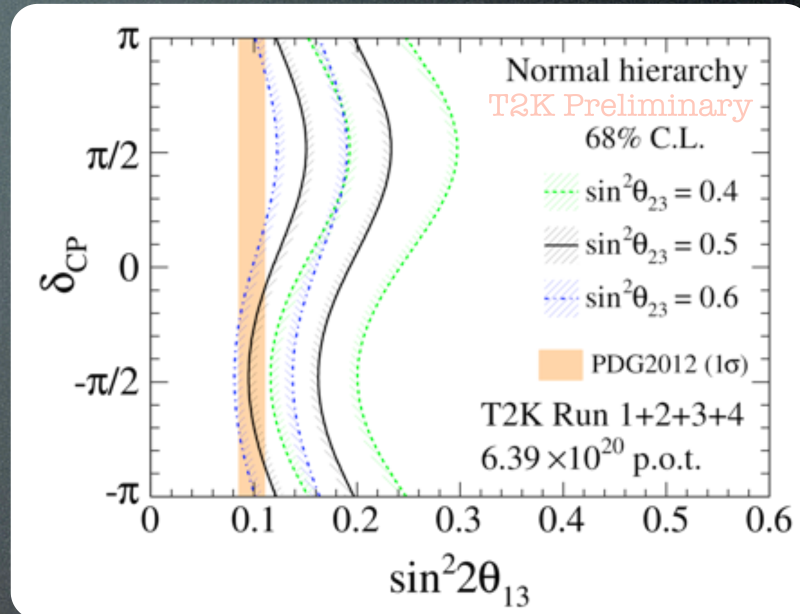


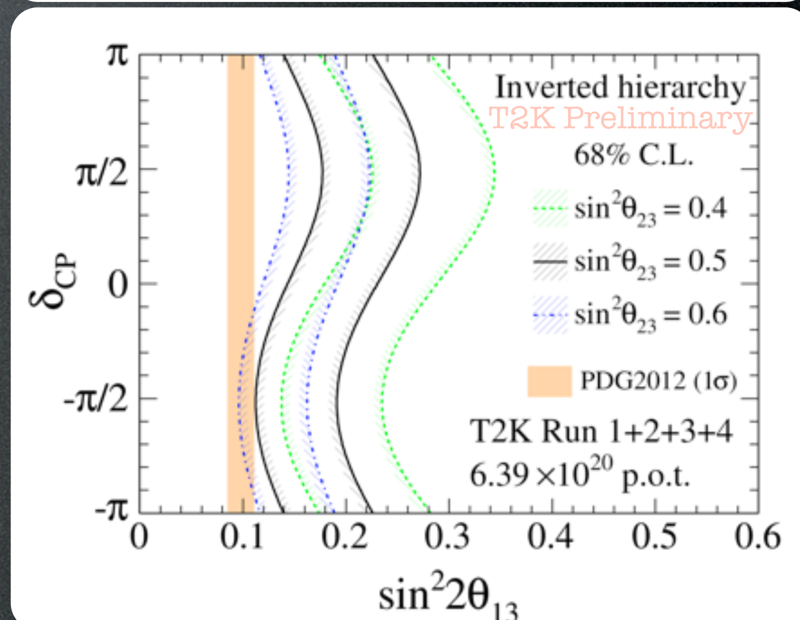
First ever observation (>5σ) of an explicit ν appearance channel

M. Wilkings EPS 2013

Effect of θ_{23} Uncertainty

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



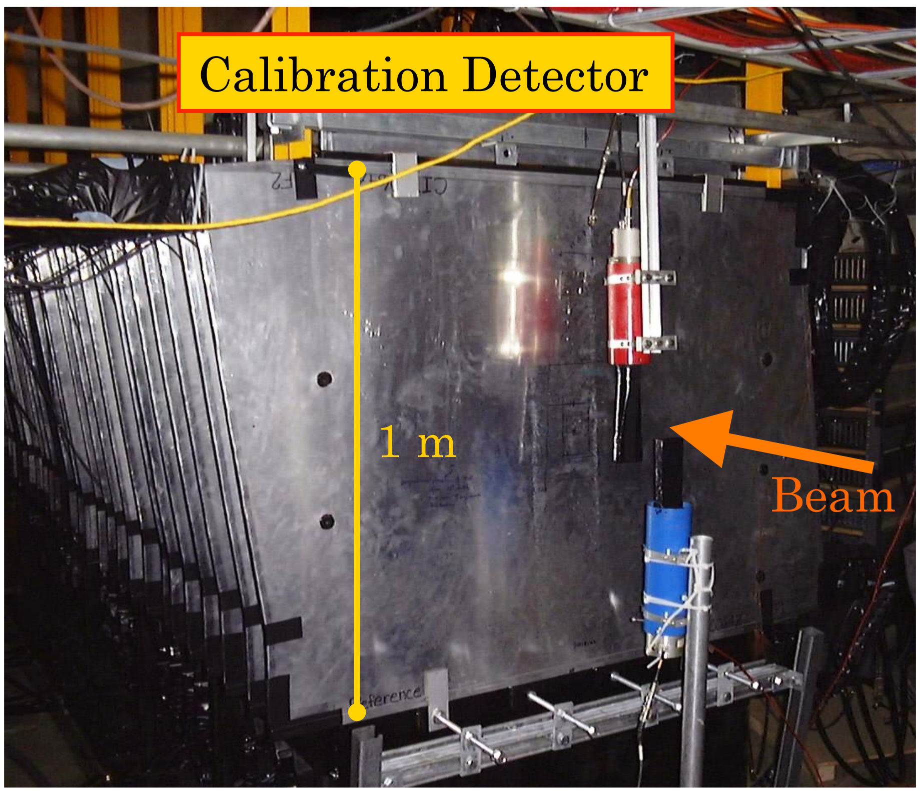


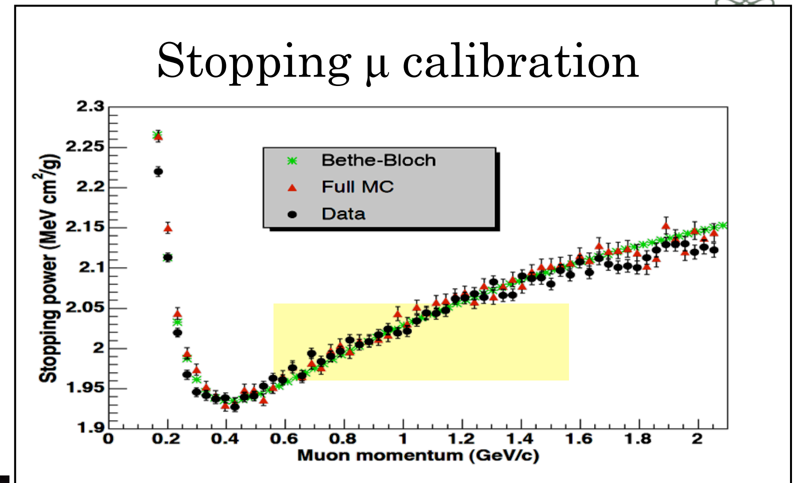
Note: these are 1D contours for various values of δ_{CP}, not 2D contours

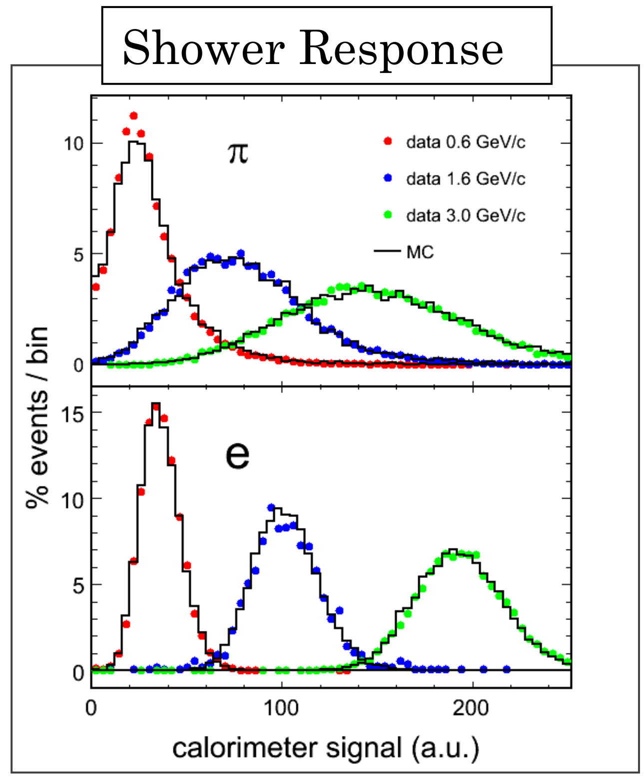
M. Wilkings EPS 2013

Calibration Detector

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

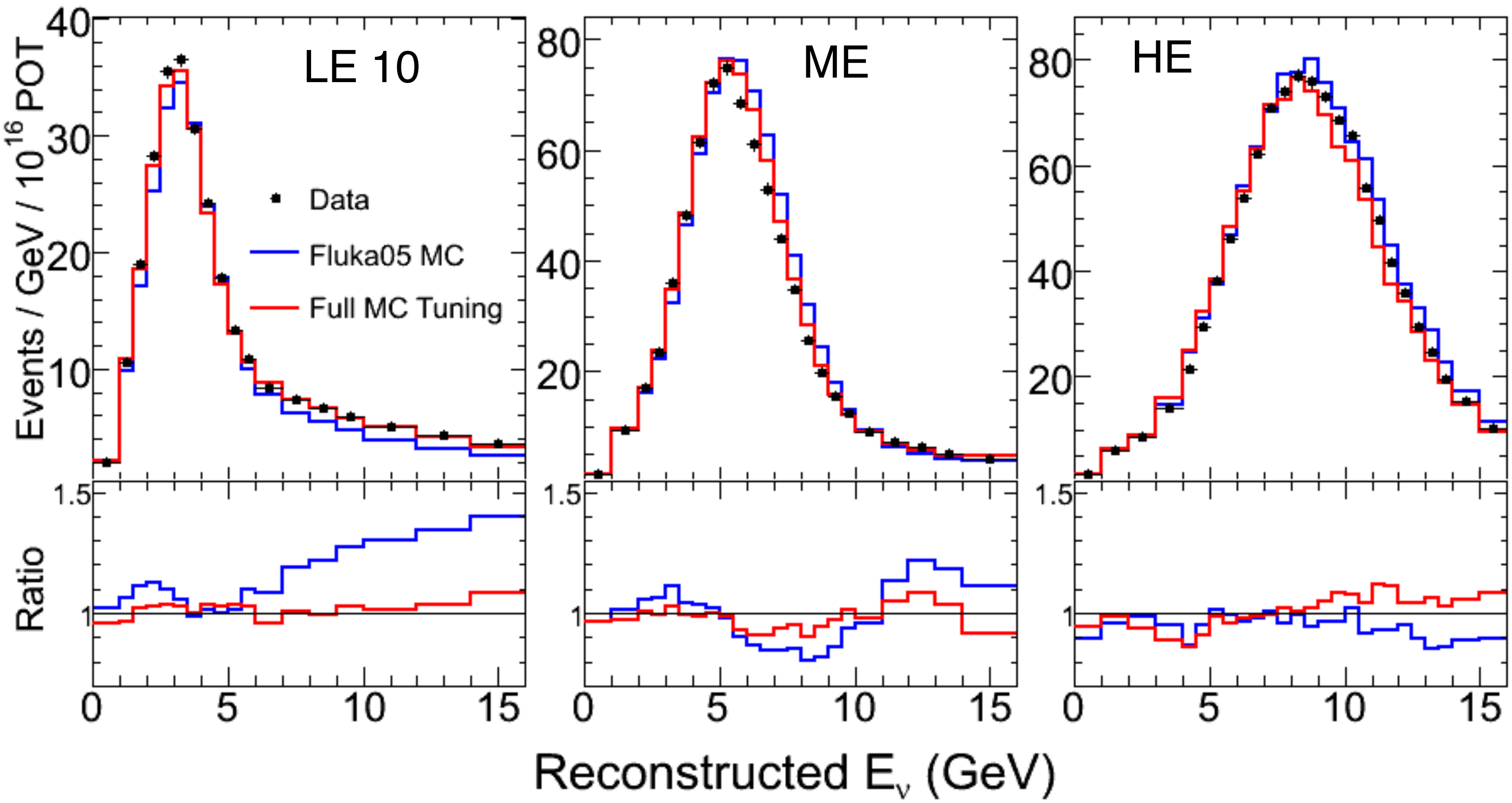






NEUTRINO SPECTRUM

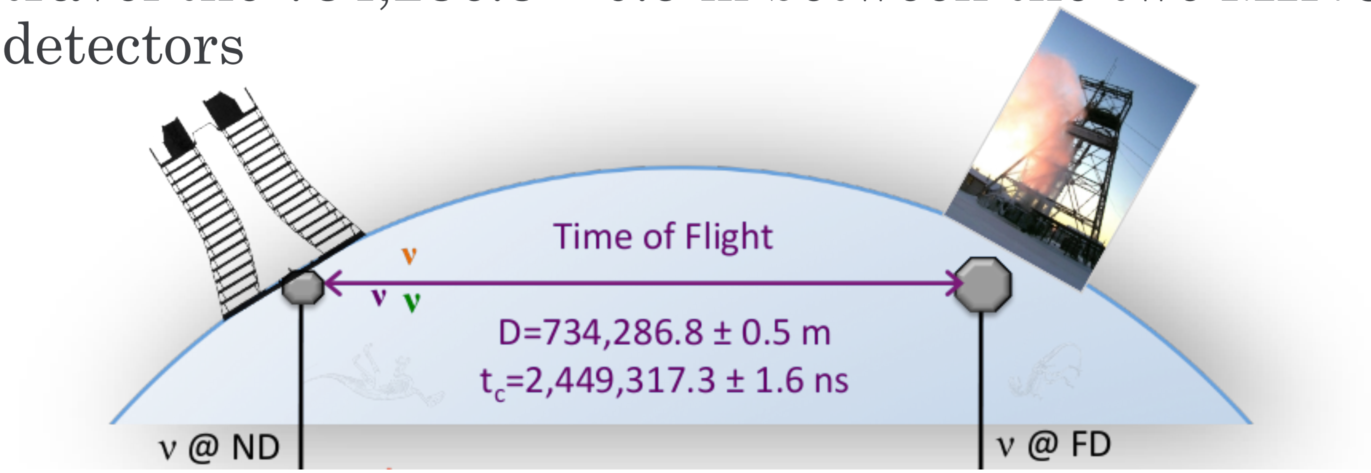
- Use flexibility of beam line to constrain hadron production, reduce uncertainties due to neutrino flux



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

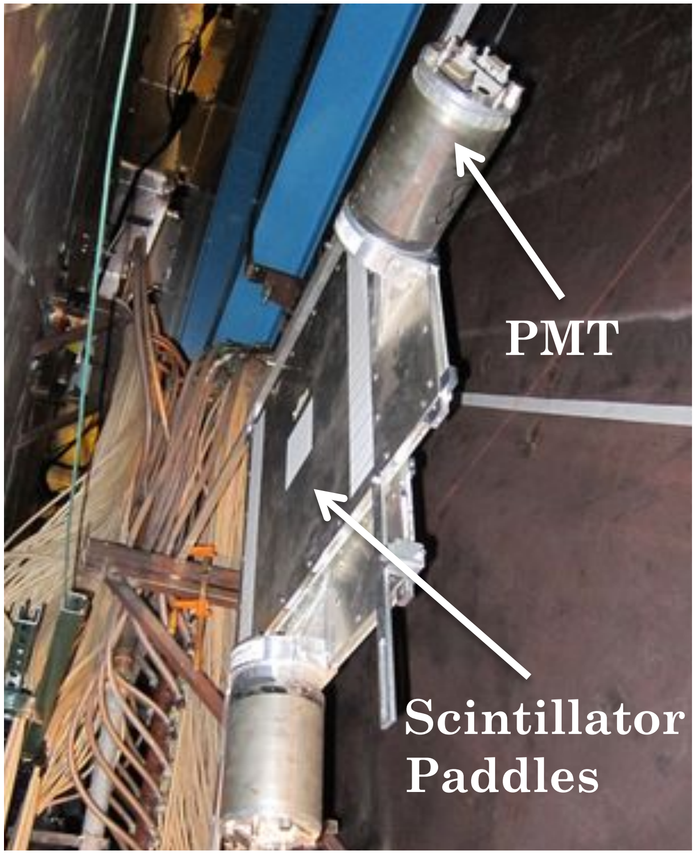
Phase II equipment provides refined understanding of current timing system systematic uncertainties

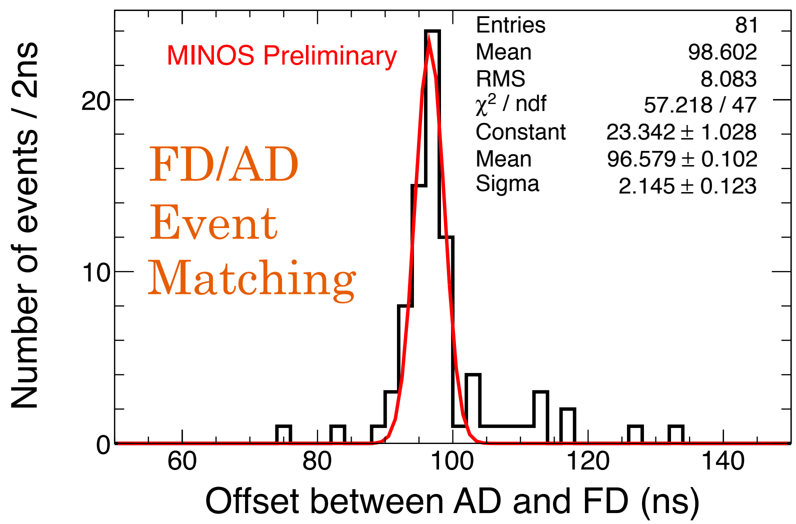
MAJOR SYSTEMATIC UNCERTAINTIES

- 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)

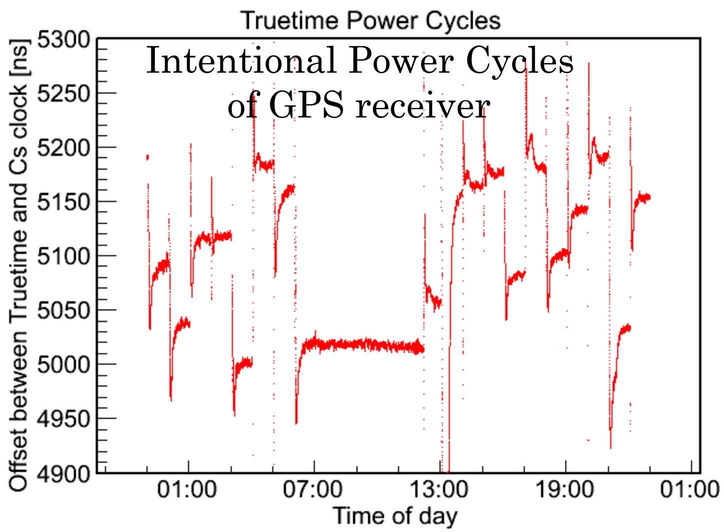


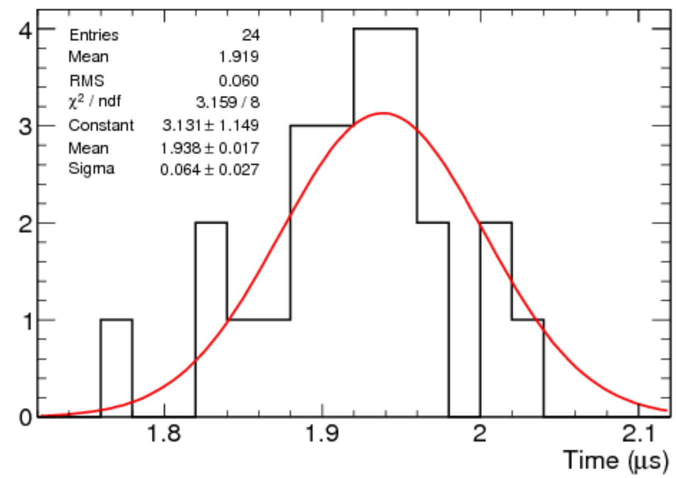


- Scintillator paddles with PMTs
- Two independent readouts
- Match muons in MINOS detectors with muons crossing AD
- Difference in matched event times recorded in each device measures latency in neutrino detector relative to AD latency
- Compare Near to Far Detector latencies, AD latency cancels
- Relative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

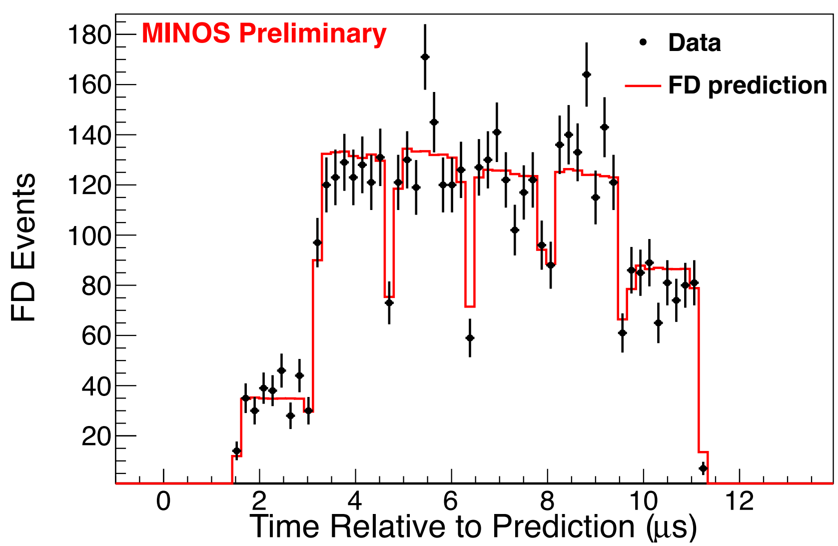
- Calibrating ND/FD GPS receivers
  - Traveling USNO TWSTT-capable GPS receiver visited FNAL and Soudan
  - Two receivers exchange timing synchronization information via the satellite
  - Comparison of ND/FD GPS time to traveling receiver reveals mean time offset between ND and FD: 22 ± 21 ns
- ND Spill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

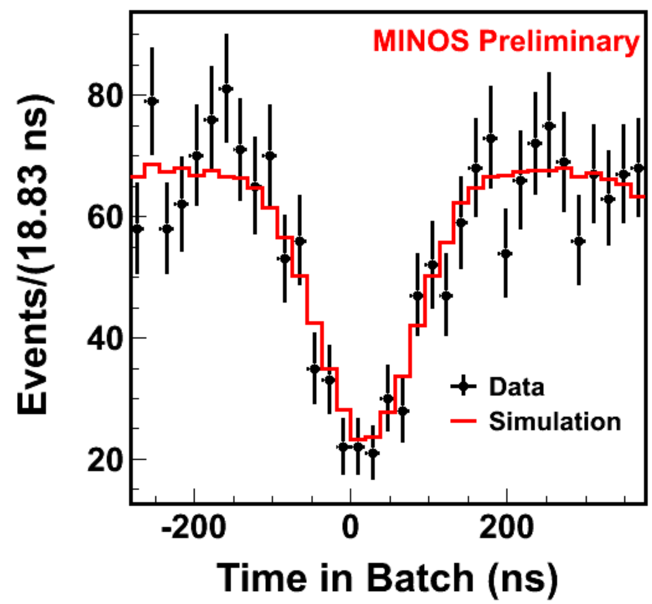
Total Systematic Error: 29 ns

THE ANALYSES

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

Two Analysis Approaches:



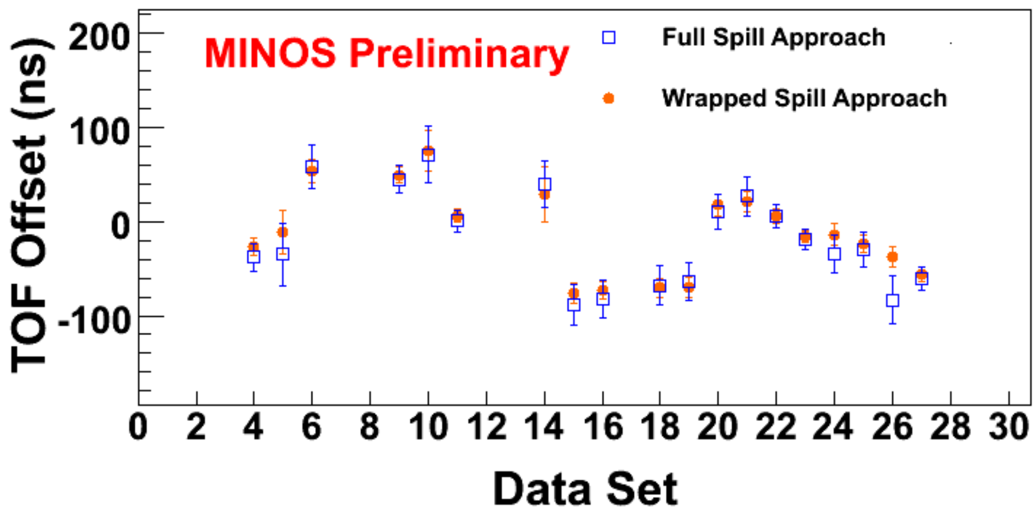


- Full spill approach
  - event time within spill in ND predicts FD distribution
  - Vary time of flight to match data

- 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 ± 11 (stat.) ± 29 (syst.) ns

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

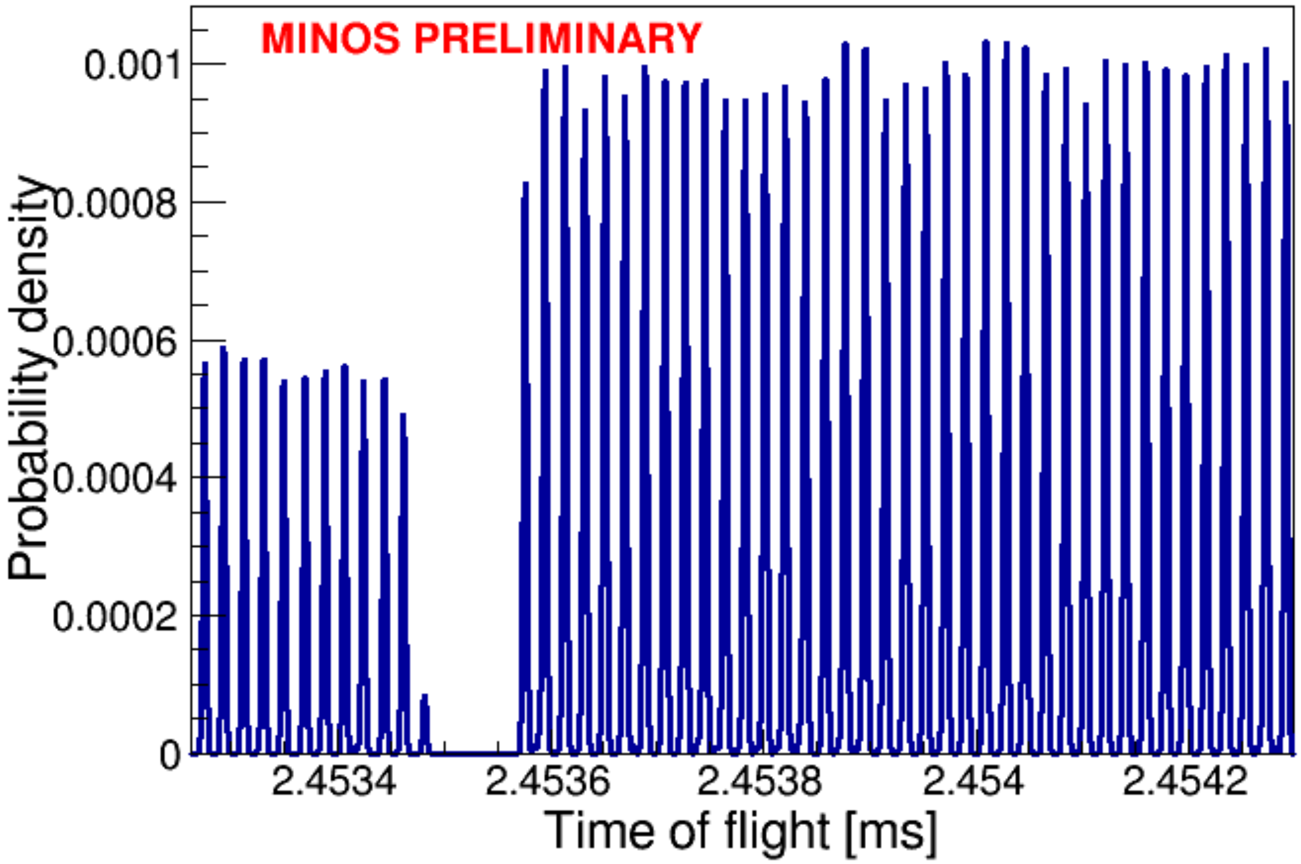
  11 ± 11 (stat.) ± 29 (syst.) ns

- 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

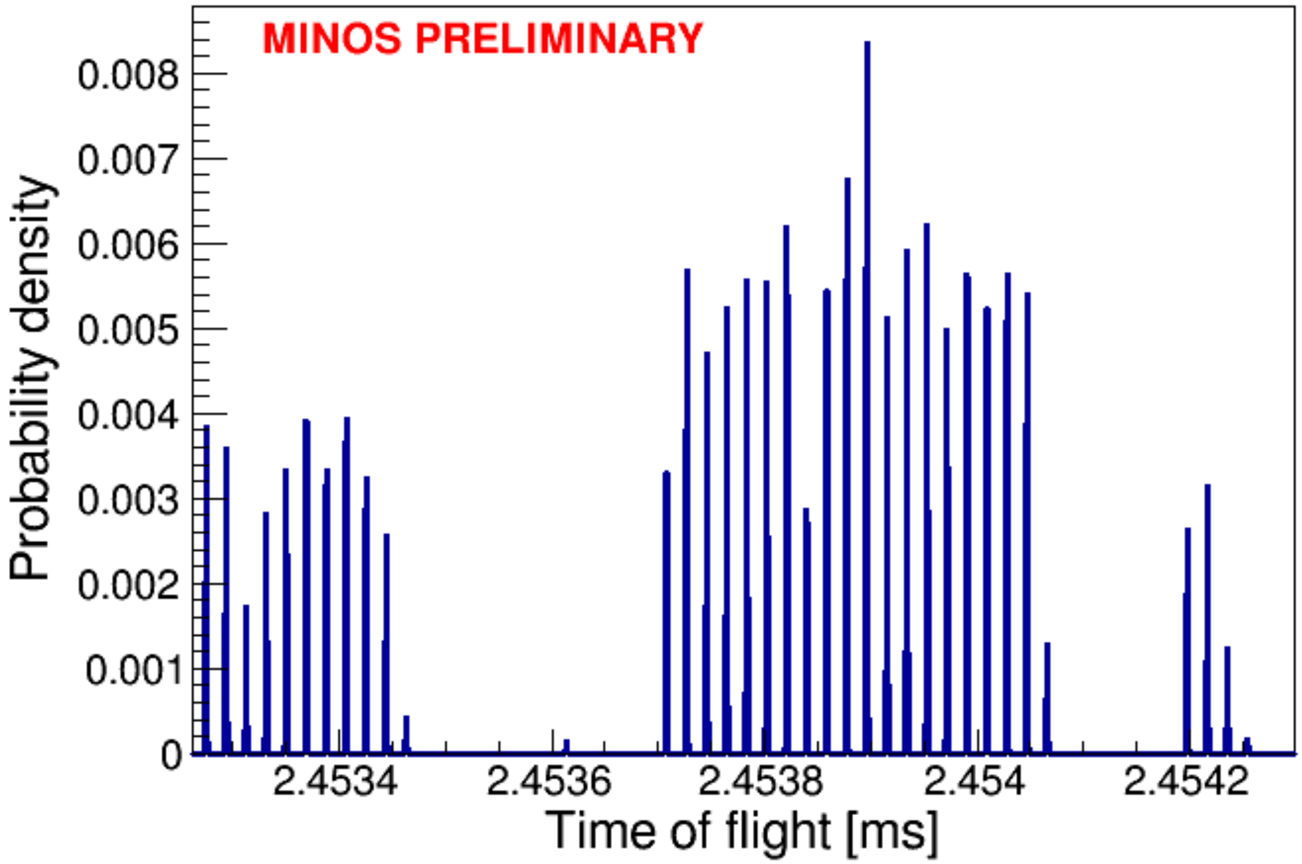
A NEW TIMING EFFORT

- Old GPS quoted 200ns accuracy
  - Actually does better
  - MINOS @Neutrino 2012: $\delta = -15 \pm 31$ 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

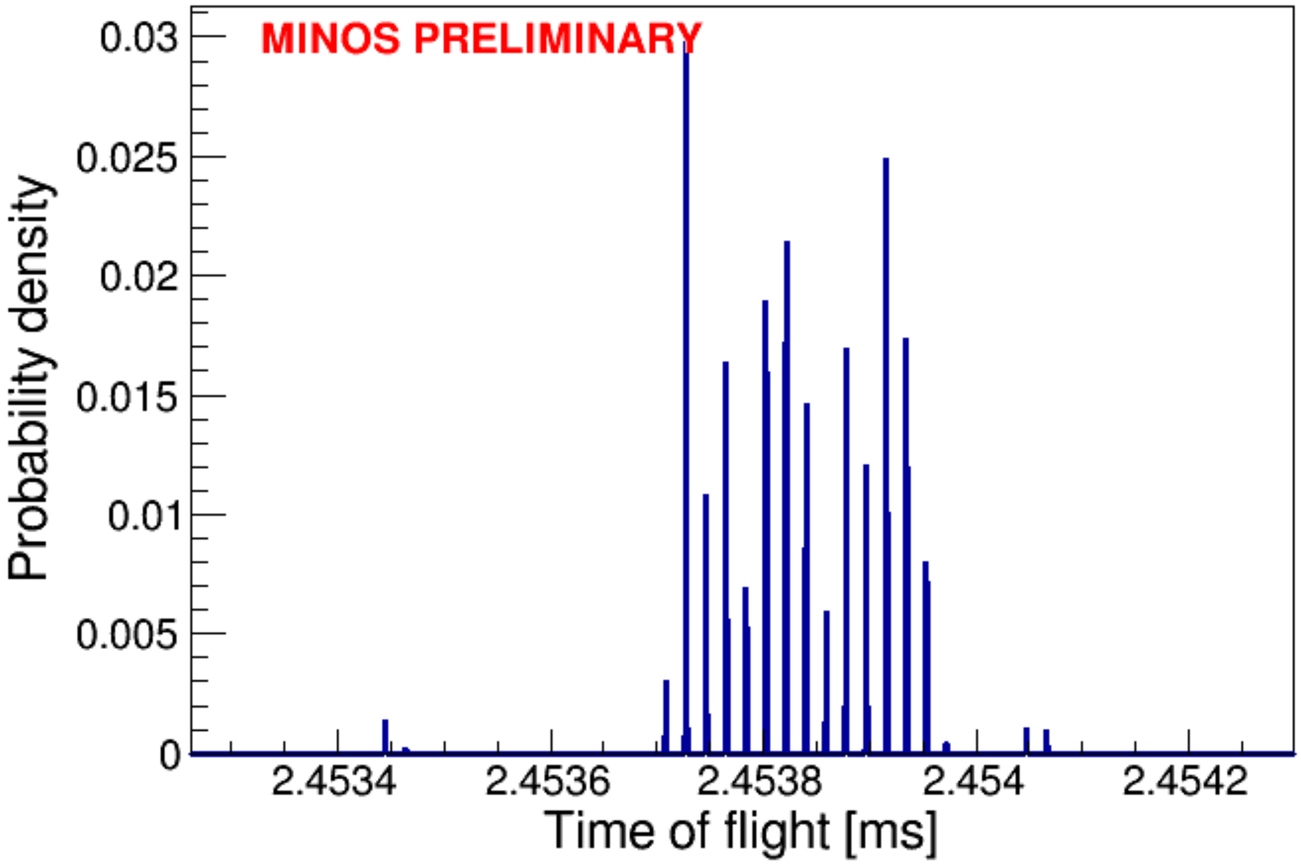
Time of flight after 1 event



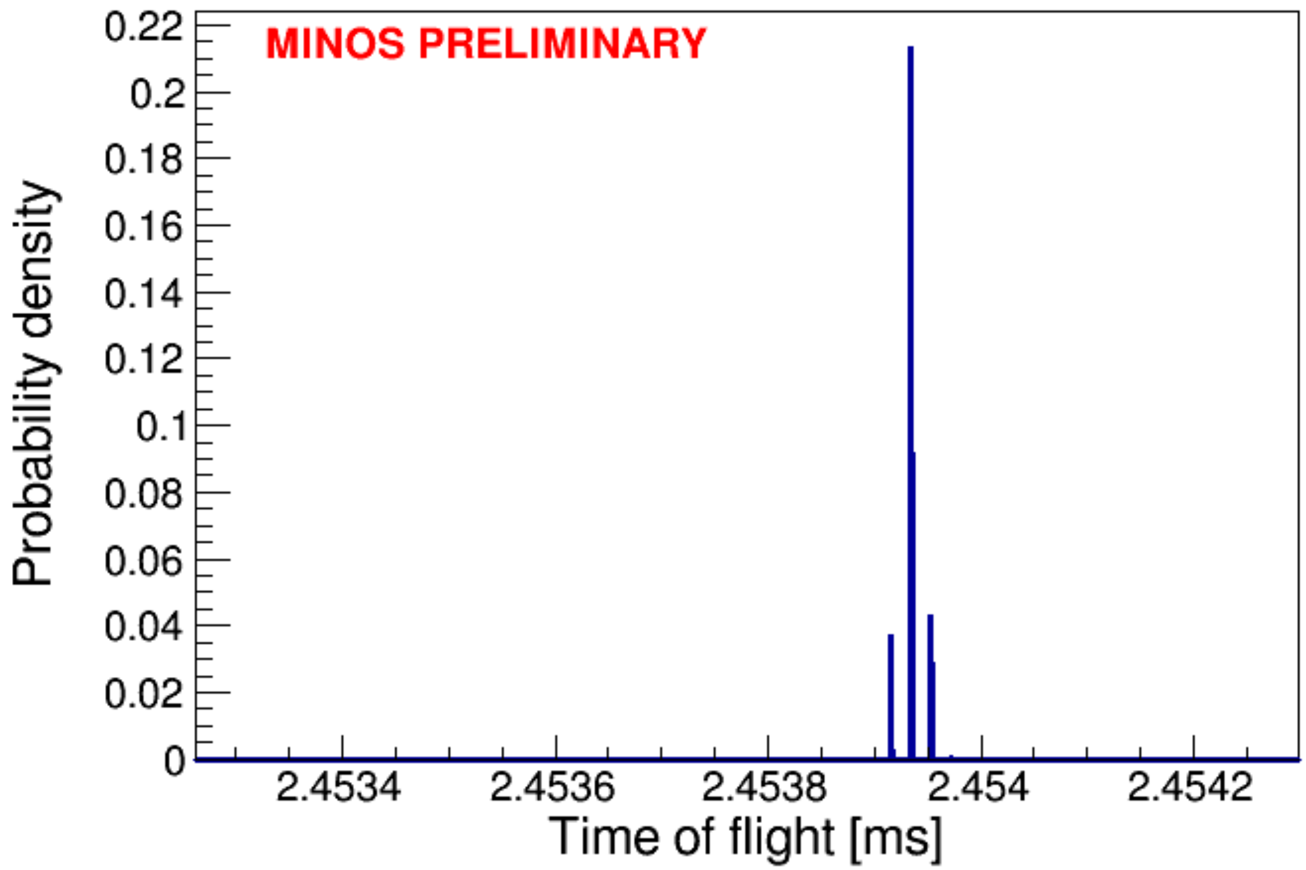
After 10 events



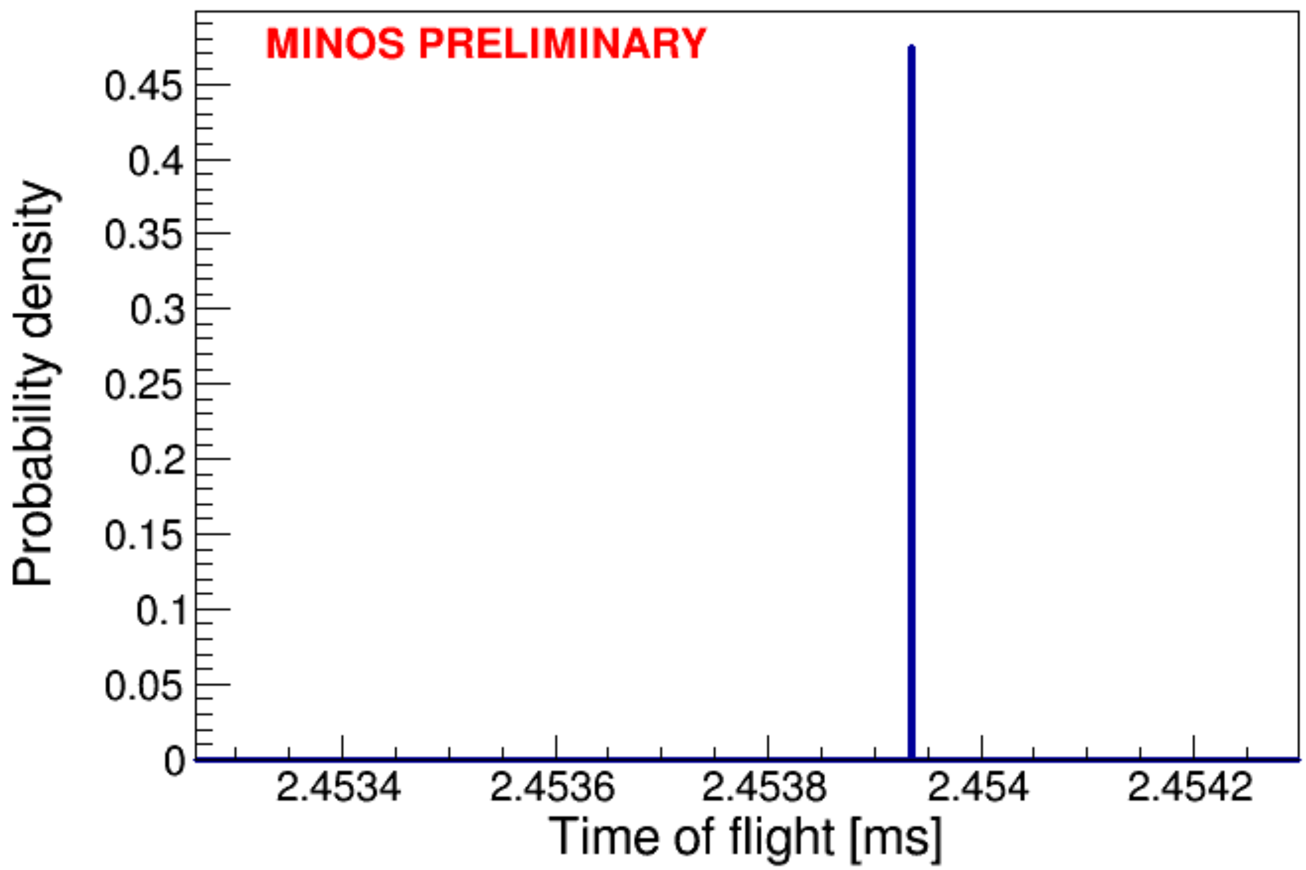
After 30 events



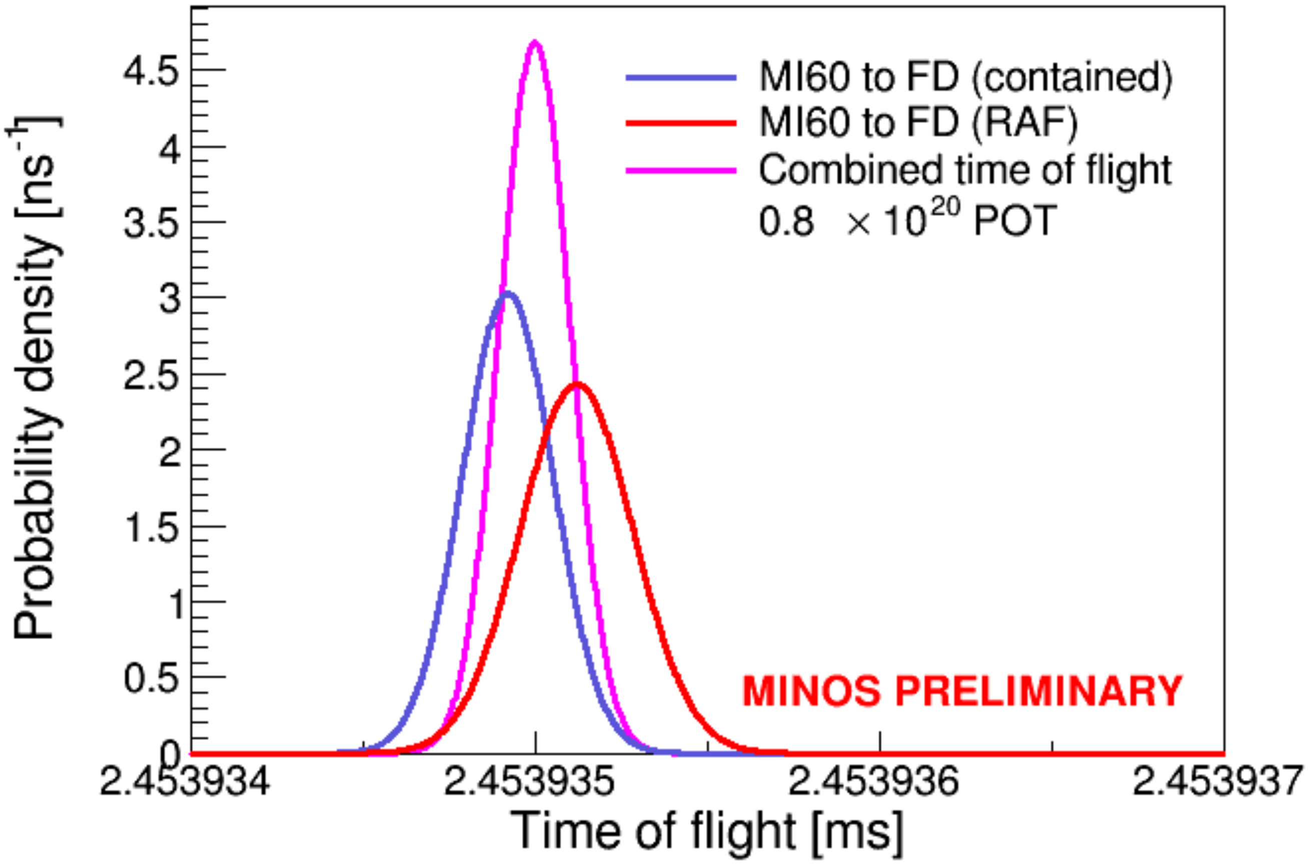
After 60 events



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**

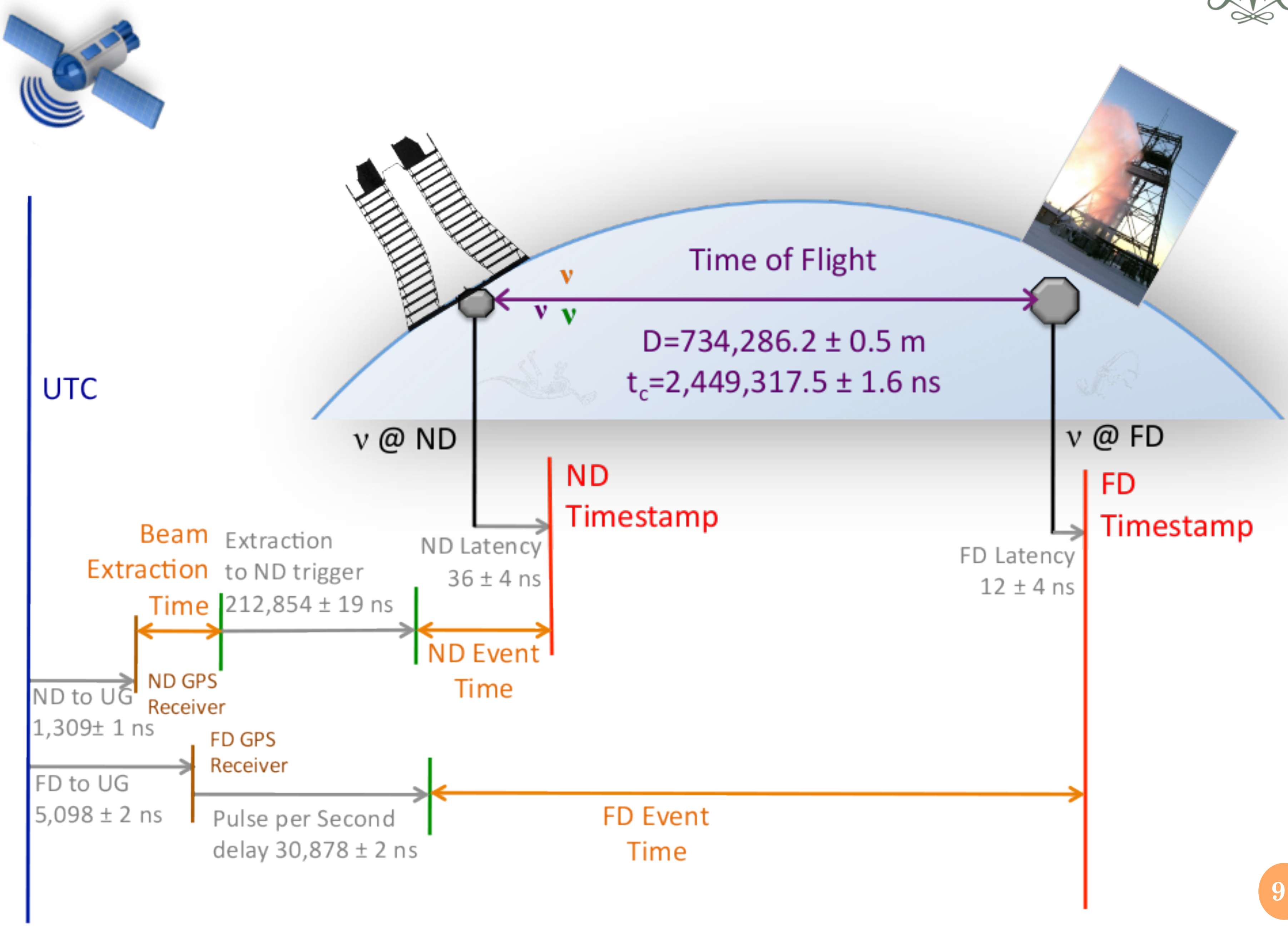
- Baseline ND – FD = 2,449,316.3 ns
- Time of flight ND – FD = 2,453,935.0 ± 0.1-4621.1 = 2,449,313.9 ns

- 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

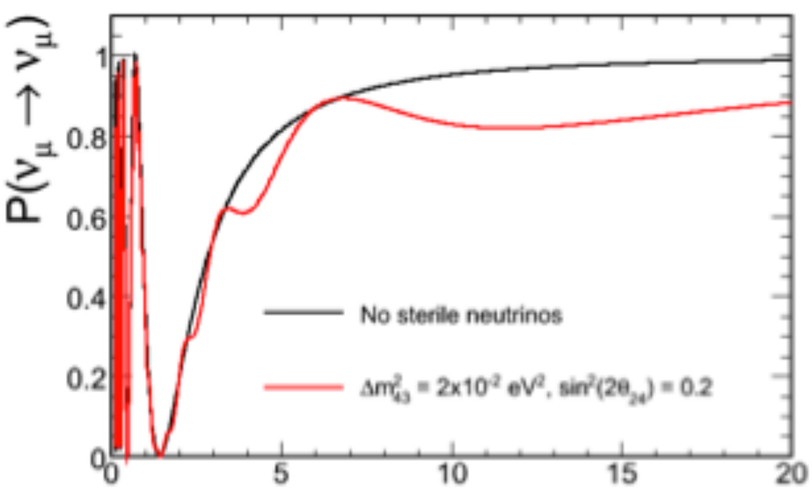


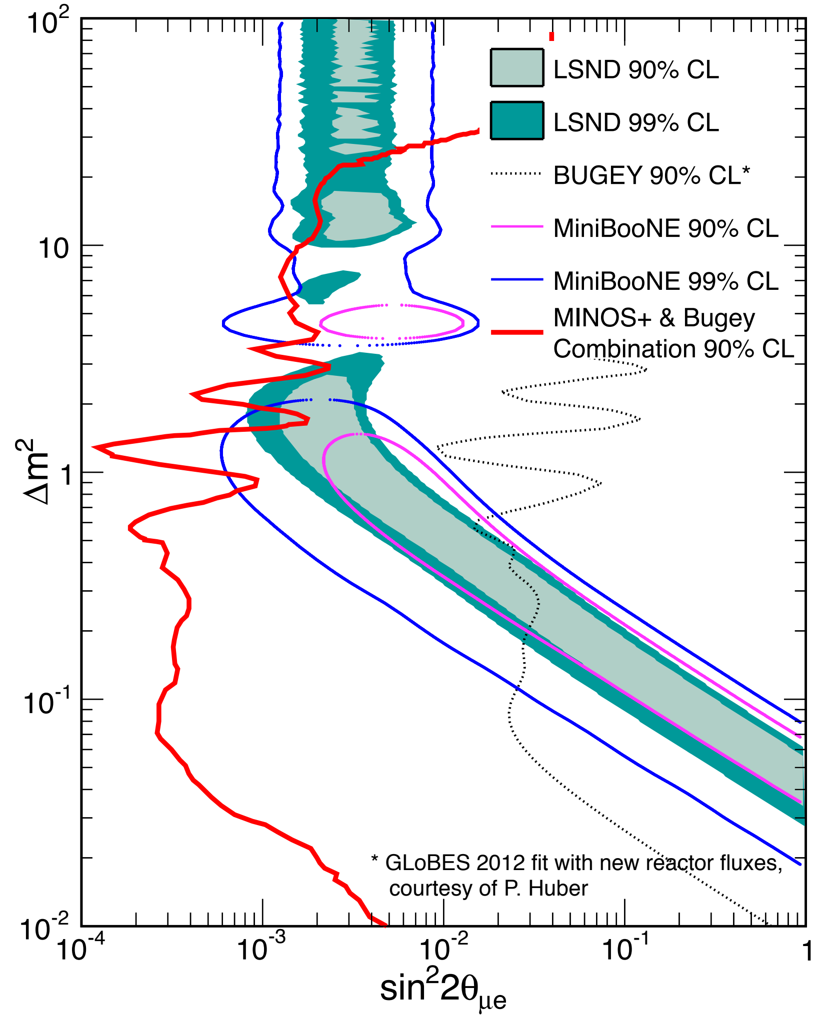
UPDATES FROM NEUTRINO2012

Photo of S. Bertolucci talk (courtesy A. Sousa)

MINOS+

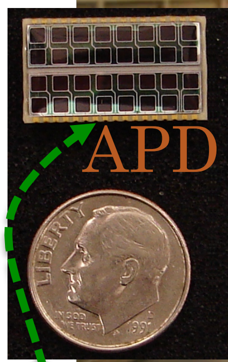
- Using complementary information from Bugey, MINOS+ can almost rule out the the low mass LSND region

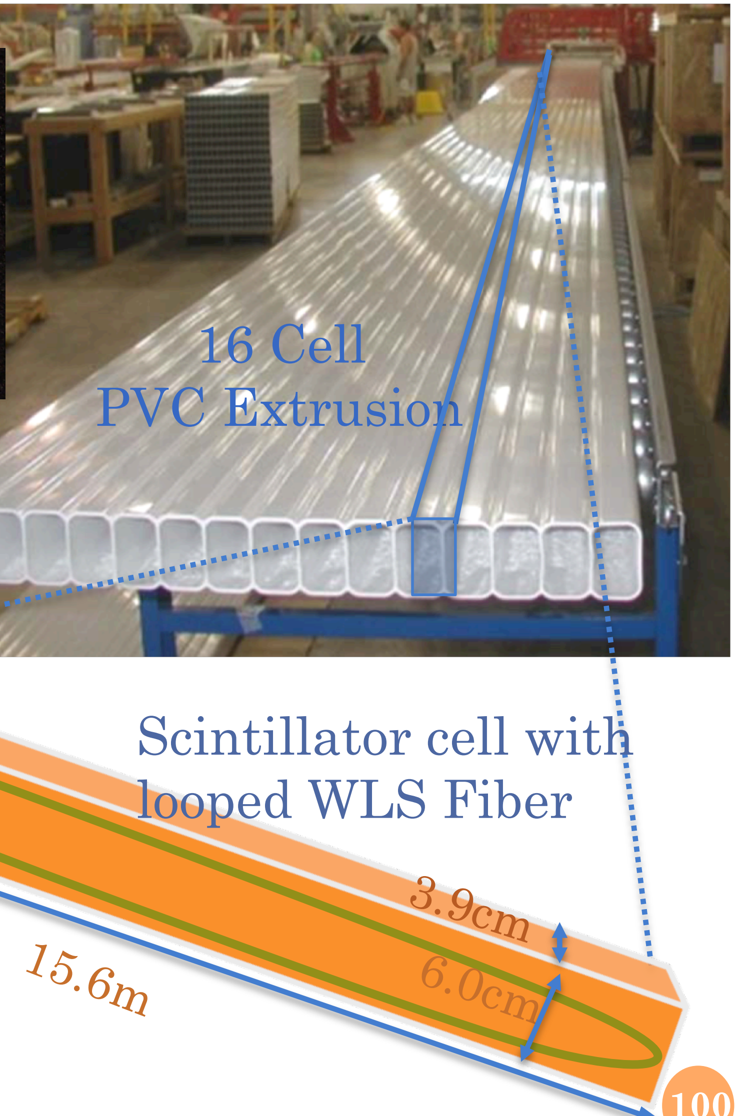


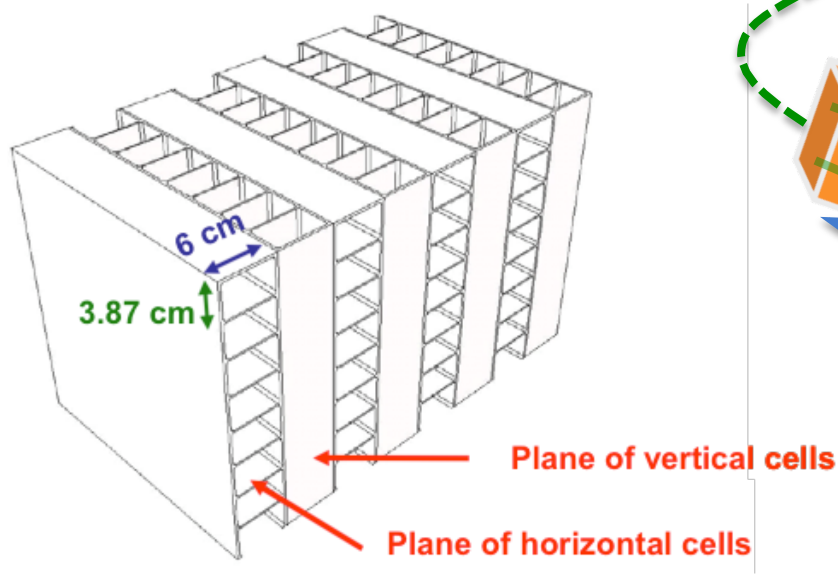


Detector Technology

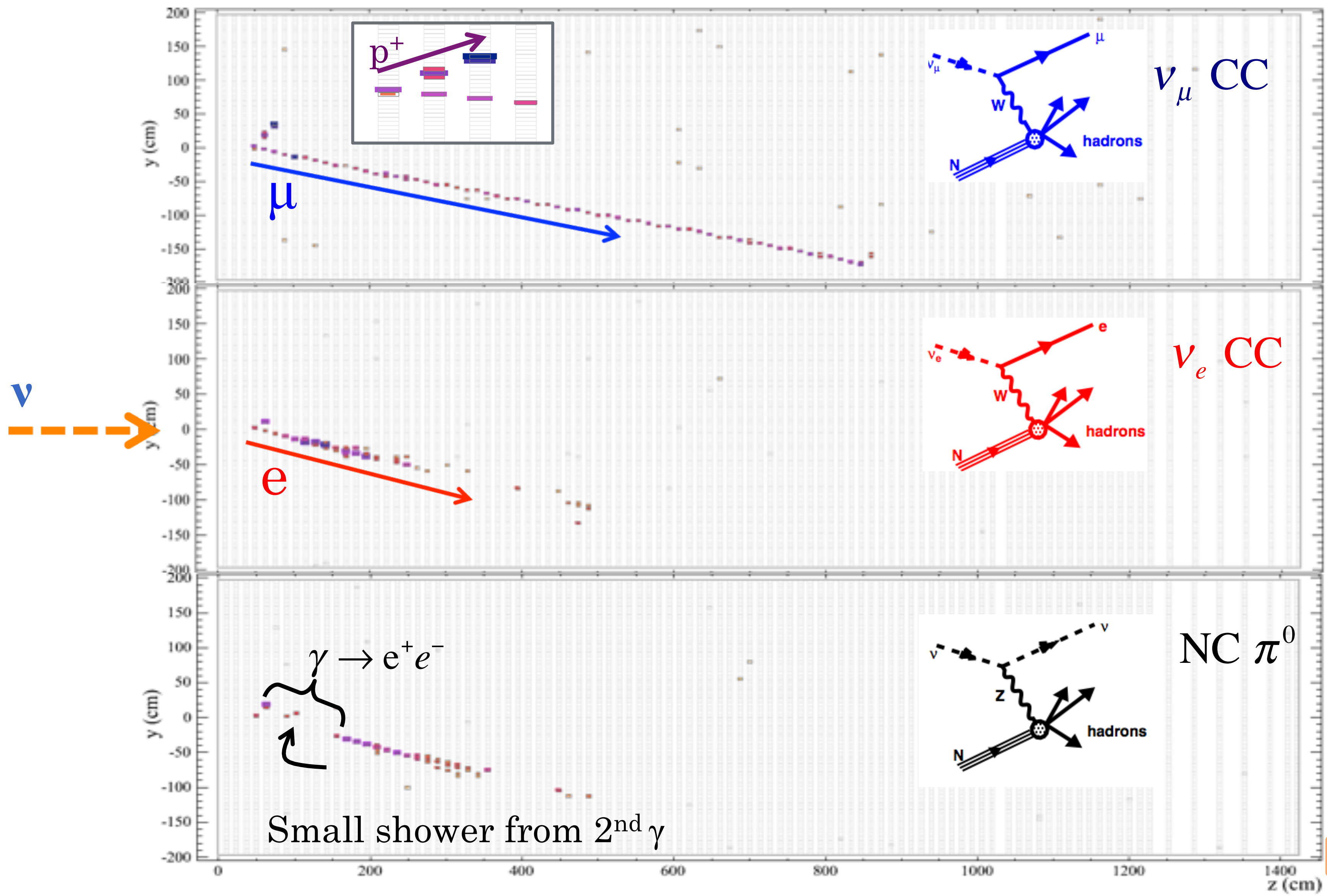
- PVC extrusion + Liquid Scintillator
  - mineral oil + 5% pseudocumene
- Read out via WLS fiber to APD
- Layered planes of orthogonal views
- muon crossing far end=38 PE
- 0.15 X0 per layer



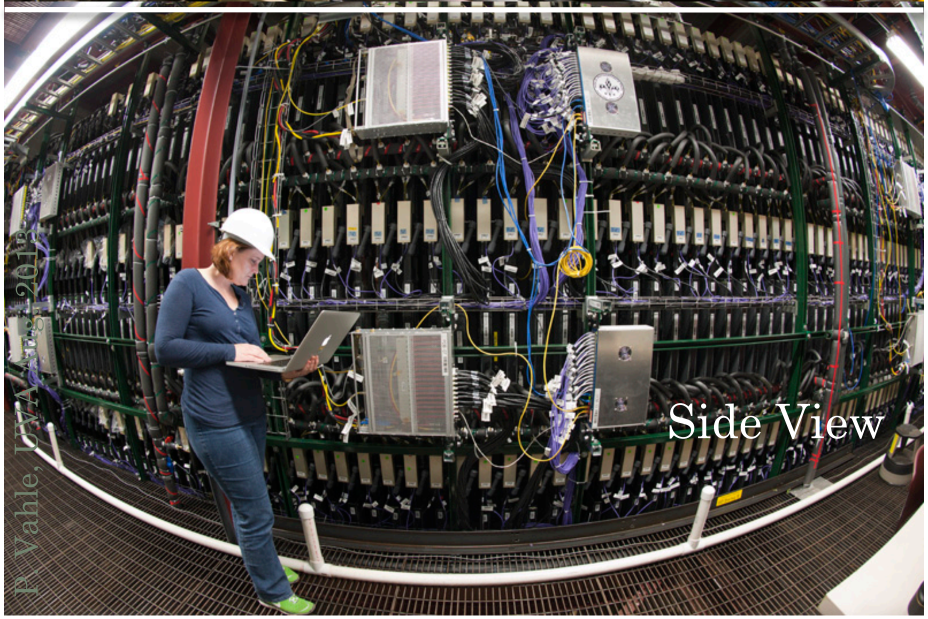




MC EVENTS IN NOVA



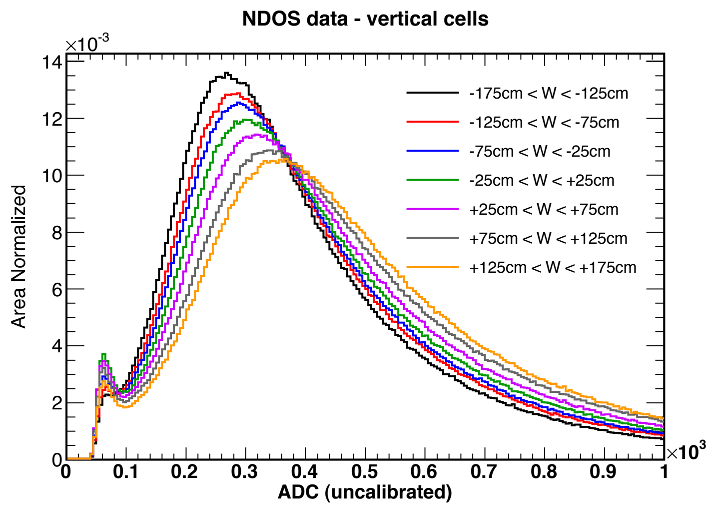
Lessons Learned

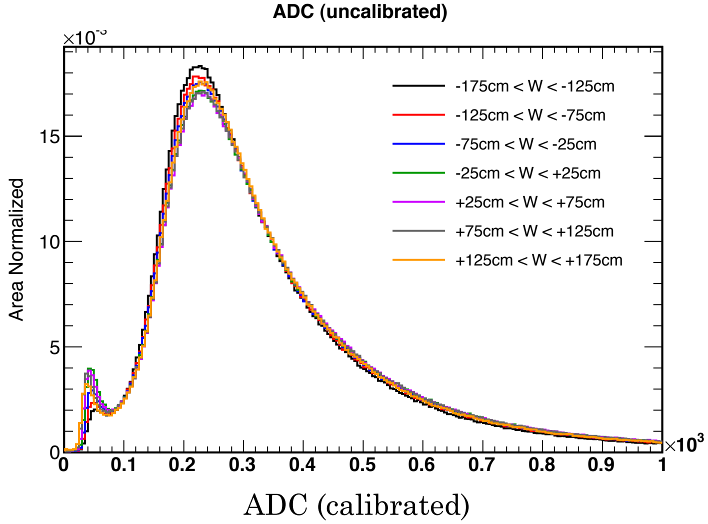


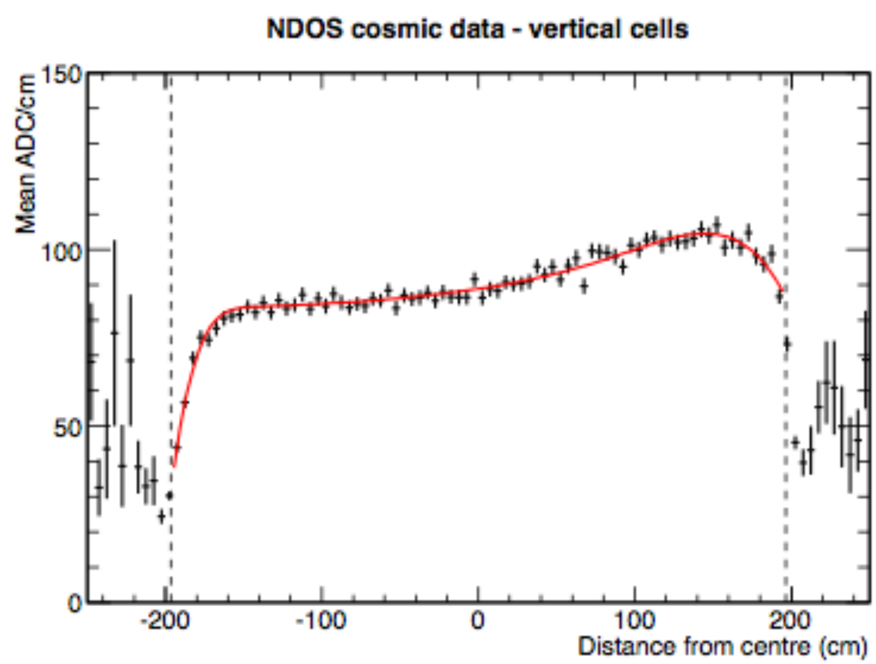
- 22% of module manifolds developed cracks during detector installation
  - “Splints” to fix NDOS
  - Changes to pressure testing
  - Redesign of manifolds
- APDs and oil do not mix
  - plan to coat APDs with epoxy
  - revamped procedures to ensure cleanliness is maintained during industrial scale installation

CALIBRATION

- Cosmic muons provide intra-detector calibration source



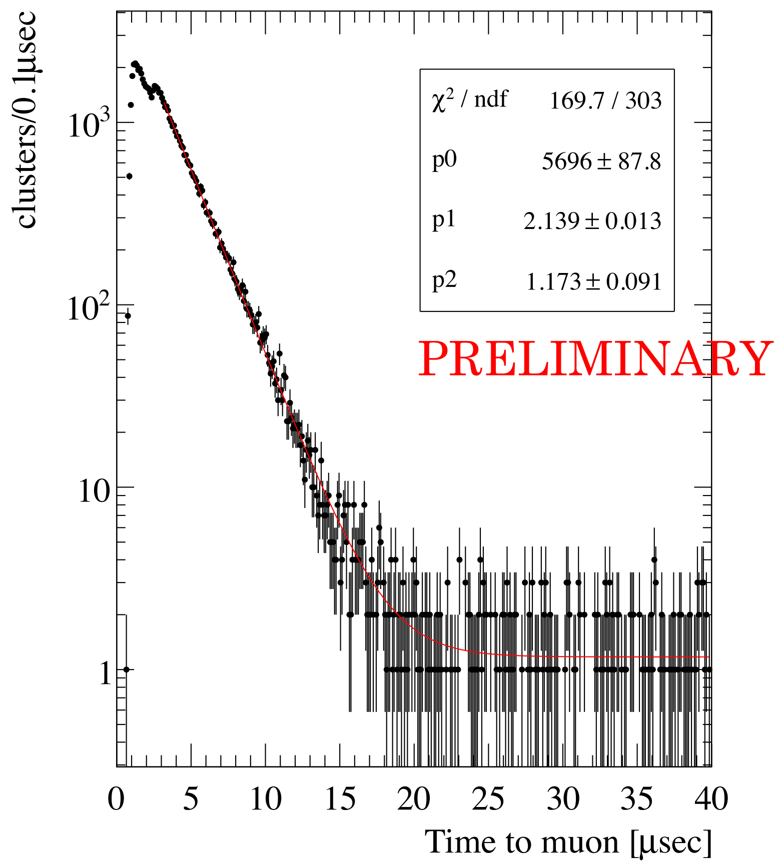


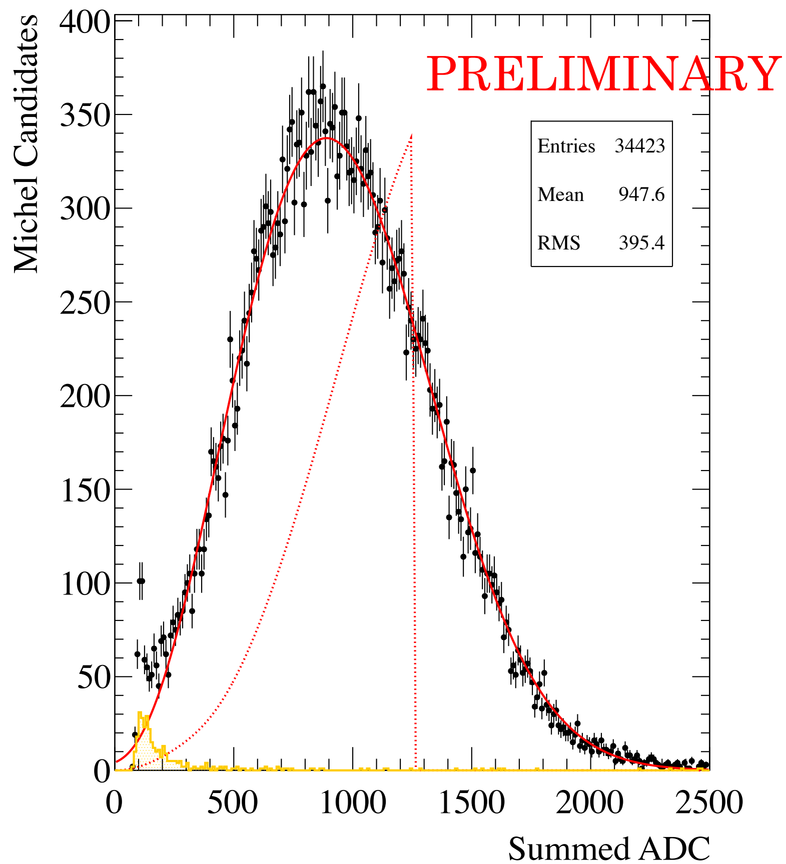


P. Vahle, UVA Aug. 2013

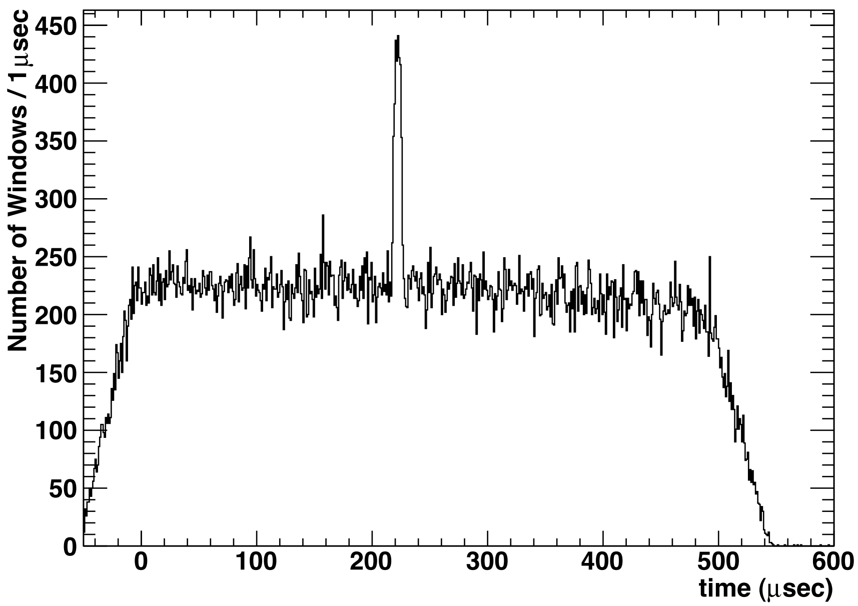
MICHEL ELECTRONS

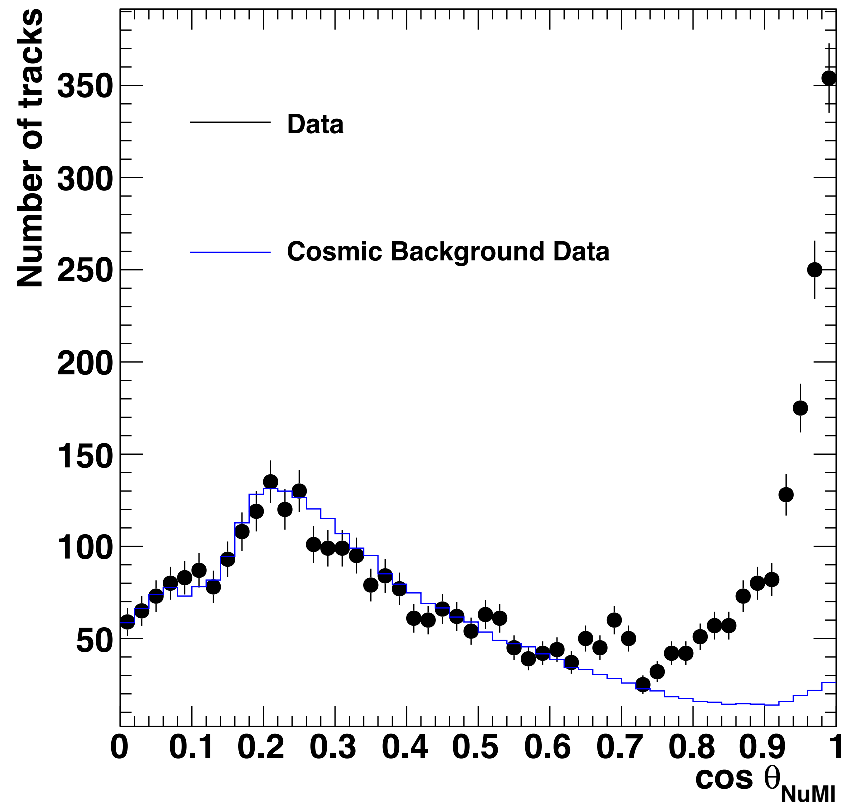
- Use Michel electrons for electro-magnetic energy calibration





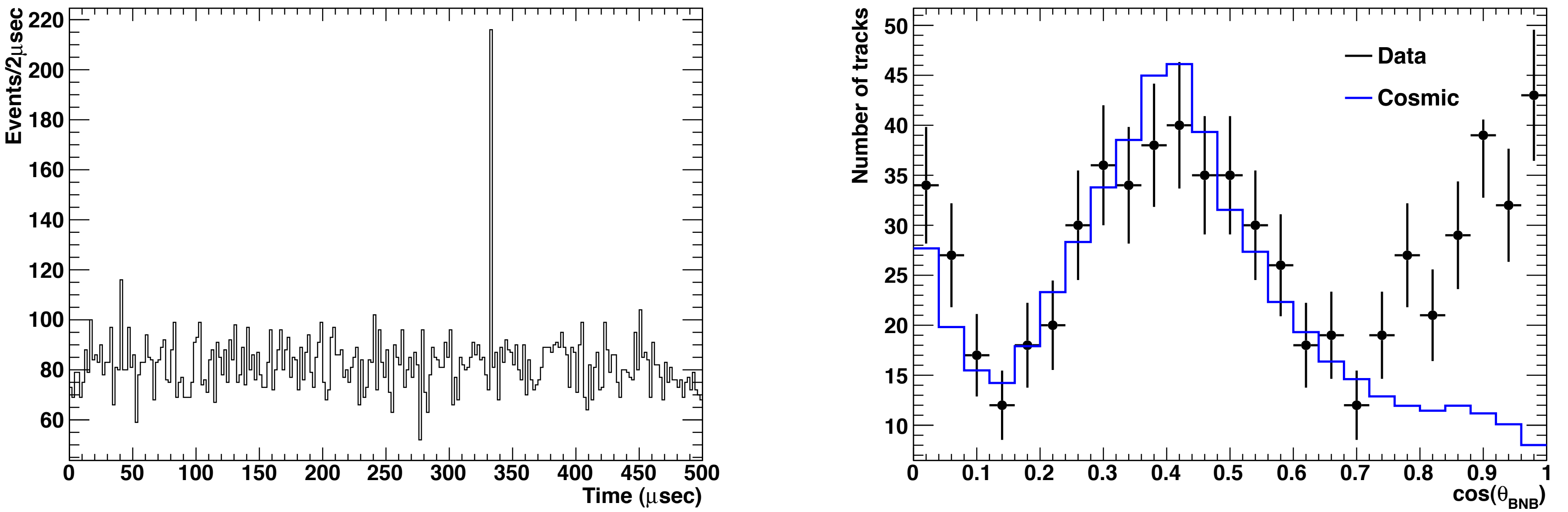
FINDING NUMI NEUTRINOS





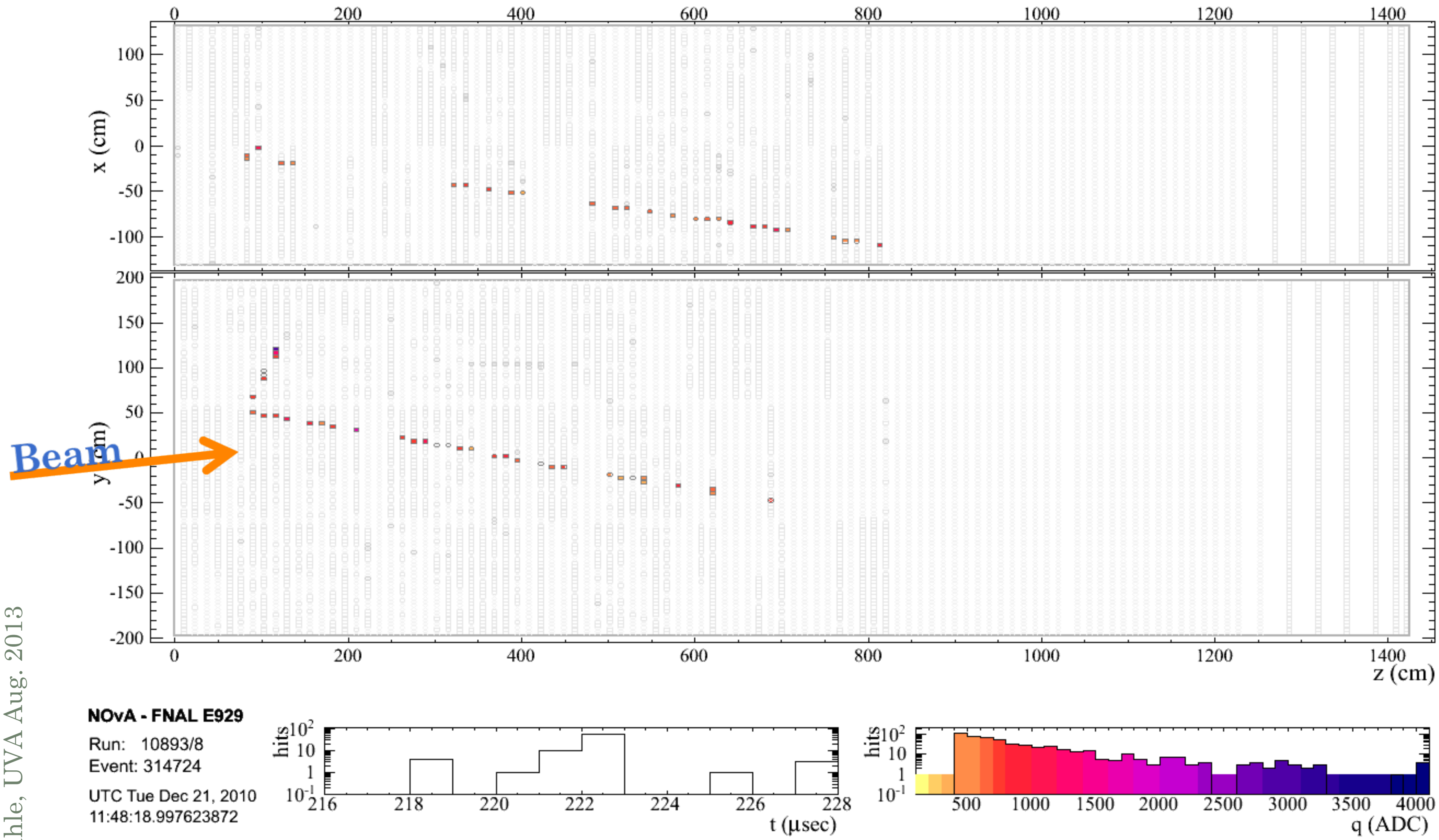
- 110 mrad off NuMI axis
- 5.6×10^{19} POT reverse horn current beam, 1001 NuMI events (69 cosmic BG)
- 8.4×10^{18} POT forward horn current beam, 253 NuMI events (39 cosmic BG)

Finding Booster Neutrinos



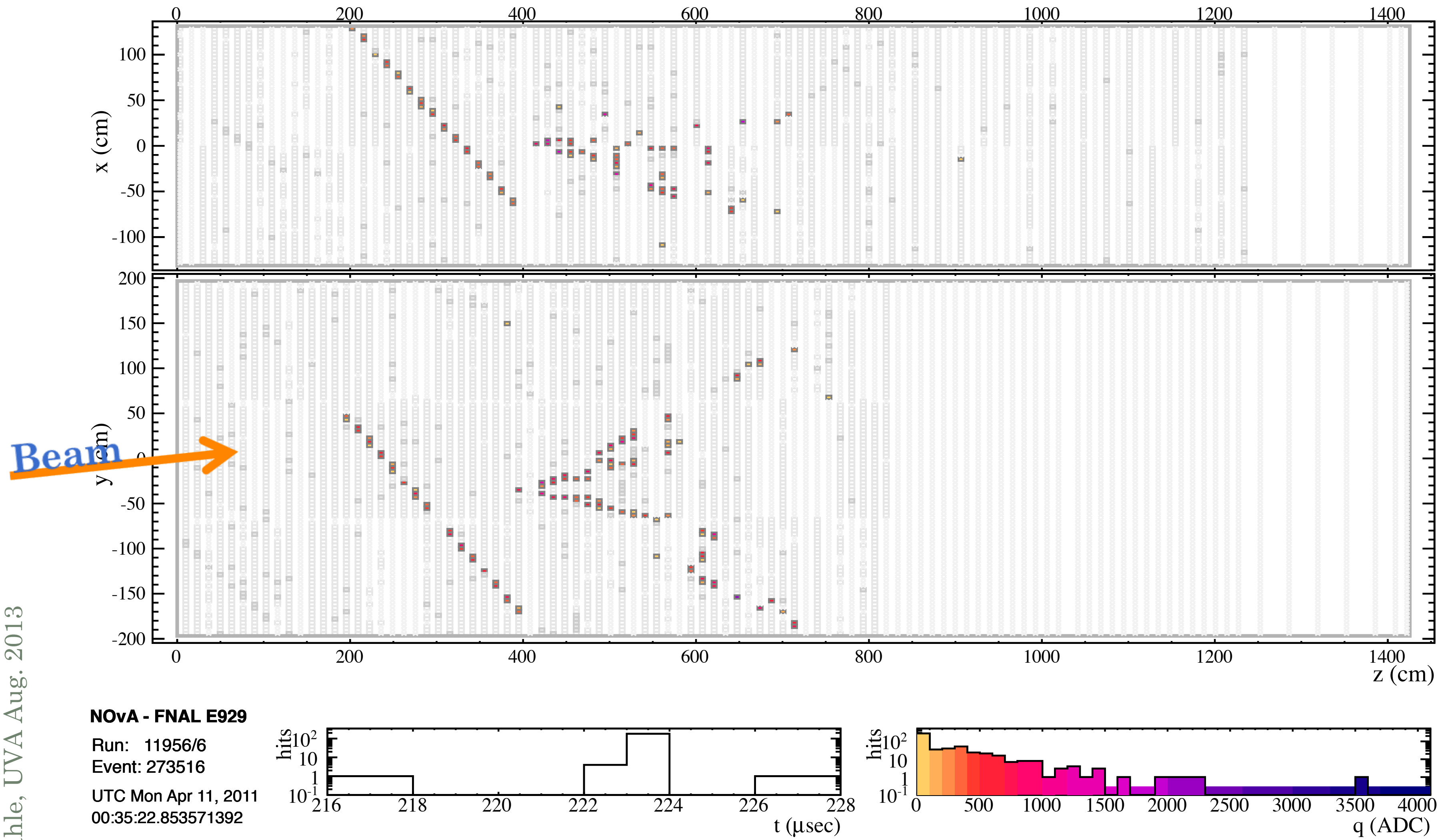
- NDOS nearly on Booster axis
- Detector rotated wrt axis
- $3x10^{19}$ POT, 222 booster events (92 cosmic BG)

NEUTRINOS



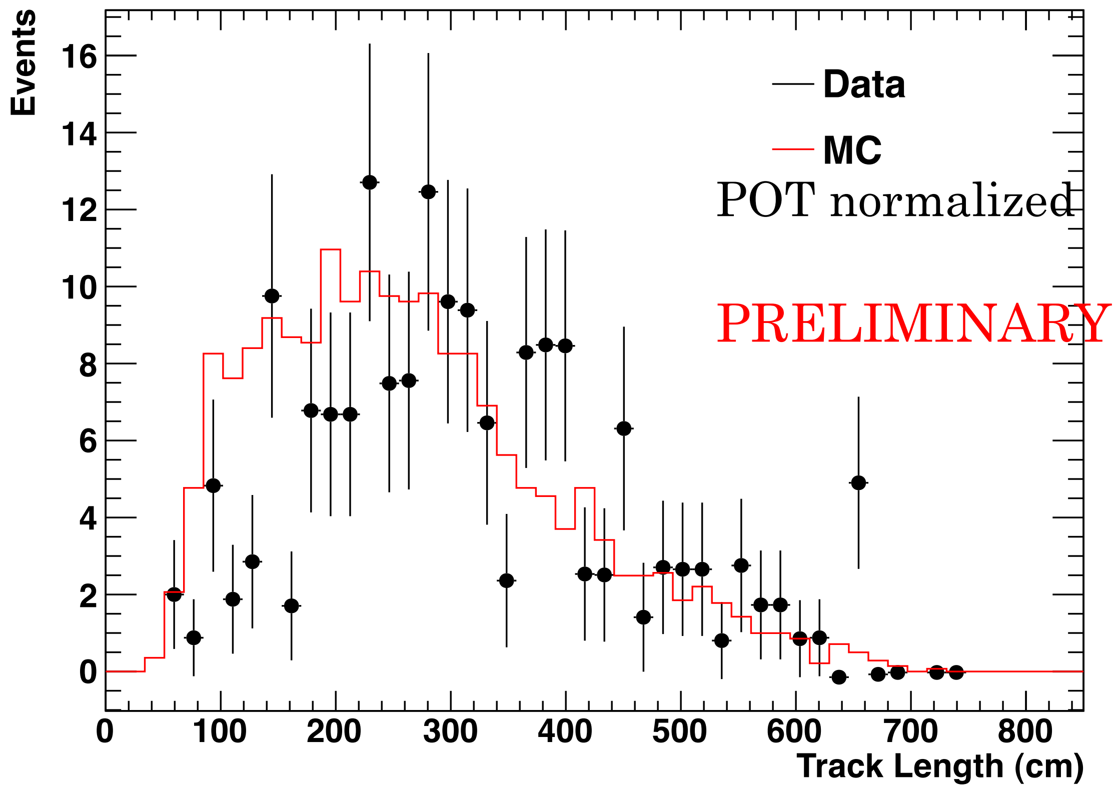
Beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 10893/8
Event: 314724
UTC Tue Dec 21, 2010
11:48:18.997623872
hits
t (μsec)
q (ADC)

NEUTRINOS



Beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 11956/6
Event: 273516
UTC Mon Apr 11, 2011
00:35:22.853571392
hits
t (μsec)
q (ADC)

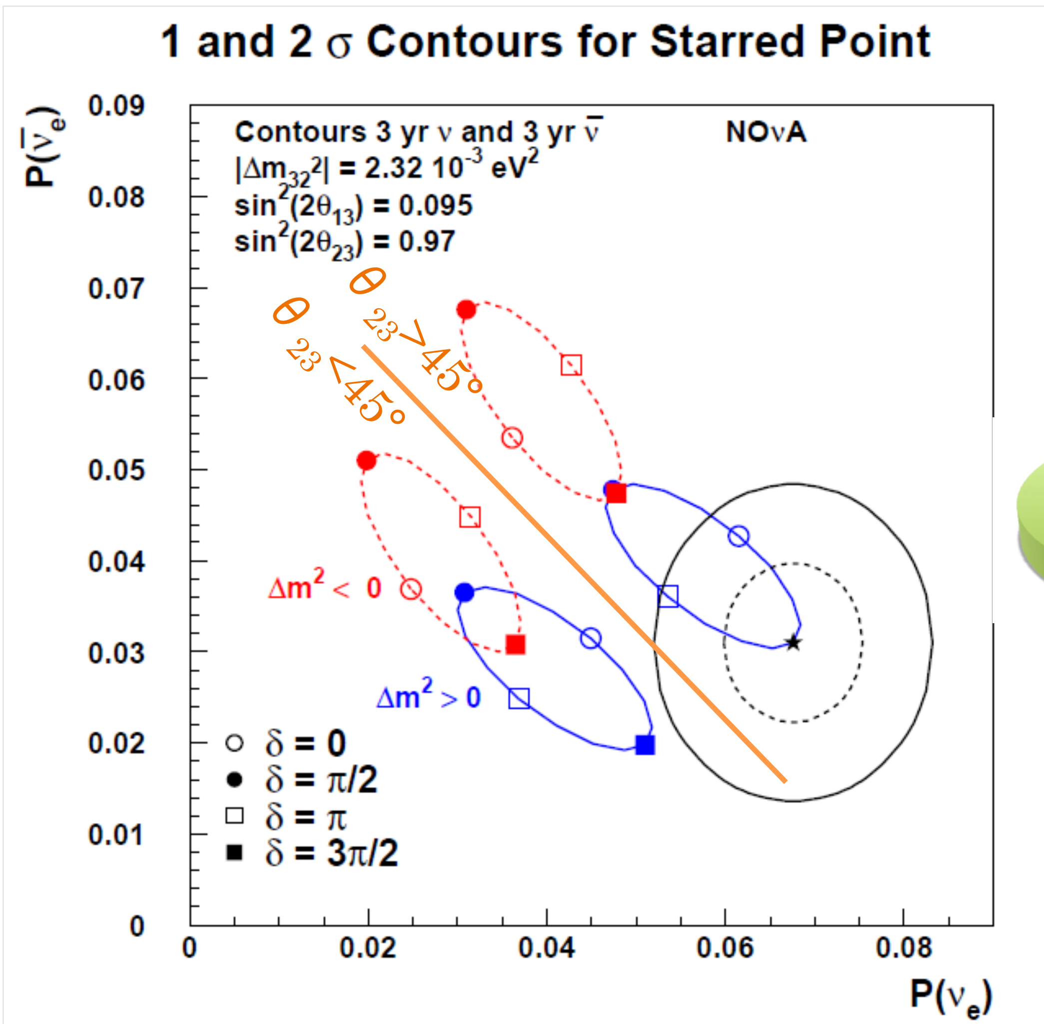
Comparisons to MC

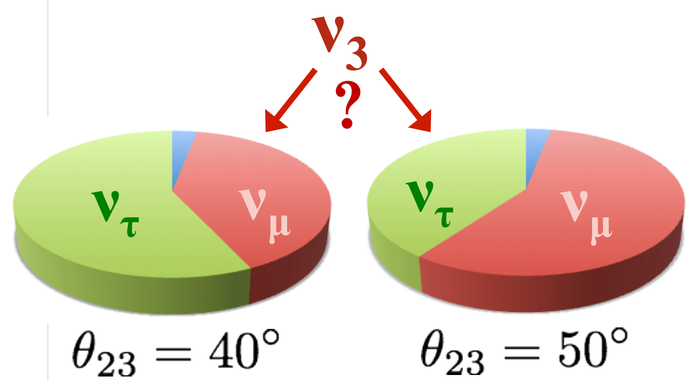


- Early look at contained events indicates NuMI MC event rate agrees with data

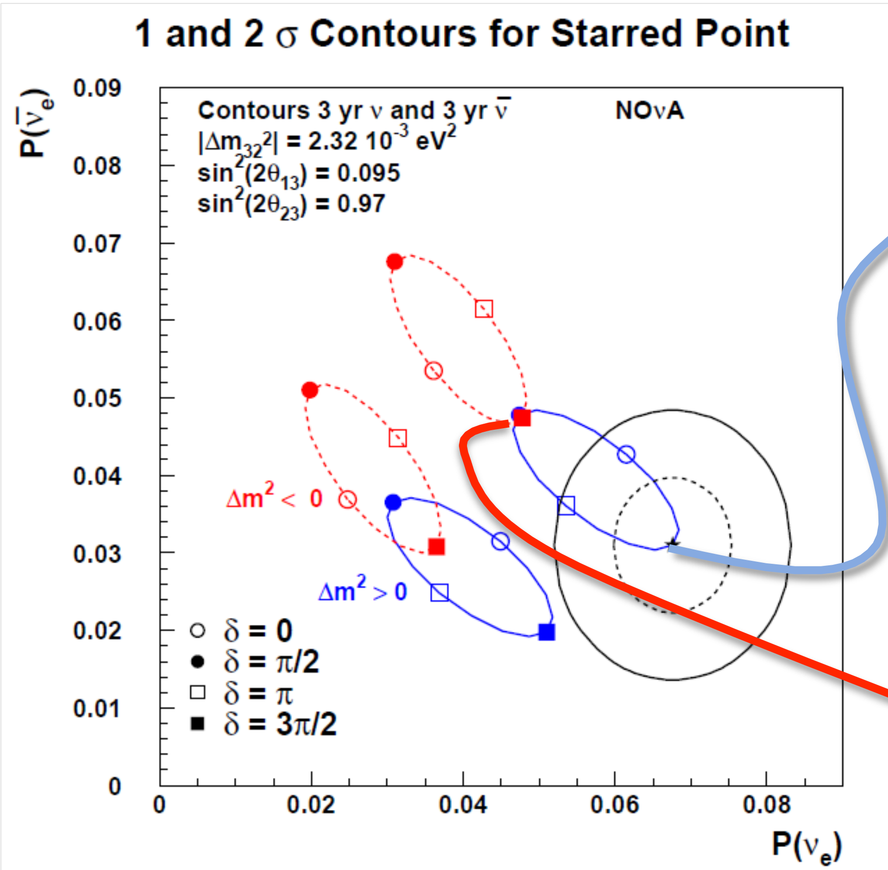
HOW ITS DONE

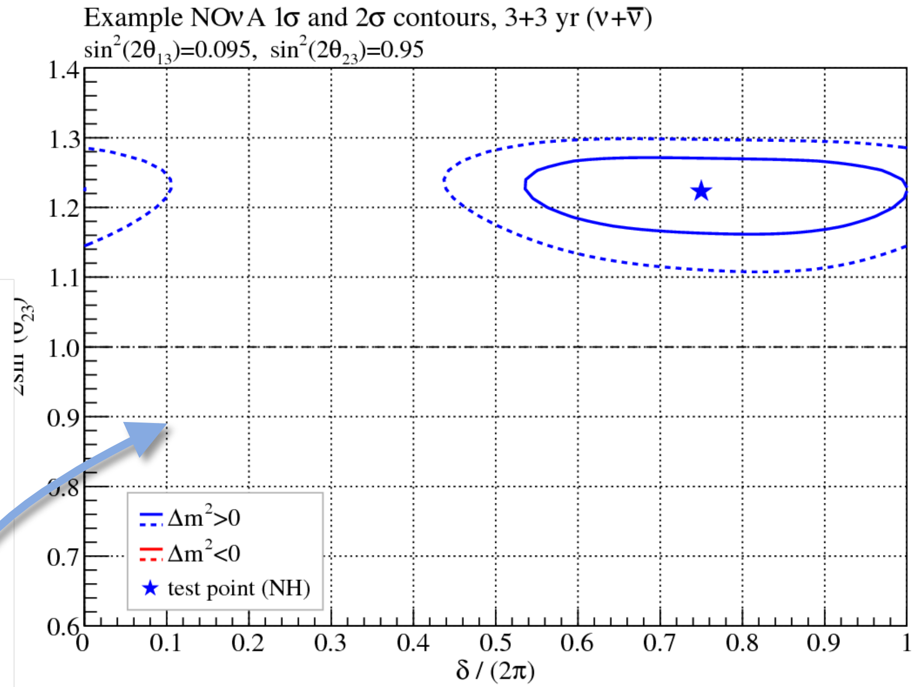
- Compare oscillation probability measured with neutrinos and antineutrinos

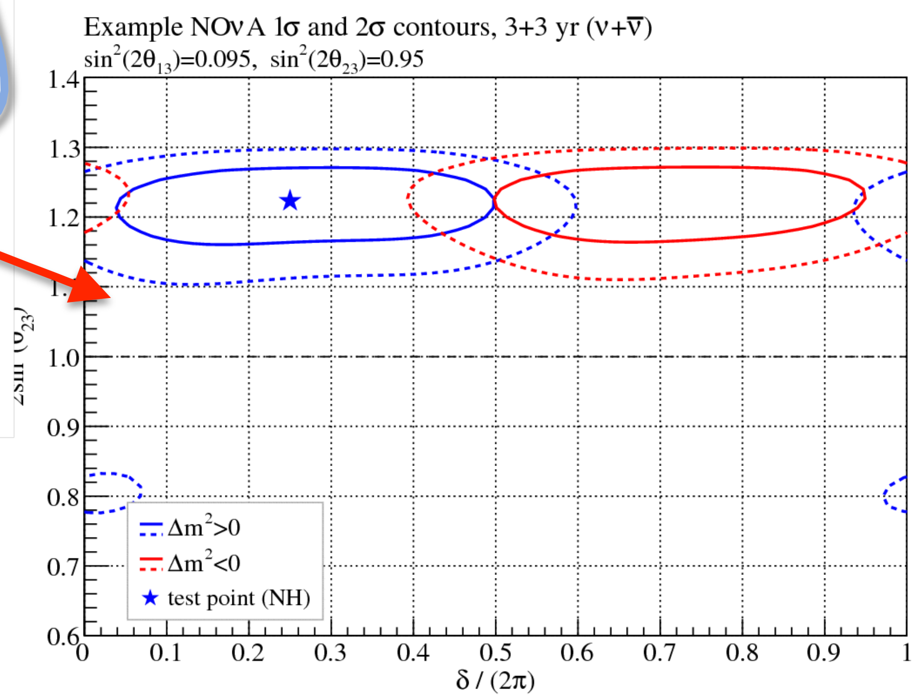




Octant Sensitivity

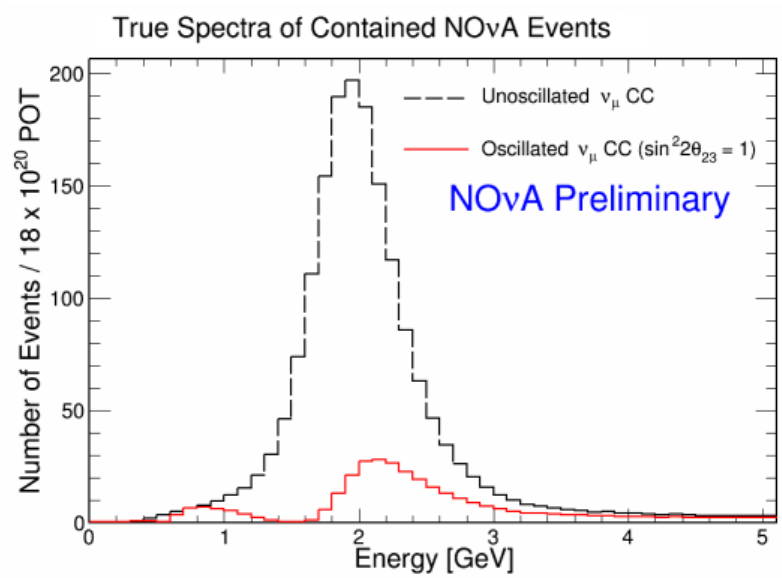


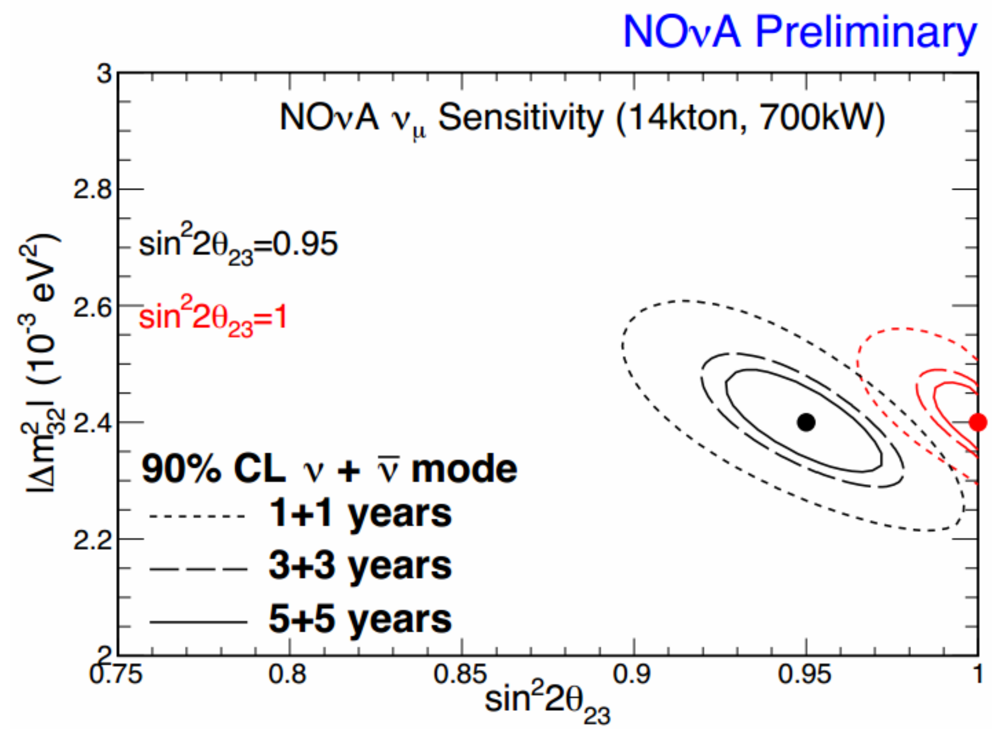




Combining appearance and disappearance

Muon Neutrino Disappearance

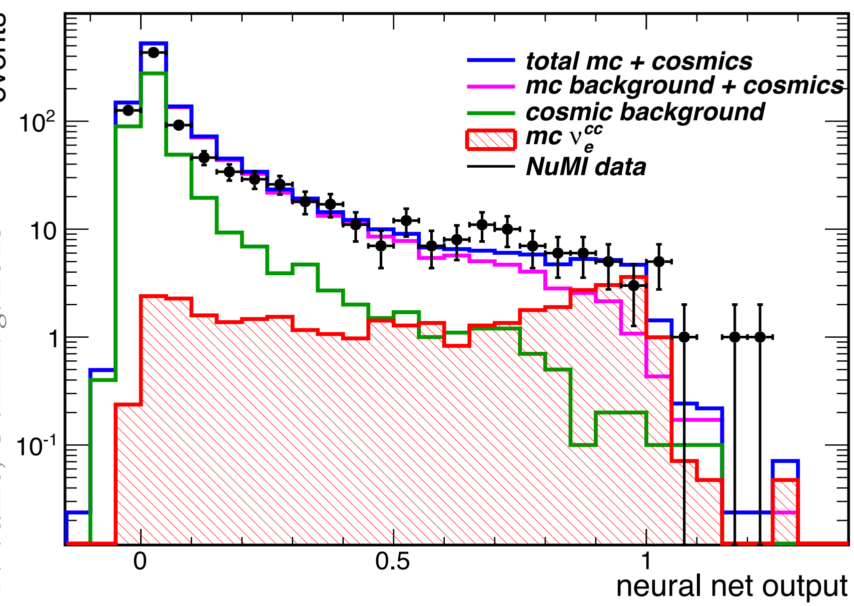




- If $\sin^2 2\theta_{23} = 0.95$, able to exclude (at 90% CL) maximal θ_{23} after 1+1 years

NDOS

- Prototype detector in the NuMI and Booster beams
- Benchmark simulation/ reconstruction against real neutrino events
- We can find the 2% electron neutrino contamination of the beam!



ENuMI

More NoVA

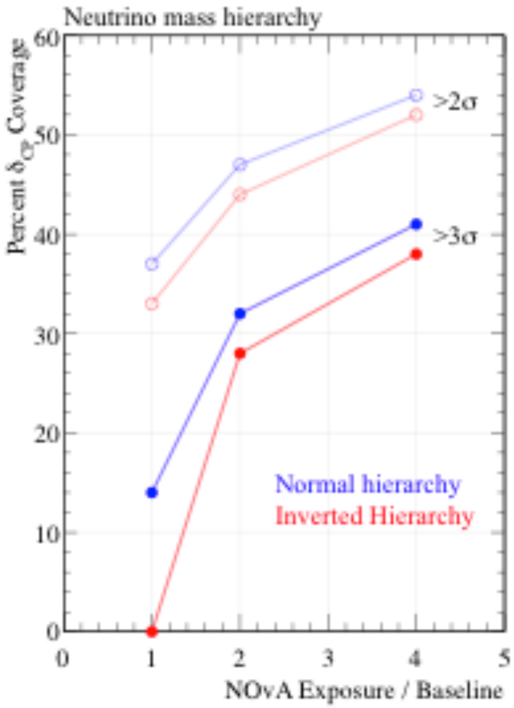


Figure 2: The percent of δ_{CP} values for which NOvA can resolve the neutrino mass hierarchy at 2 and 3σ C.L.

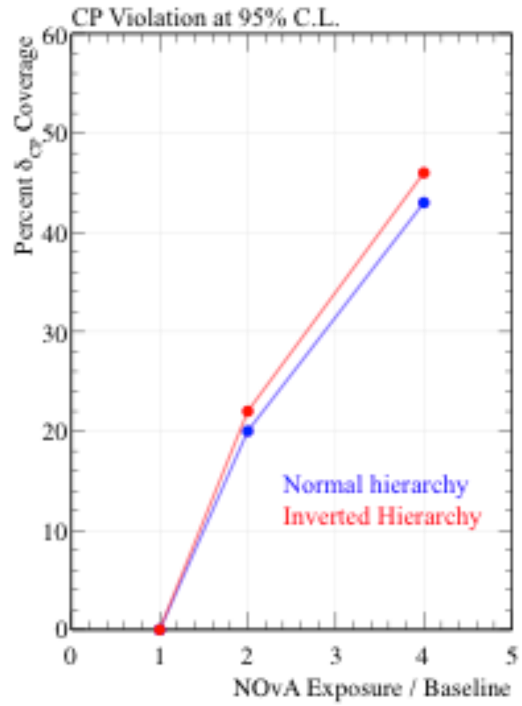


Figure 3: The percent of δ_{CP} values for which NOvA can establish CP violation at 95% C.L. or better.

RADAR

- Add LAr detector at Ash River

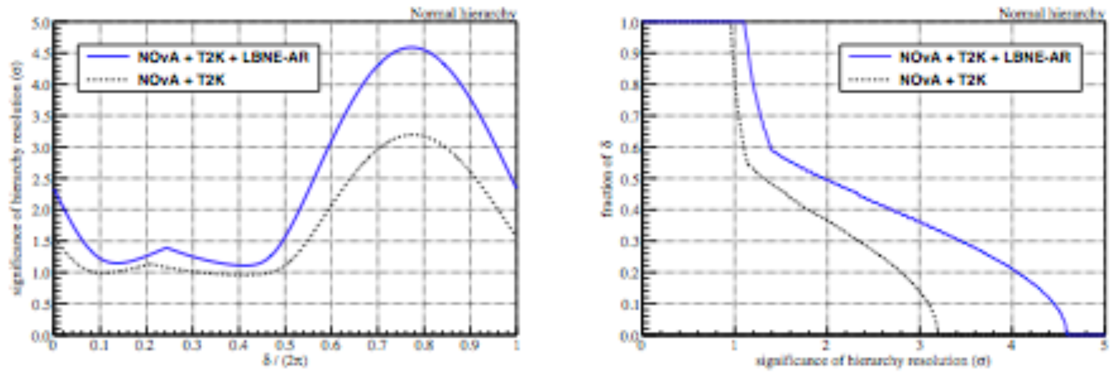


Figure 1: The significance of hierarchy resolution for NOνA +T2K alone (black dashed) and with LBNE-AR added (blue solid), shown both as a function δ (left) and in terms of the fraction of δ values covered at a given confidence level. Normal hierarchy and maximum mixing are used.

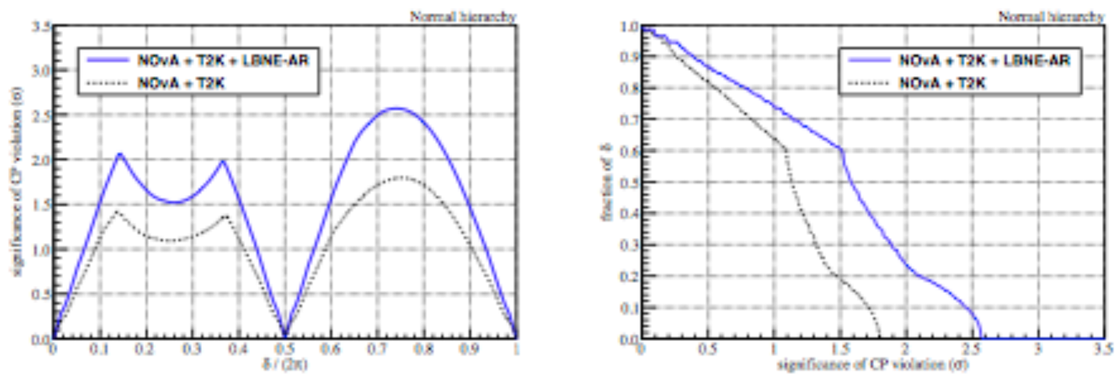


Figure 2: The significance of CP violation for NOνA +T2K alone (black dashed) and with LBNE-AR added (blue solid), shown both as a function δ (left) and in terms of the fraction of δ values covered at a given confidence level. Normal hierarchy and maximum mixing are used.

CHIPS Physics Reach

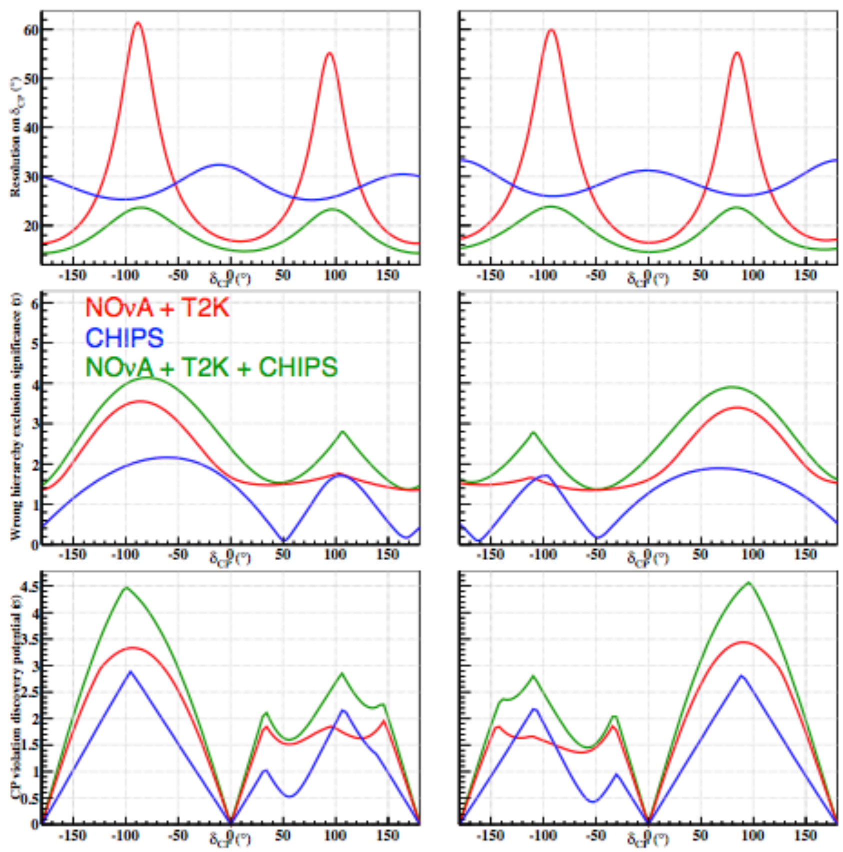


Figure 3: CHIPS physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOνA (5+5y) and T2K(8.8e21 POT), and CHIPS(3+3y). (Top) δ_{CP} resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOνA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

CHIPS IN LBNE

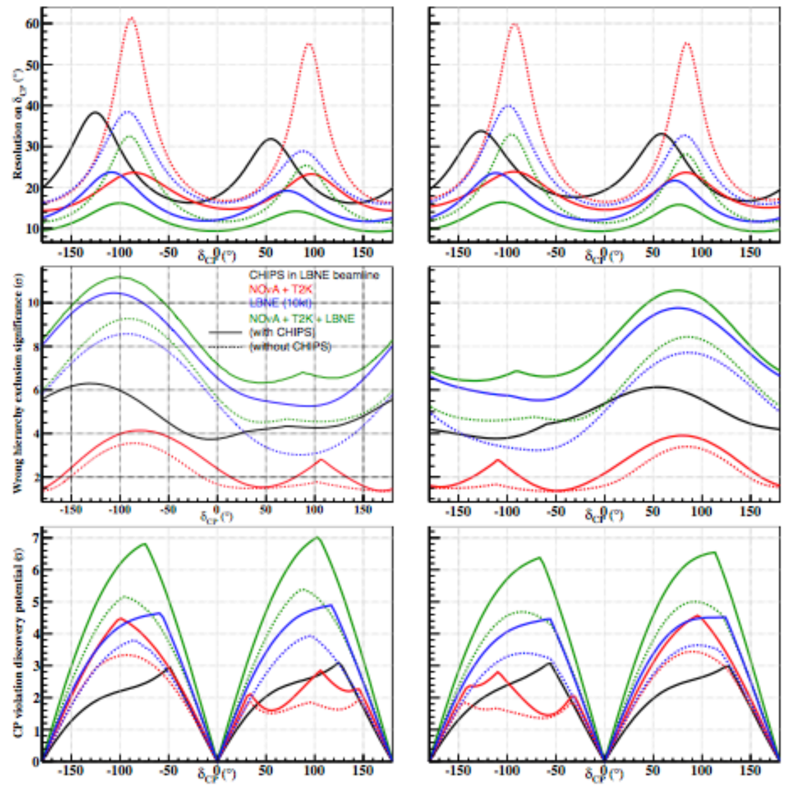


Figure 8: Physics reach in the Normal Hierarchy (left) and Inverted Hierarchy (right), for NOvA+T2K, 10 kton LAr LBNE, and CHIPS in the LBNE beam at 20 mrad. (Top) δ_{CP} resolutions. (Middle) The significance of excluding the wrong hierarchy. (Bottom) Significance of discovering CP violation. The red line is NOvA 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.