# Catching Ghost Partilcles in Iron, Plastic & Oil

## The MINOS and NOvA Experiments

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Indiana University

The Ohio State University High Energy Physics Seminar
2012 October 8

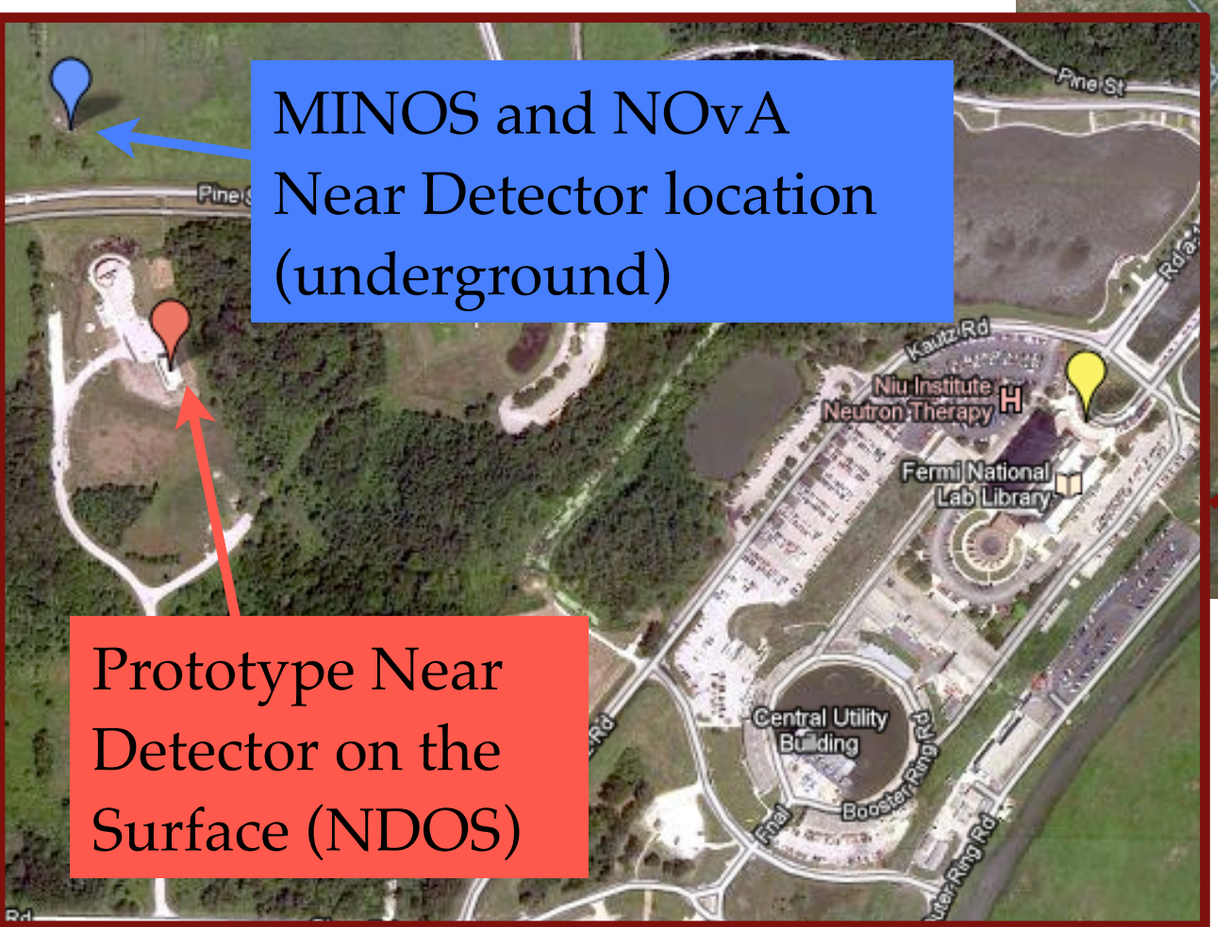
# Outline

- Overview
- Ghost Particles
- MINOS
  - Detectors
  - Current Results
  - Future Plans
- NOvA
  - Detectors
  - Current Results
  - Future Plans

MINOS = Main Injector Neutrino Oscillation Search
NOvA = NuMI Off-axis $\nu_e$ Appearance
NuMI = Neutrinos at the Main Injector

NOvA Far Detector Building

Entrance to Soudan Mine, home of the MINOS Far Detector




MINOS and NOvA Near Detector location (underground)

Prototype Near Detector on the Surface (NDOS)

# Neutrinos

## "The Ghost Particle"

# What Are Neutrinos?

- They are neural leptons, but many questions about them remain unanswered.

**FERMIONS** matter constituents spin = 1/2, 3/2, 5/2, …

**Leptons** spin =1/2

| Flavor | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\nu_L$ lightest neutrino* | $(0–0.13)\times10^{-9}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_M$ middle neutrino* | $(0.009–0.13)\times10^{-9}$ | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_H$ heaviest neutrino* | $(0.04–0.14)\times10^{-9}$ | 0 |
| $\tau$ tau | 1.777 | –1 |

**Quarks** spin =1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.002 | 2/3 |
| d down | 0.005 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 173 | 2/3 |
| b bottom | 4.2 | –1/3 |

# What We Know

- Neutrinos are included in the Standard Model
  - *Massive* neutrinos require a modification to the SM
- ~~Electromagnetism~~ ⇒ electrically neutral
- ~~Strong force~~
- Coupling with gravity ⇒ very small but *nonzero* mass
- Coupling with weak ⇒ very small cross section
- Different weak ($\nu_e$,$\nu_\mu$,$\nu_\tau$) & mass ($\nu_1$,$\nu_2$,$\nu_3$) eigenstates
  - Mass eigenstates propagate with a definite mass
  - Neutrinos are produced and detected in weak eigenstates but can "oscillate" as they propagate

# Oscillations (The Math)

- Oscillation is well modeled by the PMNS matrix, which is analogous to the CKM matrix

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

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

Atmospheric and Accelerator measurements; well measured by experiments such as **MINOS** and Super-K. **NOvA** will increase the precision of our knowledge

**This is the term NOvA is being built to study.**

Measured by reactor and solar neutrino experiments

- If neutrinos were massless, $U$ would be diagonal and oscillations would not occur.

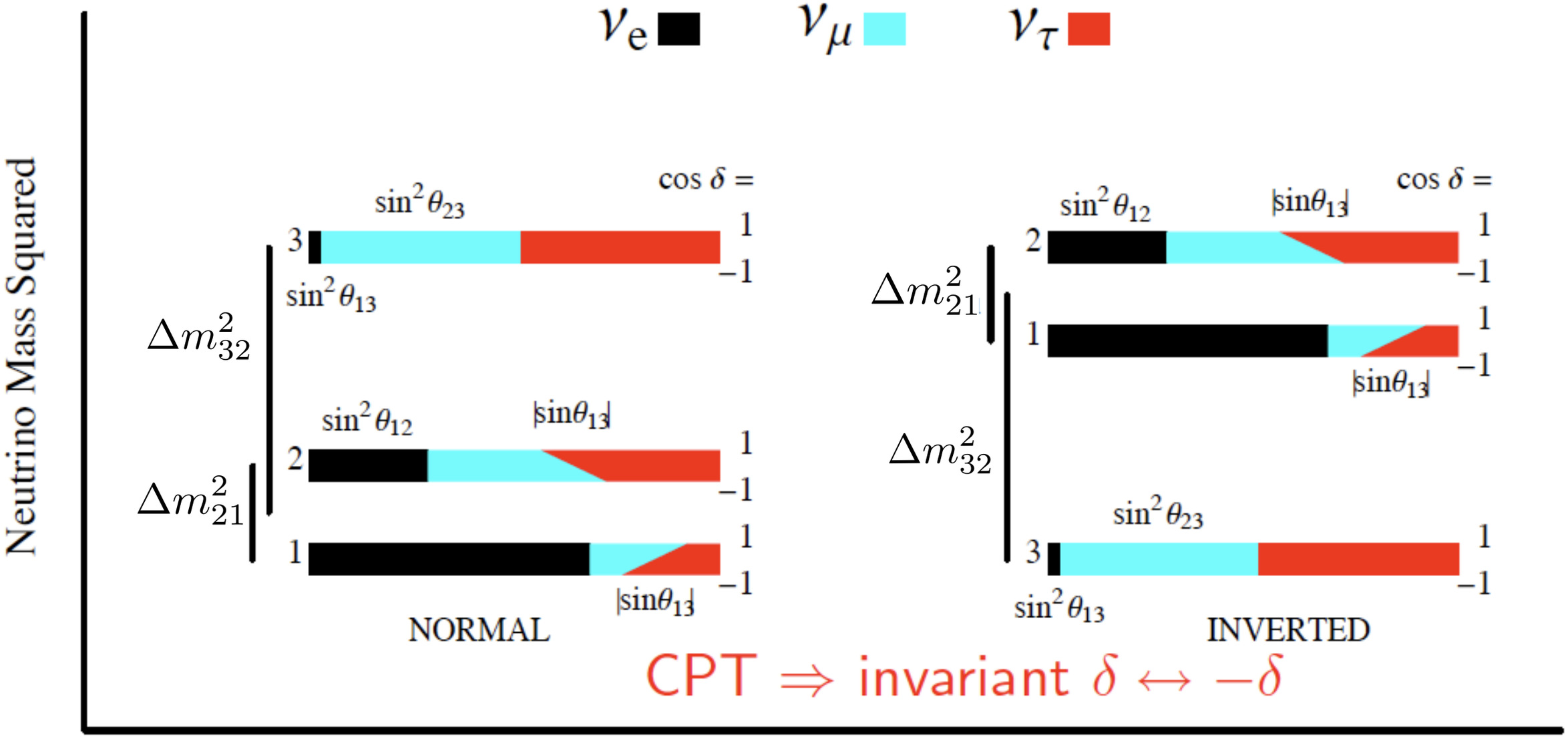
# Measured Neutrino Parameters

- Mixing angles now all measured
  - $\sin^2(2\theta_{13}) = 0.095 \pm 0.010 \ (\theta_{13} = 9.0°)$ (R. Patterson, NOvA)
  - $\sin^2(2\theta_{12}) = 0.857 \pm 0.024 \ (\theta_{12} = 33.9°)$ (PDG 2012)
  - $\sin^2(2\theta_{23}) \approx 0.957^{+0.035}_{-0.036}$ (MINOS)*
    - Note that ambiguity remains in the value of $\theta_{23}$
- Individual masses not measured, but differences masses squared are
  - $\Delta m^2_{21} \equiv m^2_2 - m^2_1 = (7.50 \pm 0.20) \times 10^{-5}\mathrm{eV}^2$ (PDG 2012)
  - $|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2| \approx (2.39^{+0.09}_{-0.10}) \times 10^{-3}\mathrm{eV}^2$ (MINOS)*
    - Note that only the absolute value is measured

* Reported at Neutrino 2012; note that MINOS measures an mixing angle that is approximately but not exactly $\theta_{23}$ and a mass difference that is an unresolved mixture of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$.

# The Final Unmeasured SM Parameters

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




$$\Delta m^2_{ij} \equiv \Delta m^2_i - \Delta m^2_j$$

From Stephen Parke "Mixing Parameters II," Int'l Neutrino Summer School, Fermilab, 14 July 2009

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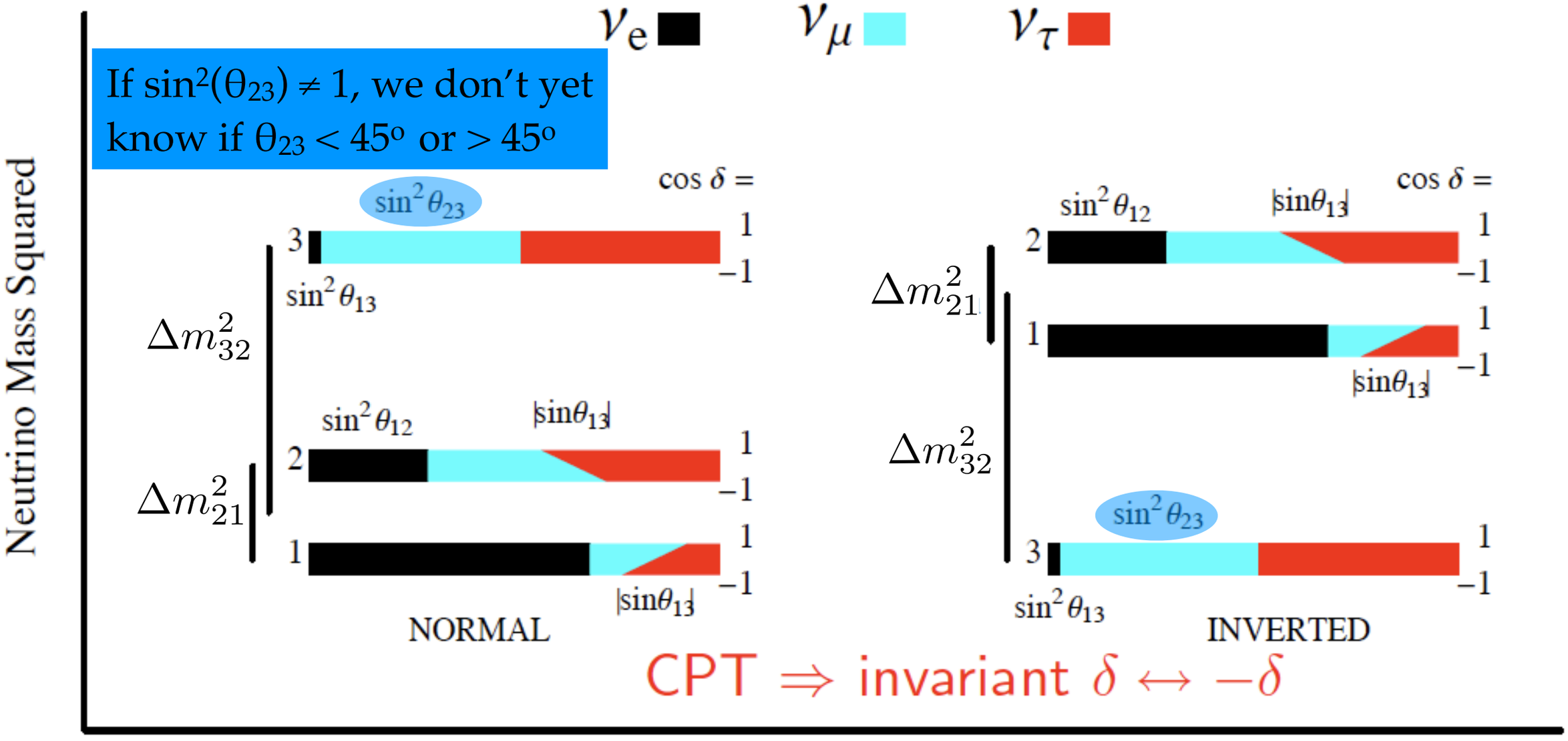


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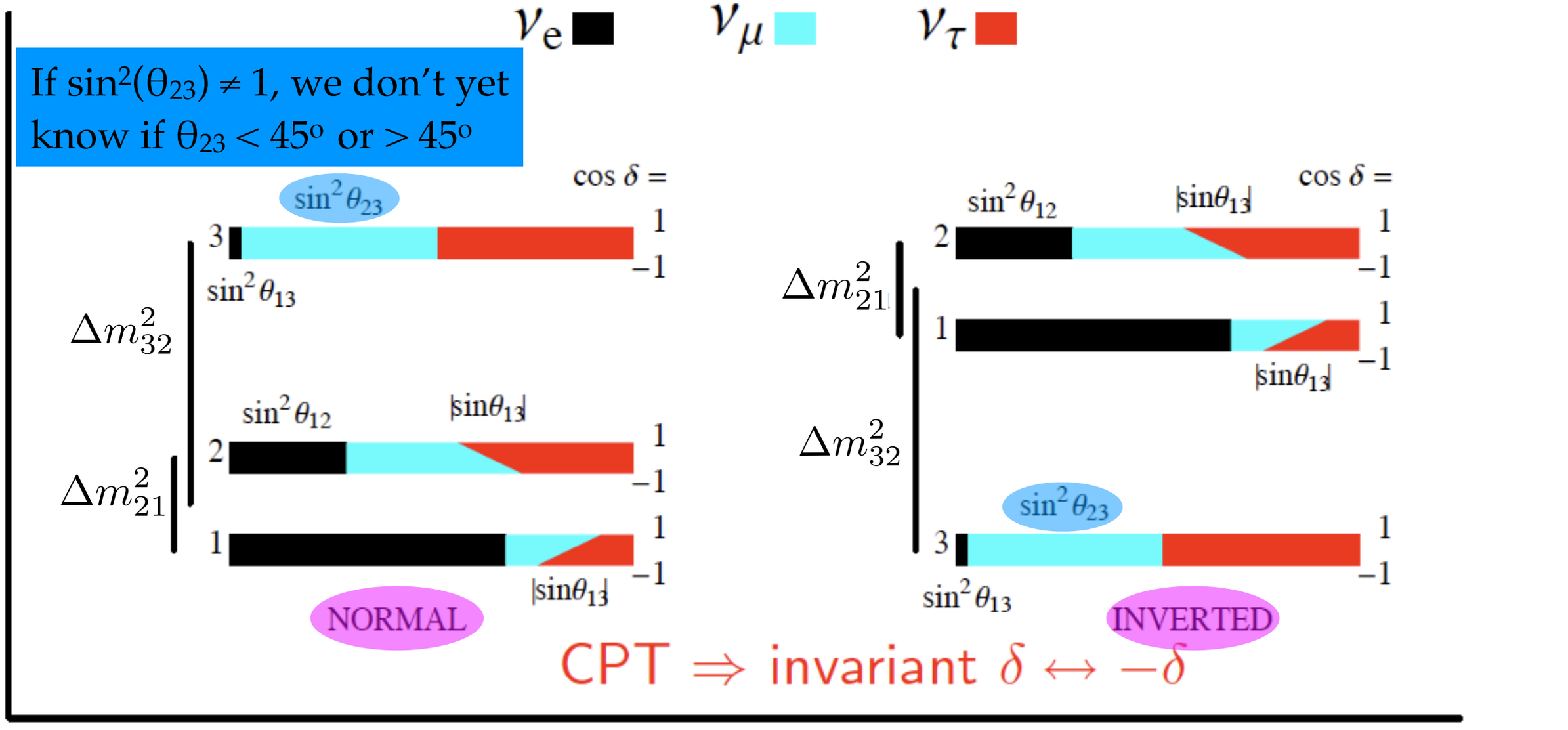


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Mass Hierarchy. Is $\nu_3$ heaviest or lightest?

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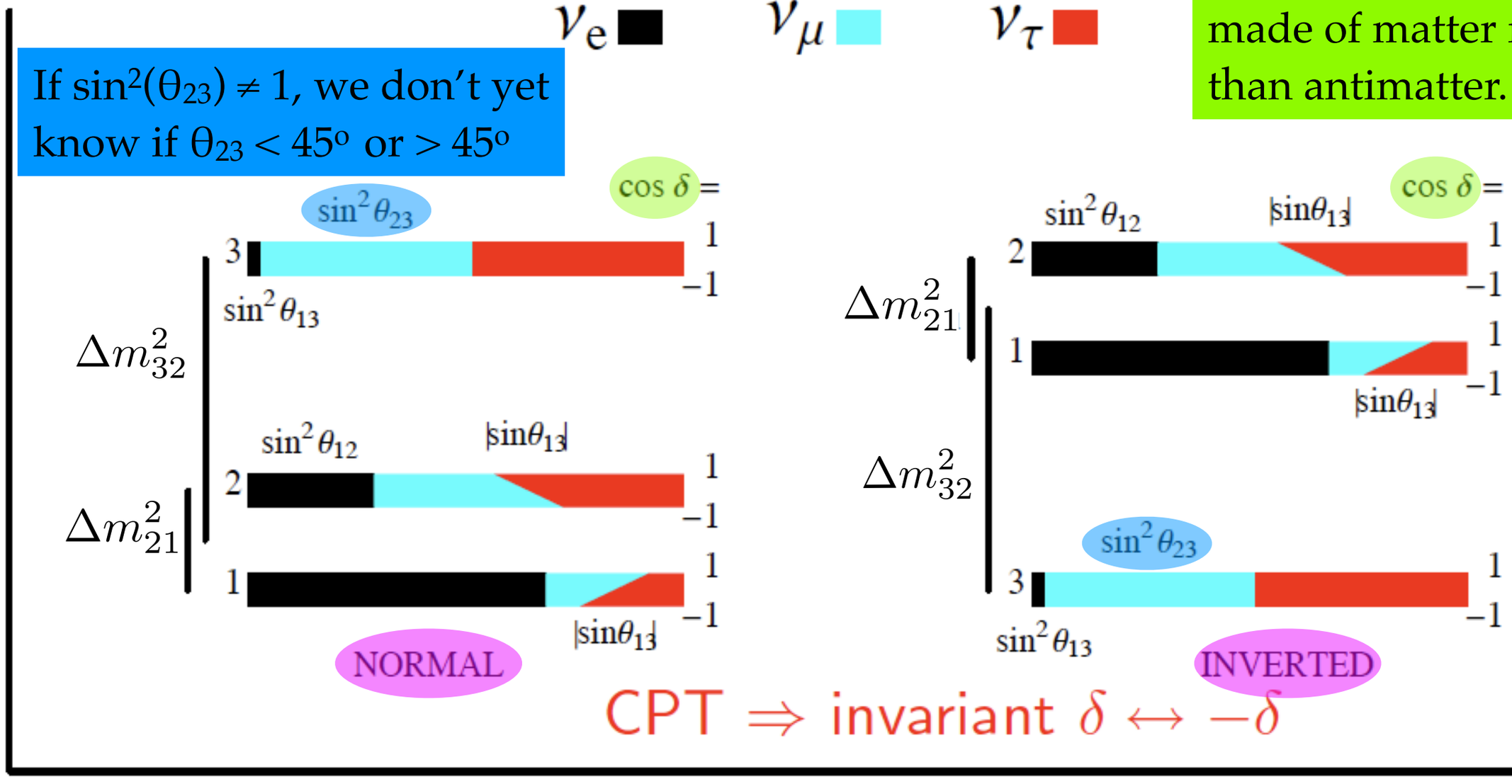
CP Phase. If nonzero, this could help explain why the universe is made of matter rather than antimatter.

If $\sin^2(\theta_{23}) \neq 1$, we don't yet know if $\theta_{23} < 45^o$ or $> 45^o$

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Mass Hierarchy. Is $\nu_3$ heaviest or lightest?

# Oscillations (Beer Analogy)

$\nu_\mu$ Source

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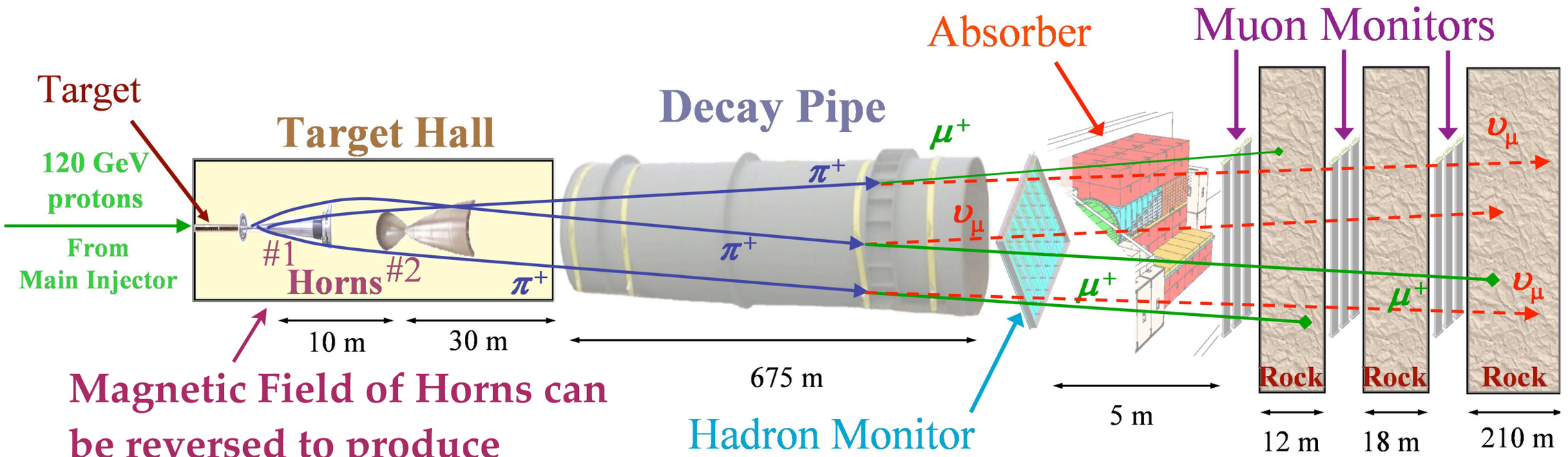
# The NuMI Beam




**Magnetic Field of Horns can be reversed to produce antineutrino beam**

- Small Cross section ⇒ we need large number of neutrinos ⇒ we need an intense neutrino beam
- Different configurations used for MINOS & NOvA
- Currently being upgraded for NOvA

# Beam Comparisons

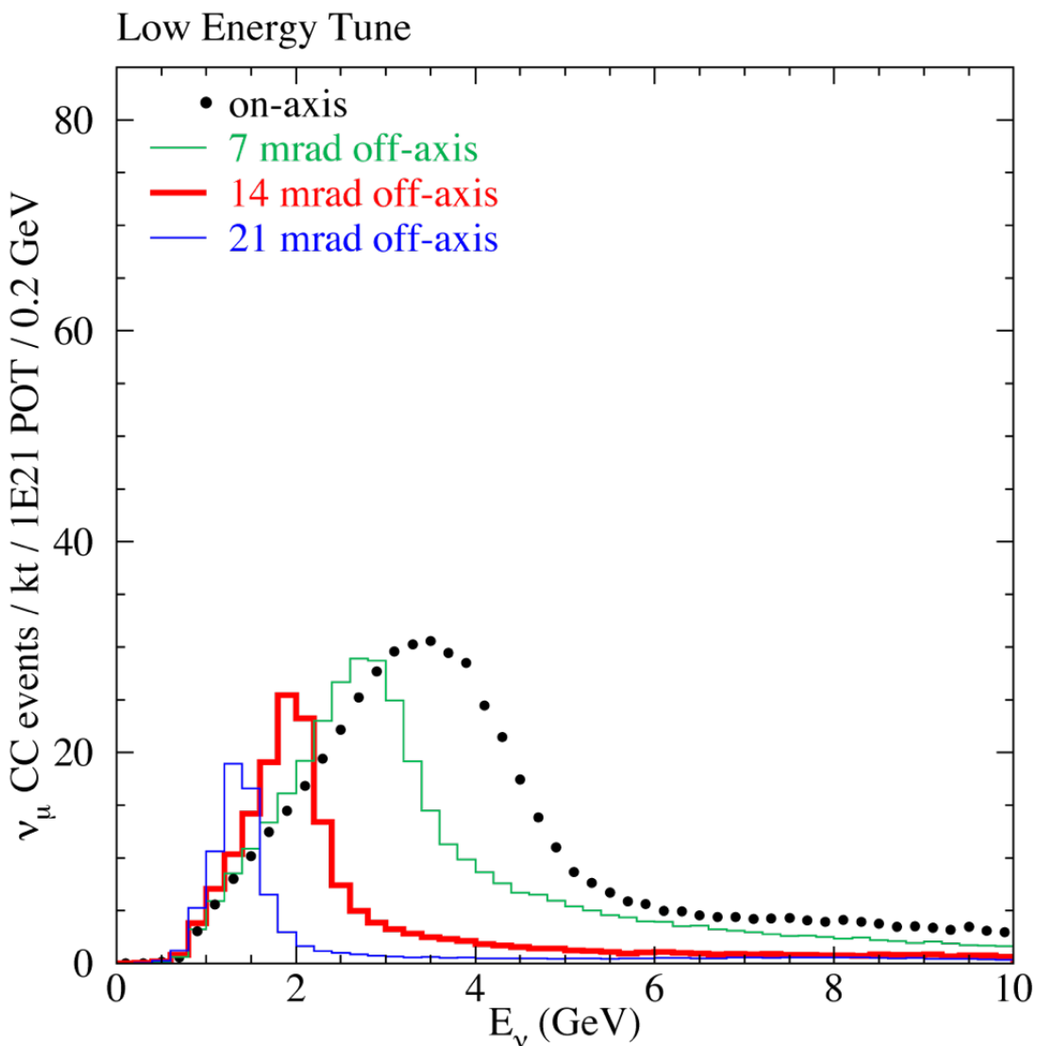
## MINOS (Low Energy) Beam

Horn 2 at 10m from start of Horn 1

Horn Current 185 kA

Beam Power 350 kW

Downstream Target End partially inside upstream end of Horn 1



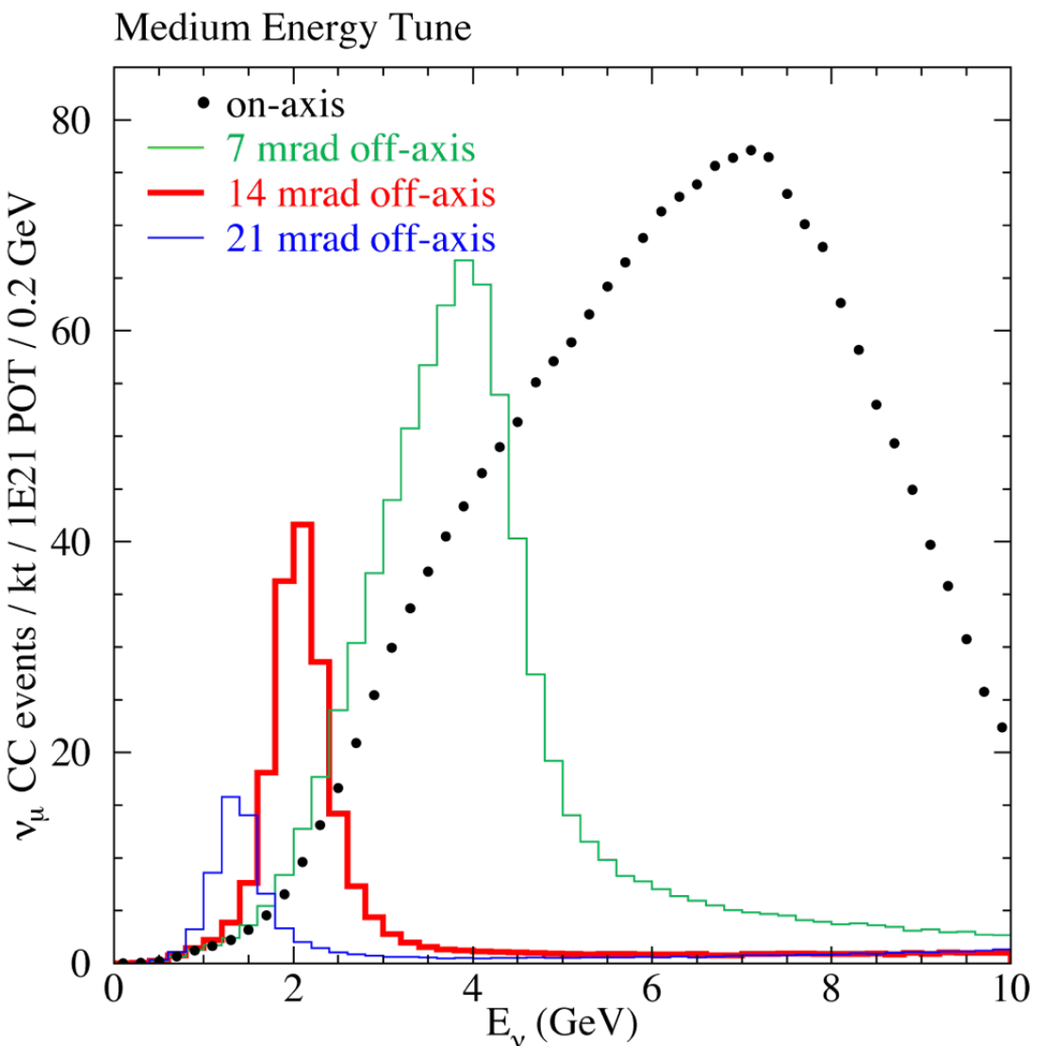

## NOvA (Medium Energy) Beam

Horn 2 at 19m from start of Horn 1

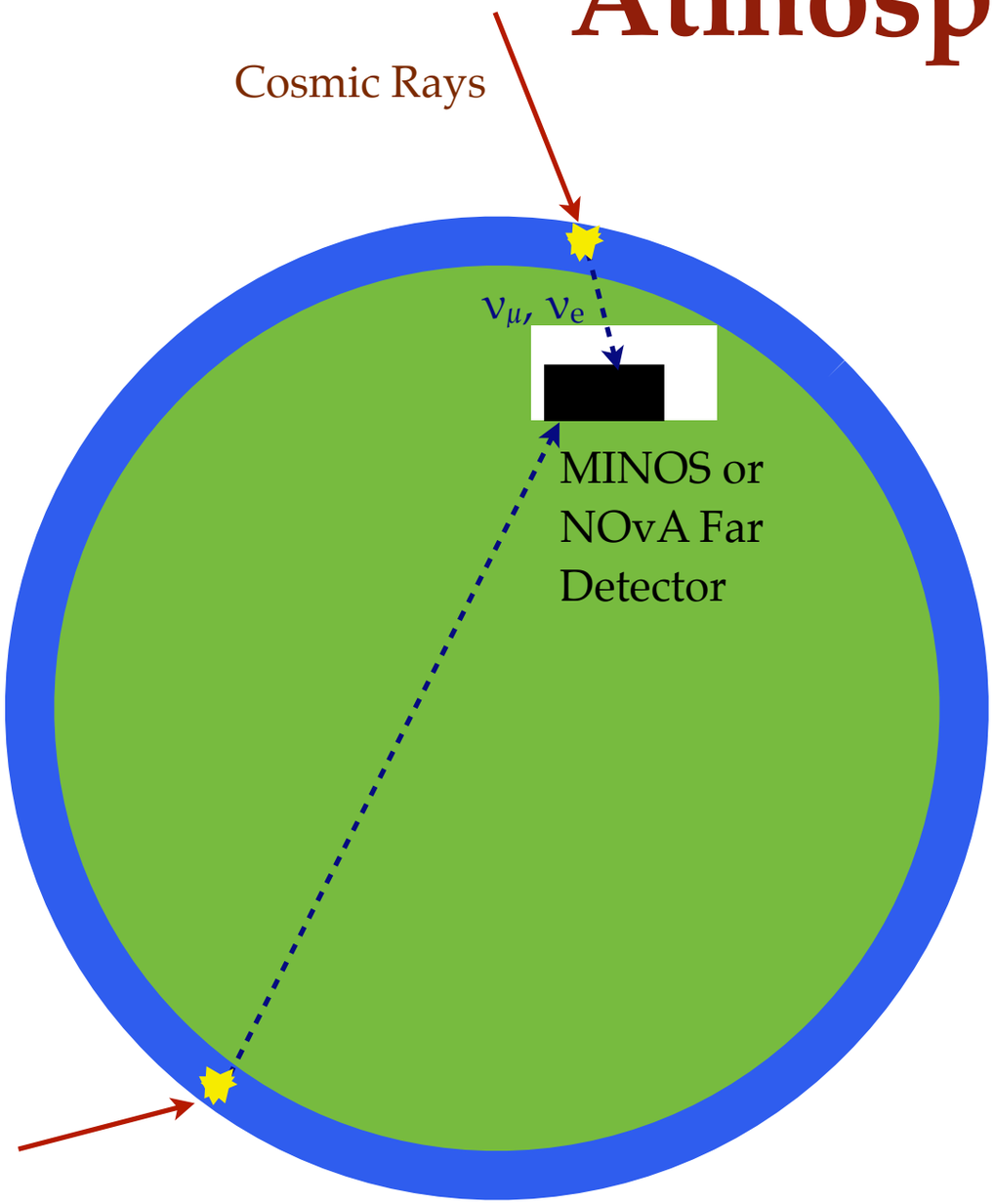
Horn Current 200 kA

Beam Power 700 kW

Downstream Target End 20 cm upstream of start of Horn 1



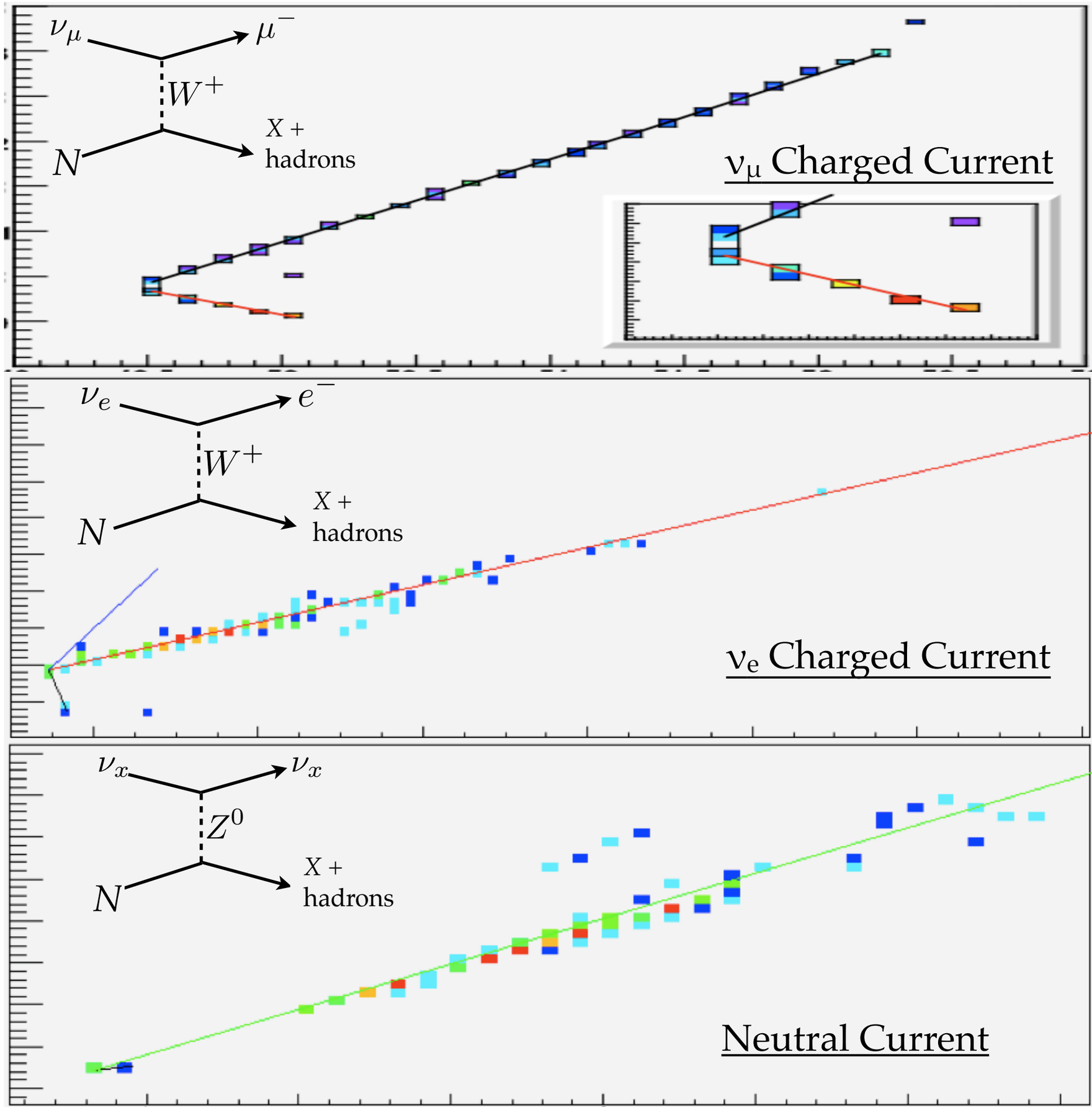
# Atmospheric Neutrinos




- Far Detectors can detect neutrinos from cosmic ray interactions
- L varies from ~10 to ~13000 km
- L/E spans 4 orders of magnitude
- Oscillations in $\nu_\mu$ and $\bar{\nu}_\mu$ are detected in MINOS

# Neutrino Interactions

- Simulated events for NOvA
- MINOS is denser less granular; $\nu_e$ CC events are much less distinct

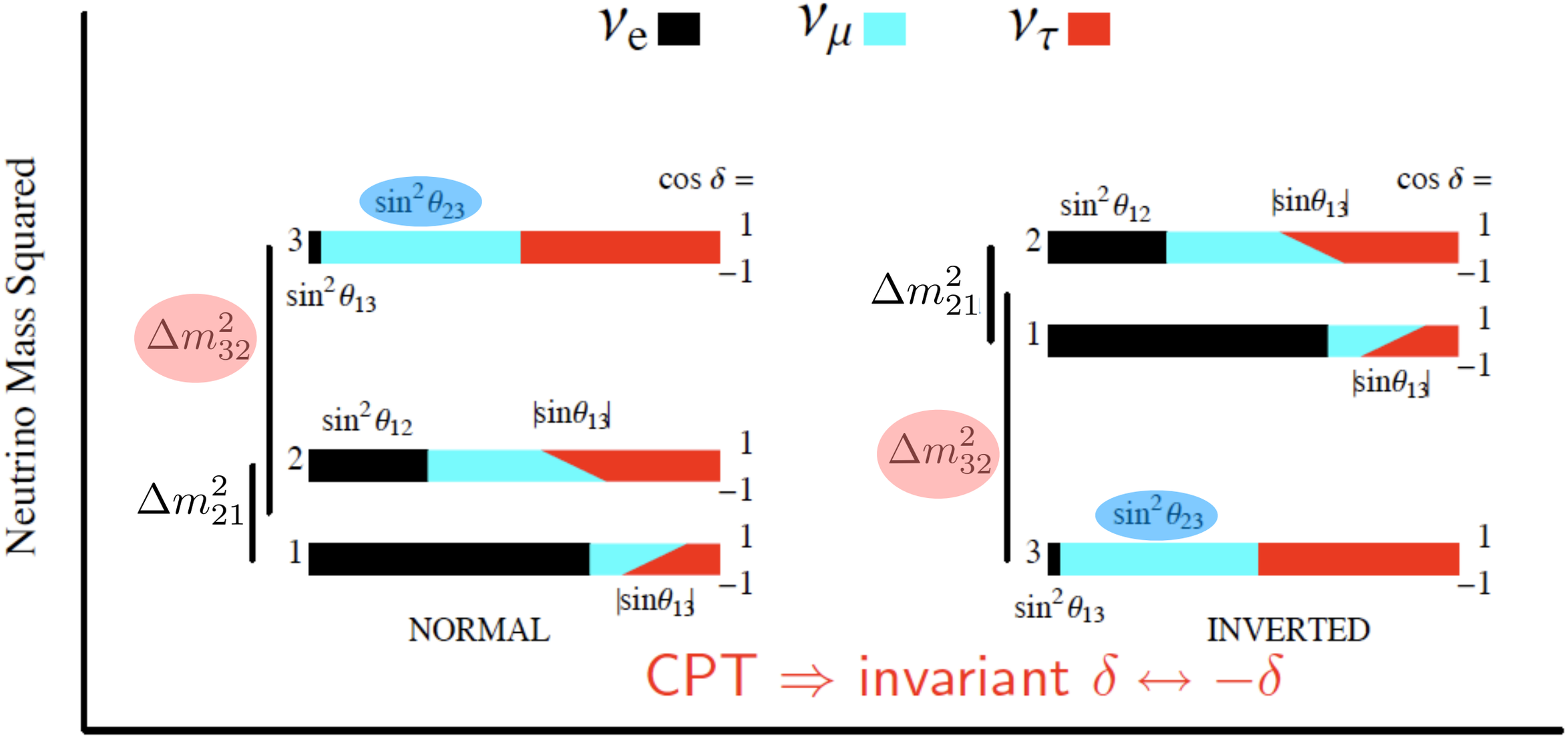


# MINOS

## "Catching Neutrinos in Iron & Plastic"

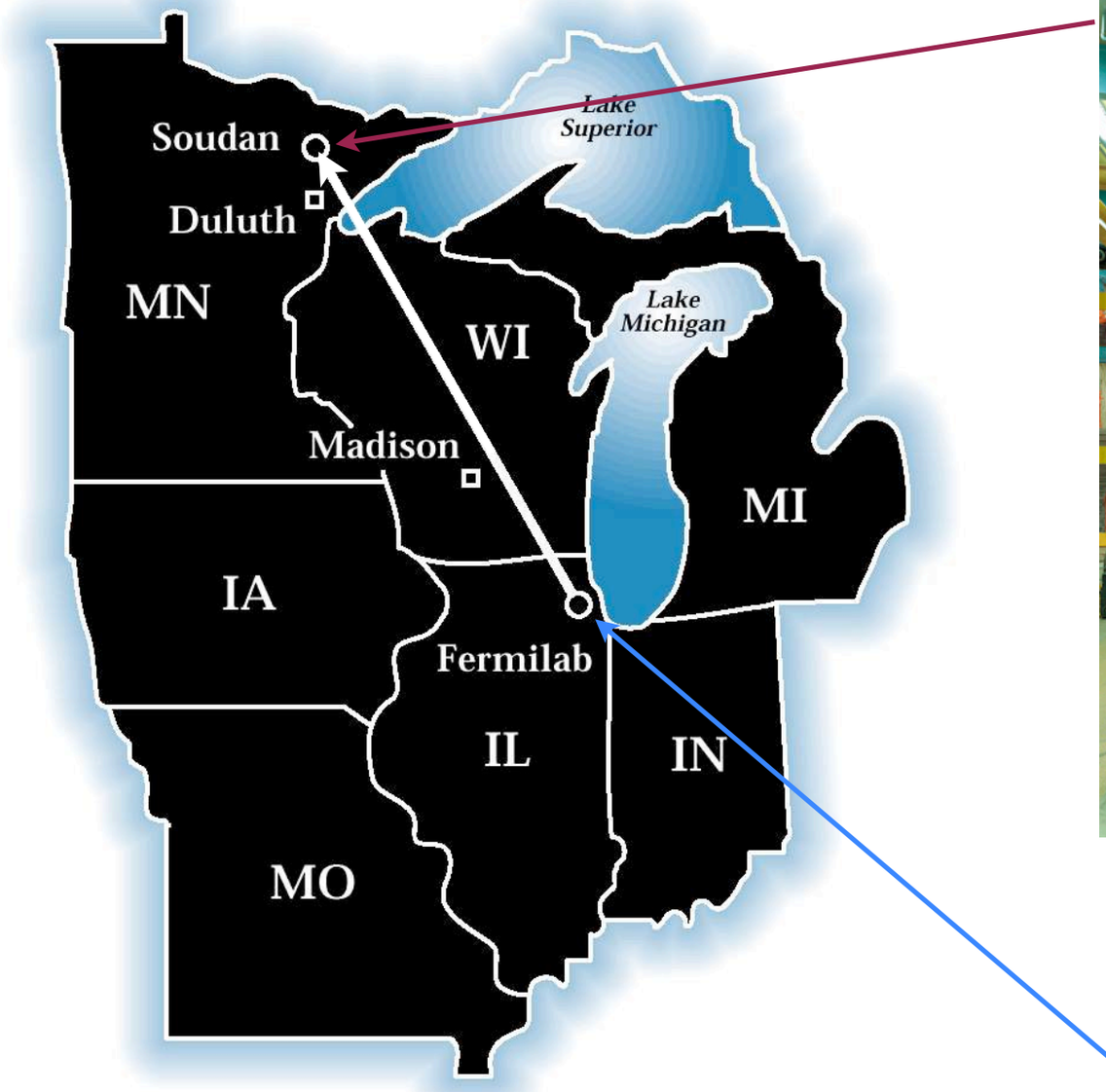
# What MINOS Studies

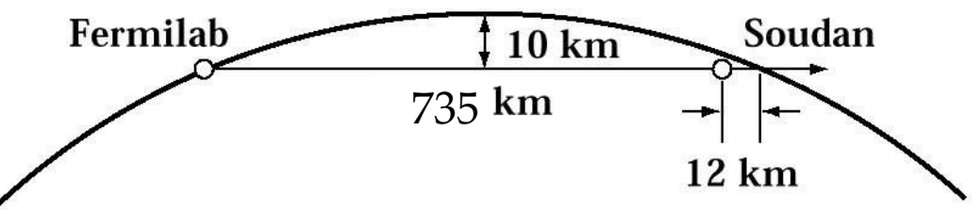
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \times \Delta m^2_{32}/\text{eV} \times L/\text{km}}{E/\text{GeV}}\right)$$




$$\Delta m^2_{ij} \equiv \Delta m^2_i - \Delta m^2_j$$

http://www.hep.ucl.ac.uk/minos/minosmap.jpg



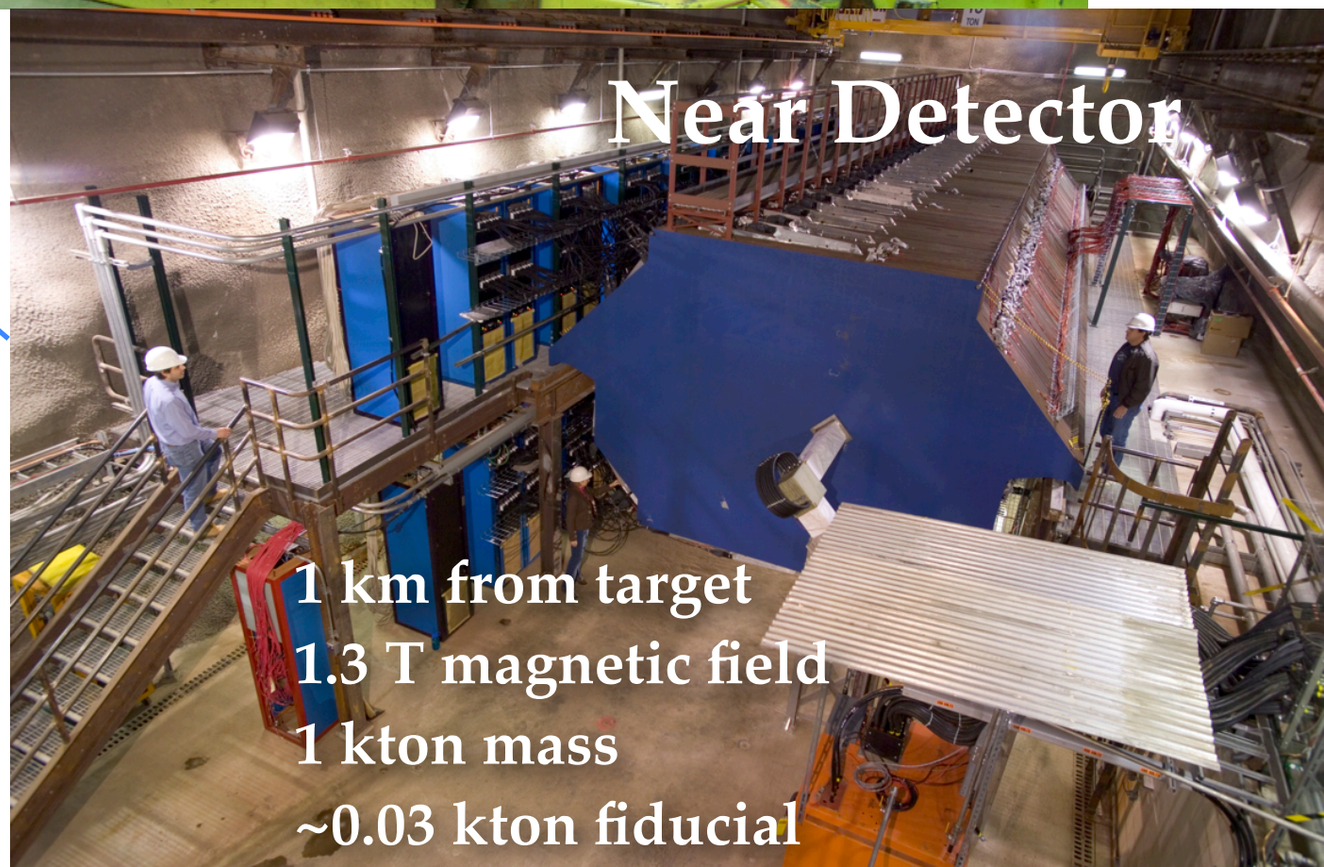



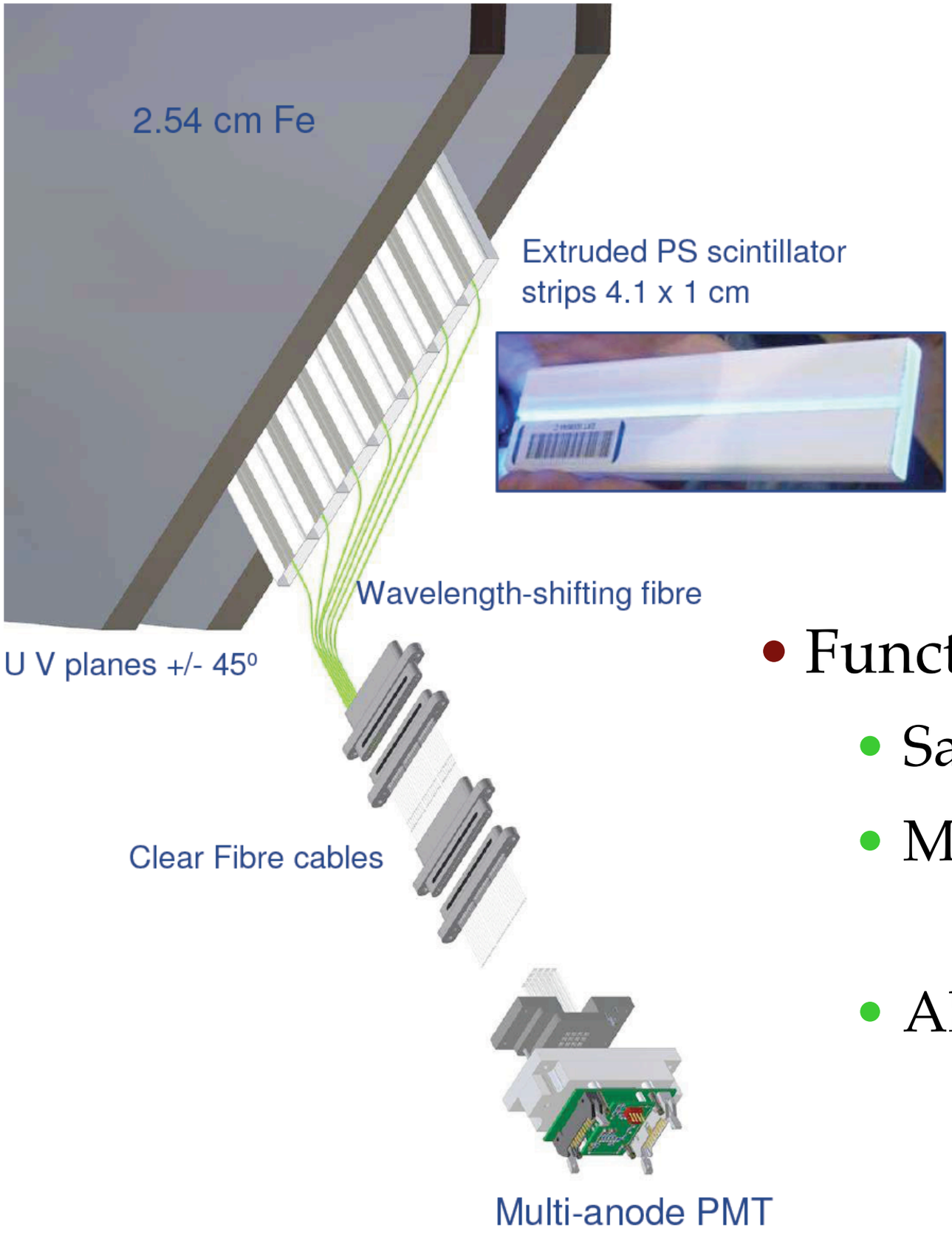

# Detectors

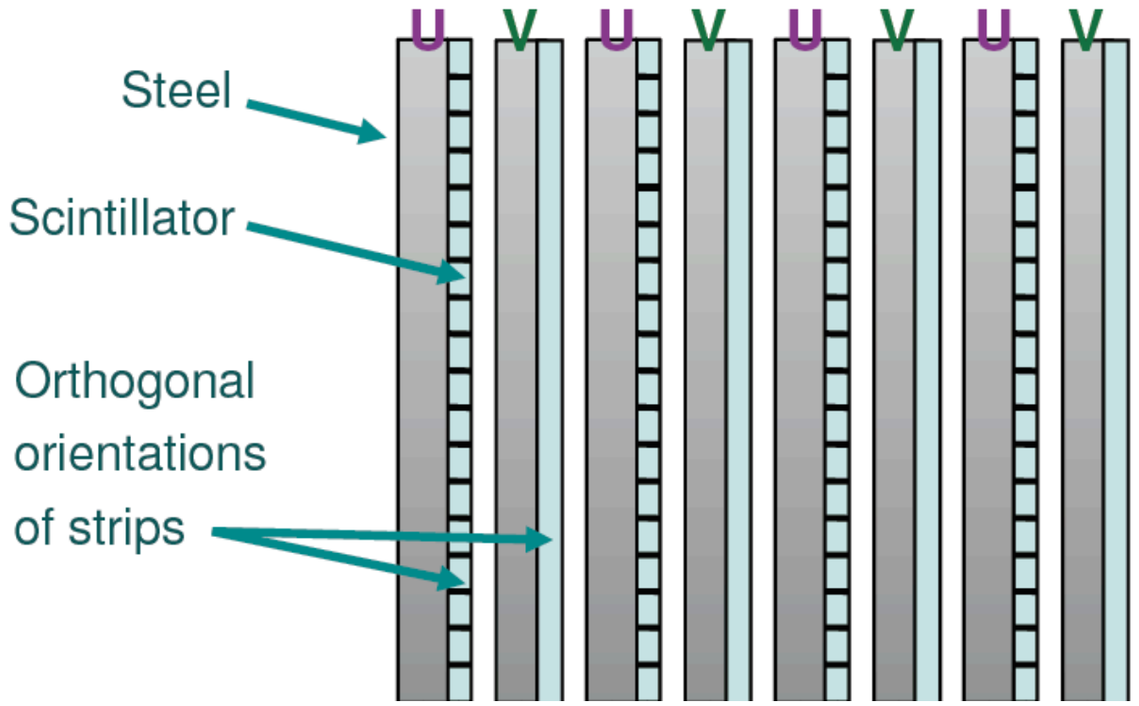
## Far Detector

Detector Images From http://www-visualmedia.fnal.gov/

## Near Detector

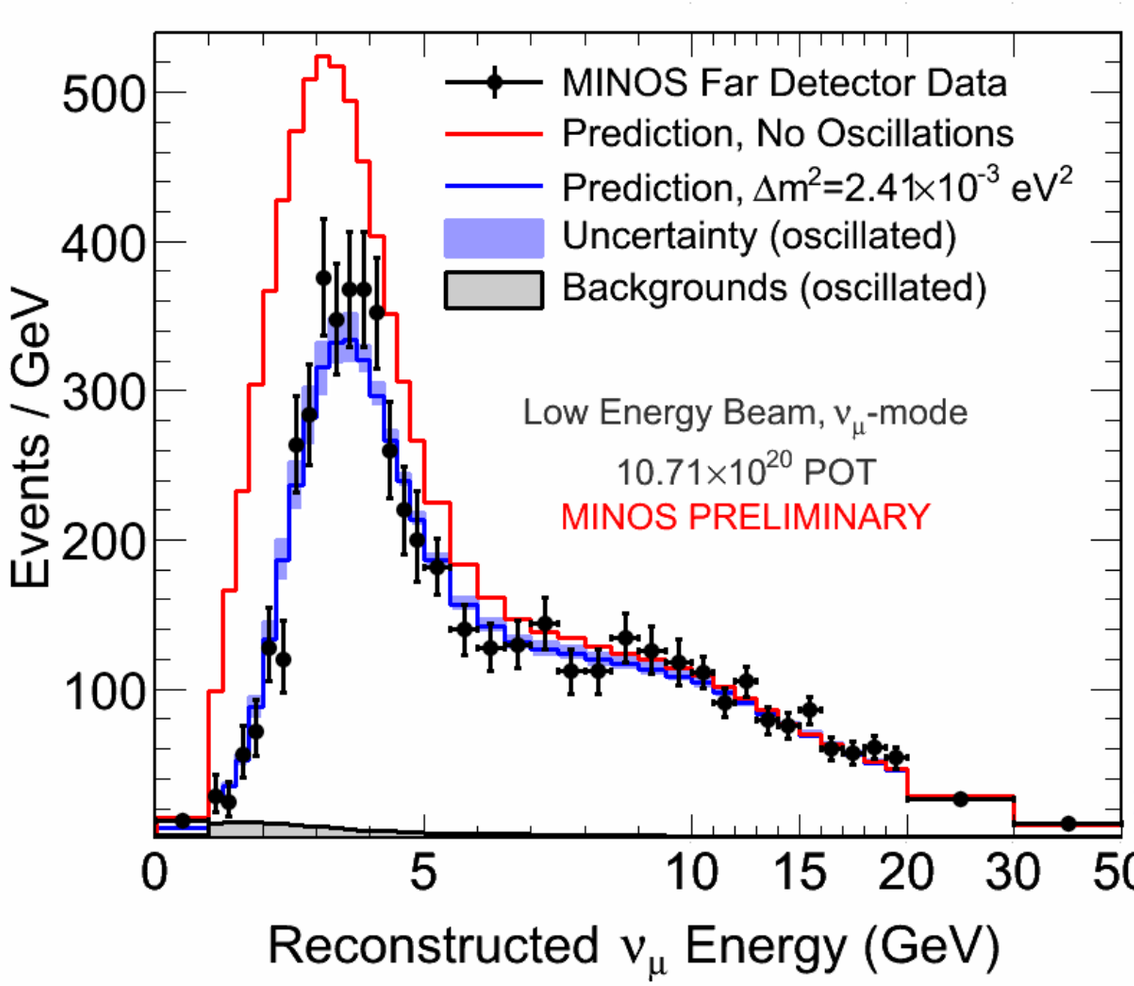


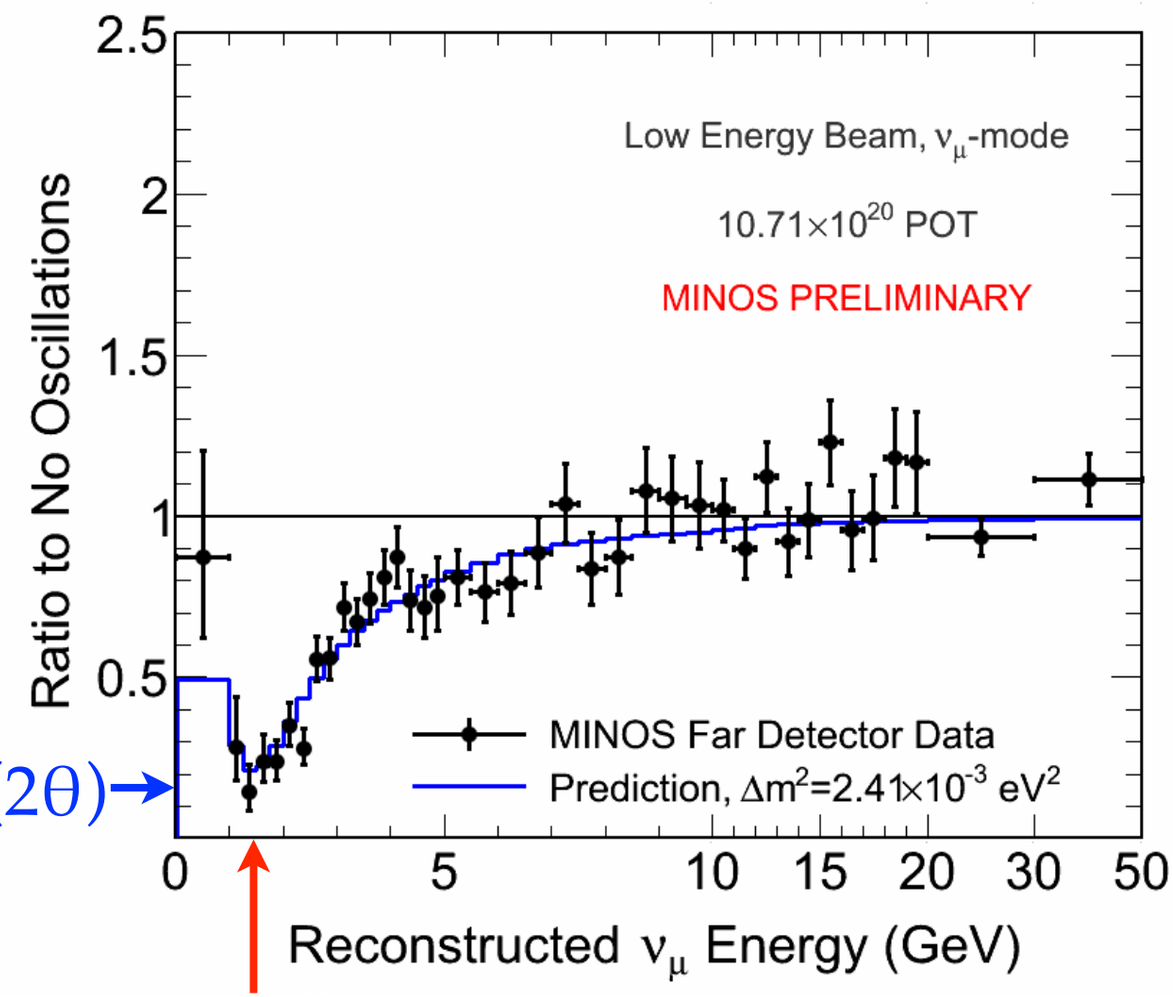



- Functionally Identical Detectors
  - Same iron and scintillator
  - Magnetic fields as similar as possible
  - Allows cancellation of systematic errors when using both detectors

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \times \Delta m^2_{32}/\mathrm{eV} \times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

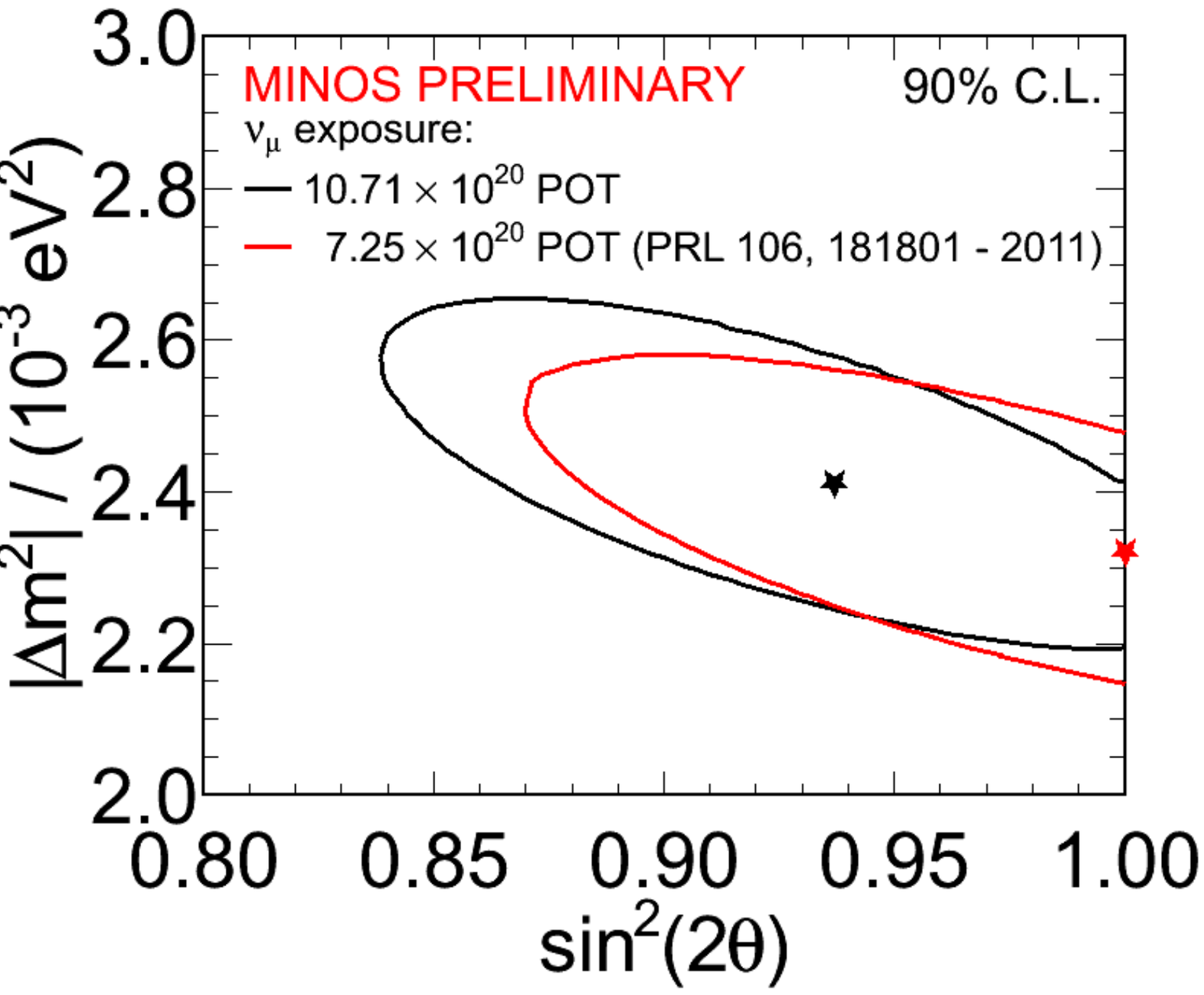



$\sin^2(2\theta)$

$\Delta m^2$

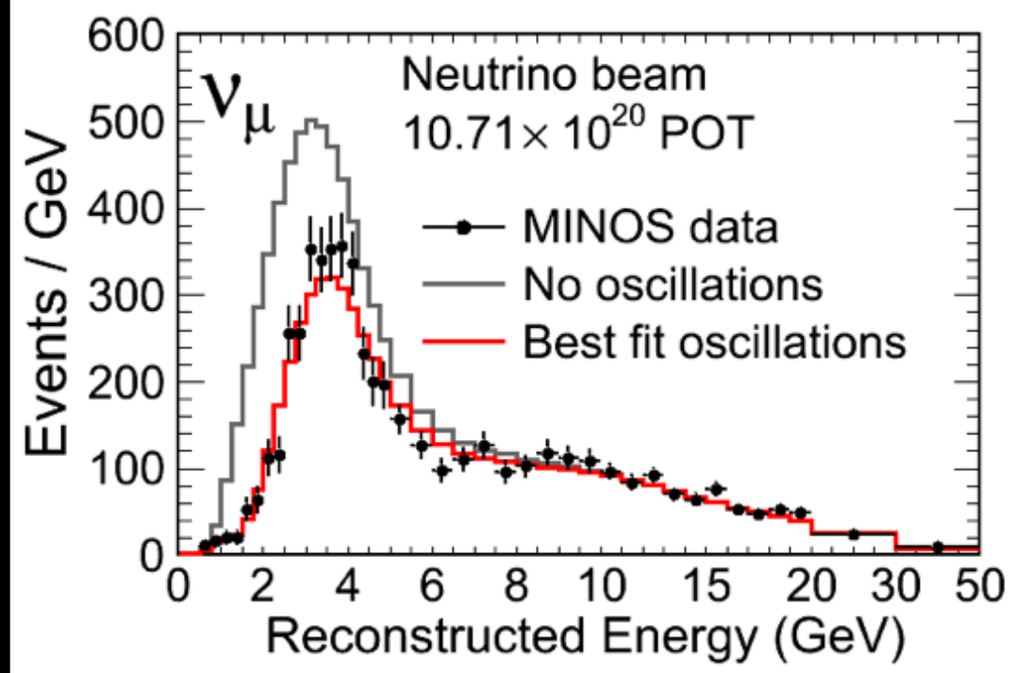
# Resulting Contour

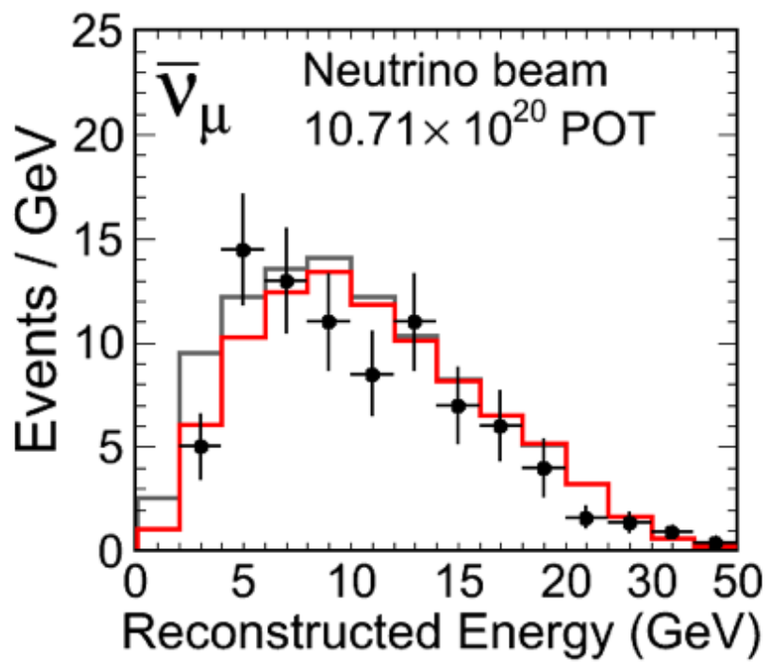


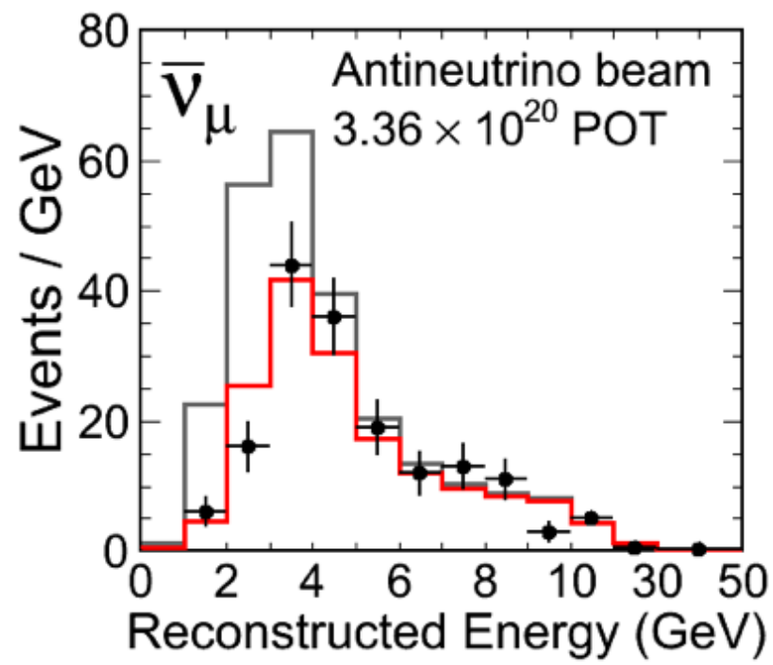

- Fit to the neutrino spectrum is translated into likelihood contours
- Parameter values are taken from projections of the contours onto each axis

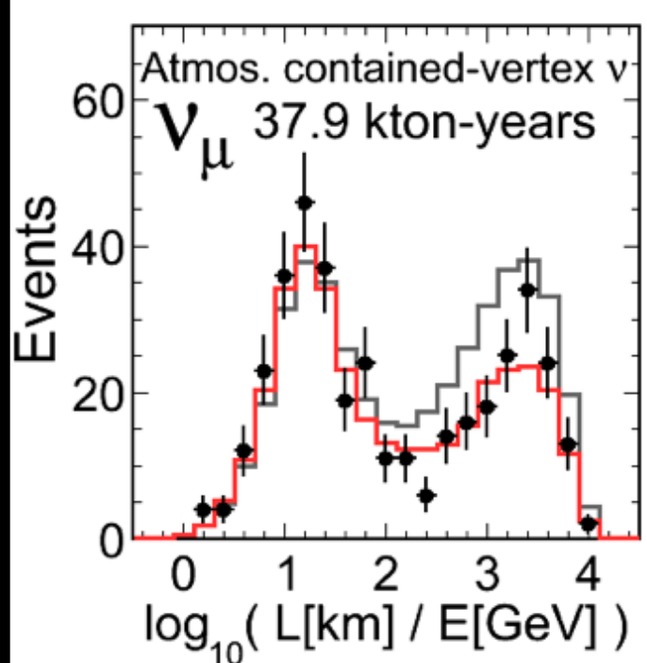
# All MINOS Data

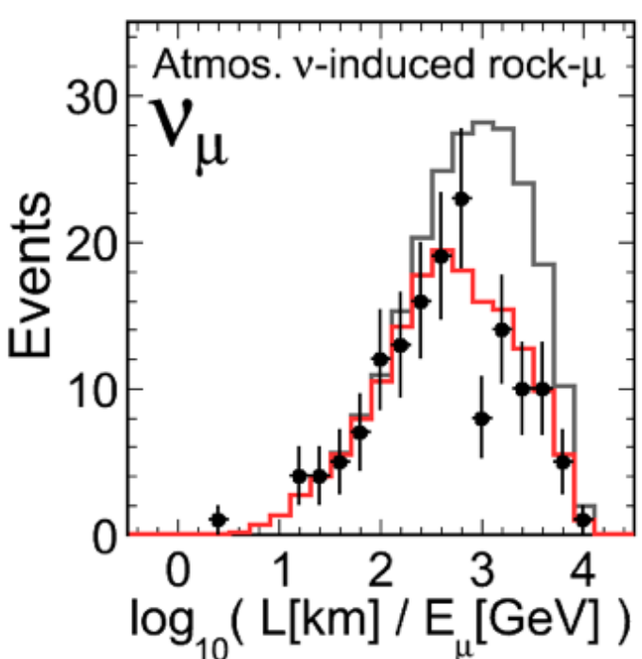
MINOS PRELIMINARY

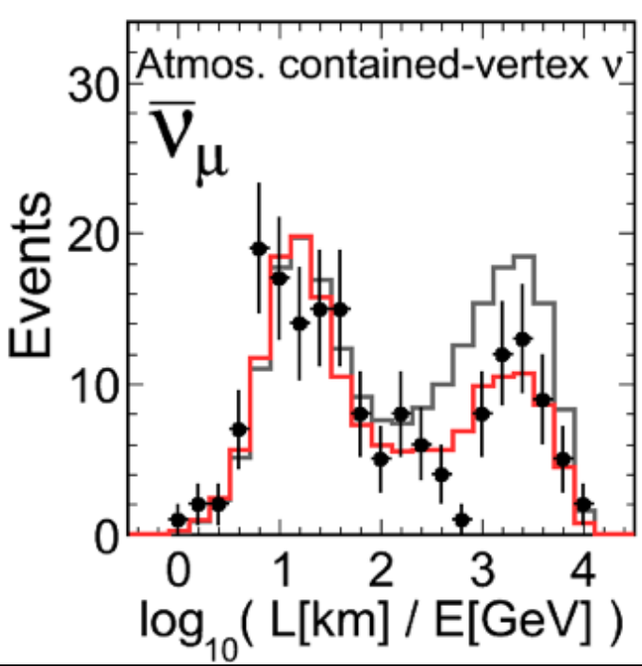


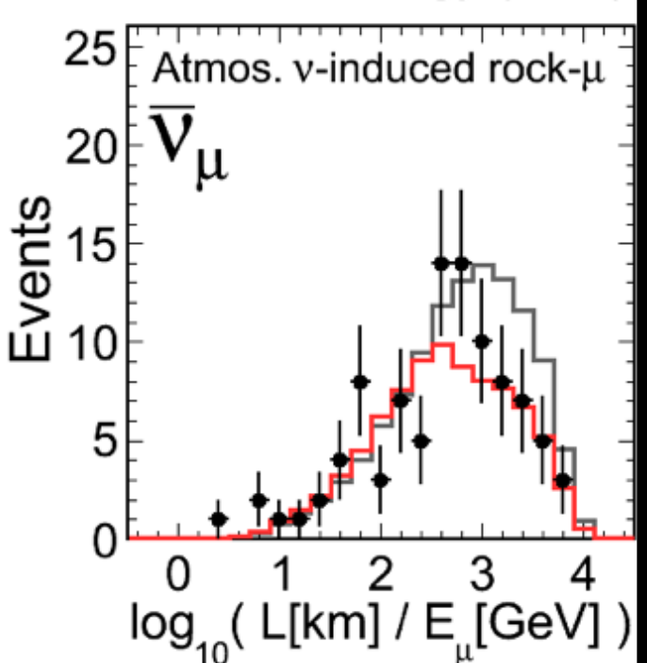



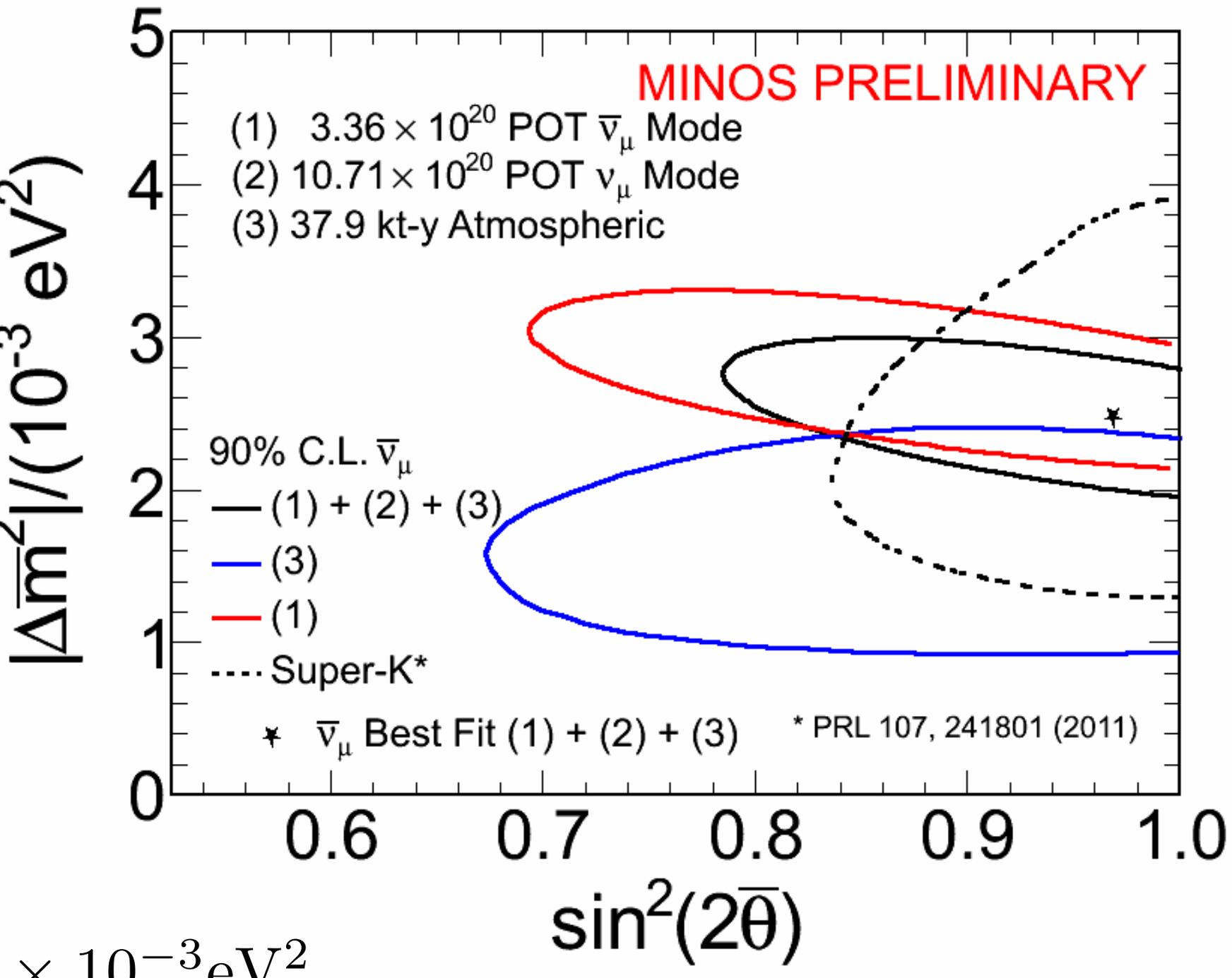



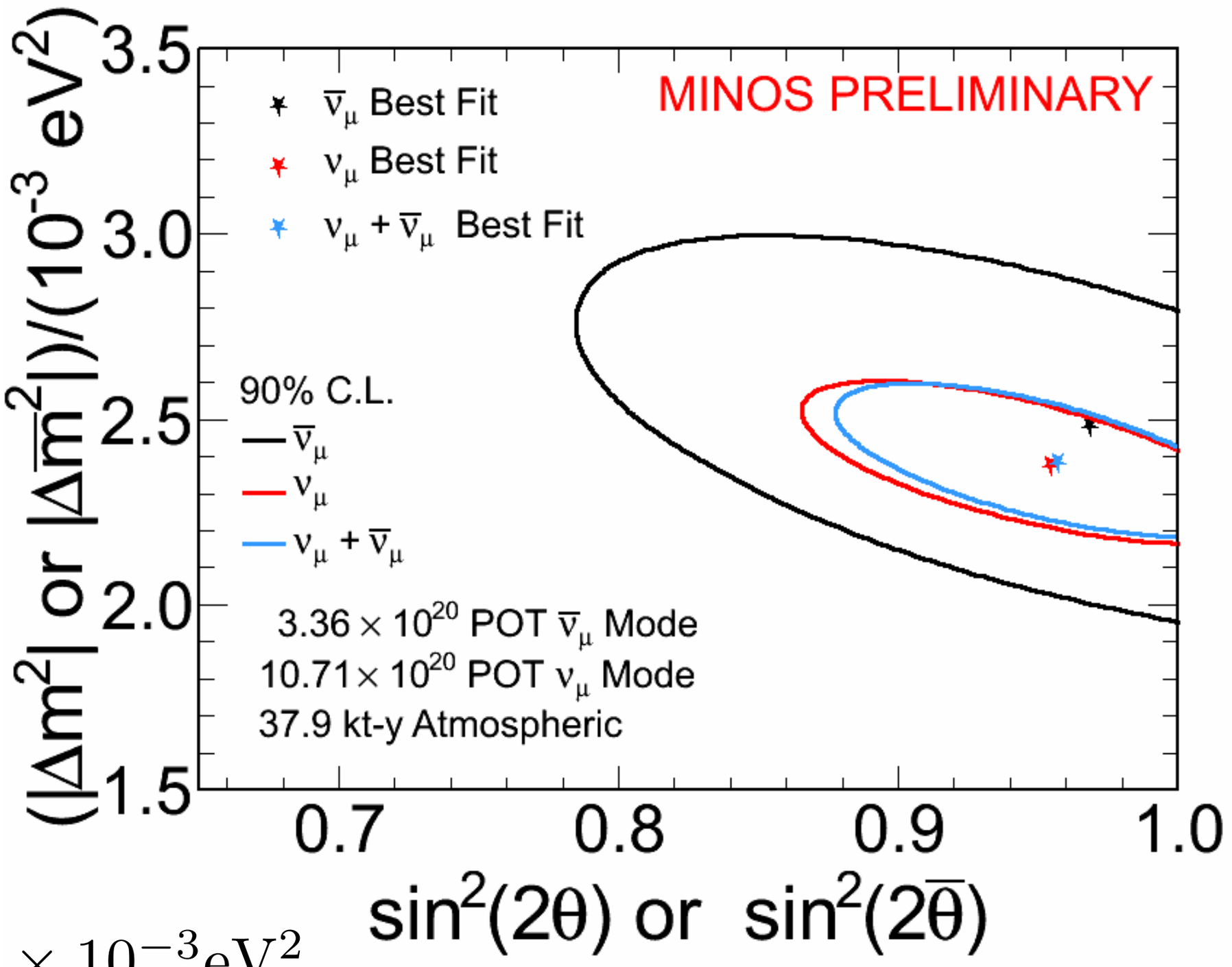
# Results for Muon Antineutrinos




$$|\Delta\overline{m}^2| = (2.48^{+0.22}_{-0.27}) \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\overline{\theta}) = 0.97^{+0.03}_{-0.08}\ (> 0.83 \text{ at } 90\%\ \mathrm{C.L.})$$

# Results For Muon Neutrinos




$$\Delta m^2 = (2.39^{+0.09}_{-0.10}) \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\theta) = 0.957^{+0.035}_{-0.036}\ (> 0.896 \text{ at } 90\%\ \mathrm{C.L.})$$

$$|\Delta\overline{m}^2| - |\Delta m^2| = (1.0^{+2.4}_{-2.8}) \times 10^{-4}\mathrm{eV}^2$$

# MINOS+

- Collaboration will use the MINOS detectors in the NOvA beam
- Will investigate many new interesting phenomena with high statistics
  - Search for deviations from PMNS model
    - Sterile Neutrinos
    - Non-Standard Interactions
  - High-precision ν time of flight measurement
  - Competitive measurements of oscillation parameters in the short term

# NOvA

## "Catching Neutrinos in Oil & Plastic"

# The Collaboration

**34 Institutions**
**180 Physicists**
**and growing**

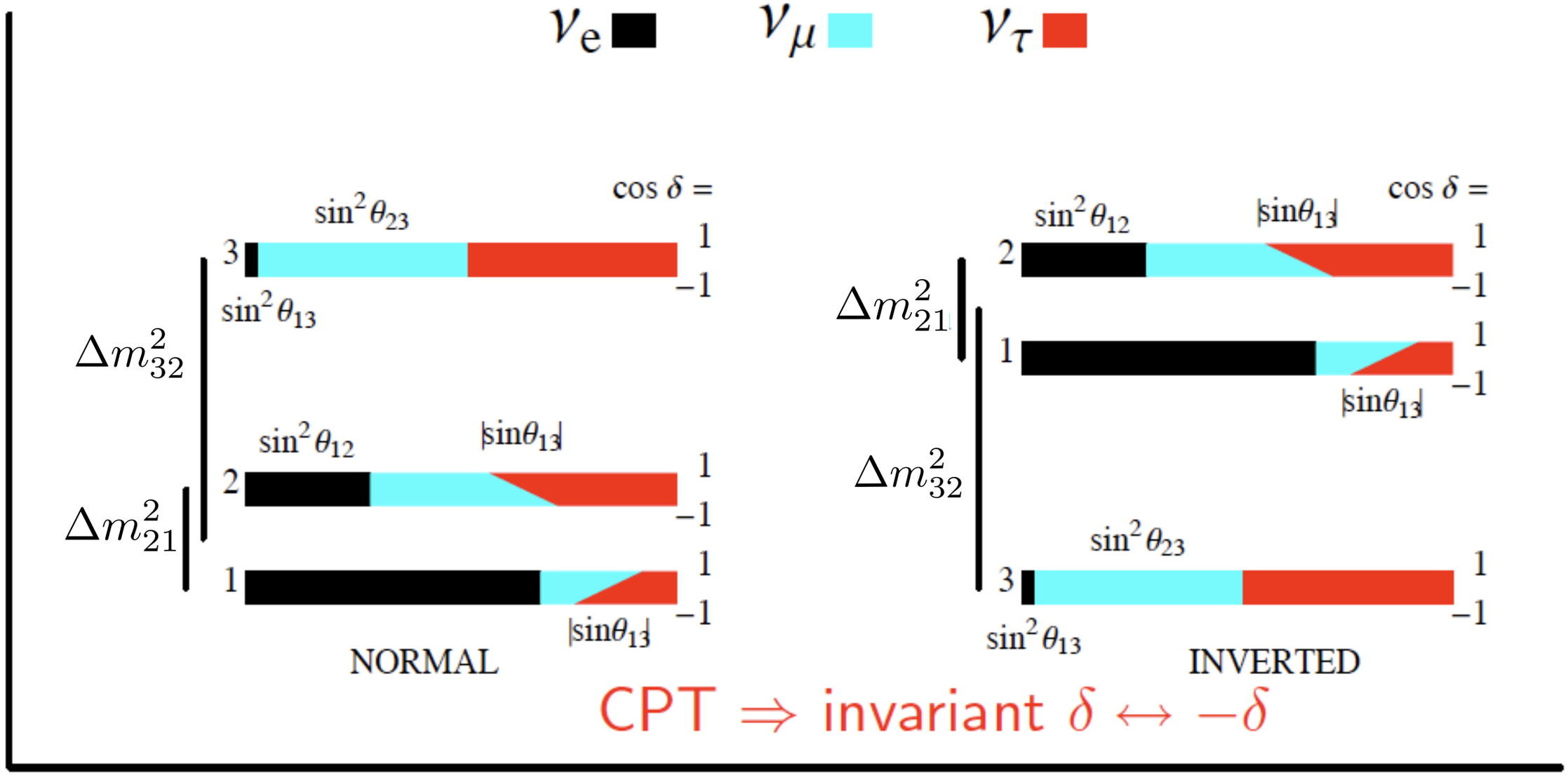
www.twitter.com/NOvANuz

www.facebook.com/novaexperiment

**Argonne, Athens, Banaras Hindu, Caltech, Delhi, Charles University, Cincinnati, Czech Technical, FNAL, Harvard, Hyderabad, IIT Guwahati, IIT Hyderabad, Indiana, INR Moscow, IoP of Czech Republic, Iowa State, Jammu, Lebedev, Michigan State, U of MN (Crookston, Duluth, Twin Cities), Panjab, South Carolina, SMU, Stanford, Sussex, U of TN - Knoxville, U of TX - Austin, Tufts, Virginia, Wichita State, William & Mary.**

# What NOvA is Designed to Study

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




CPT $\Rightarrow$ invariant $\delta \leftrightarrow -\delta$

$$\Delta m^2_{ij} \equiv \Delta m^2_i - \Delta m^2_j$$

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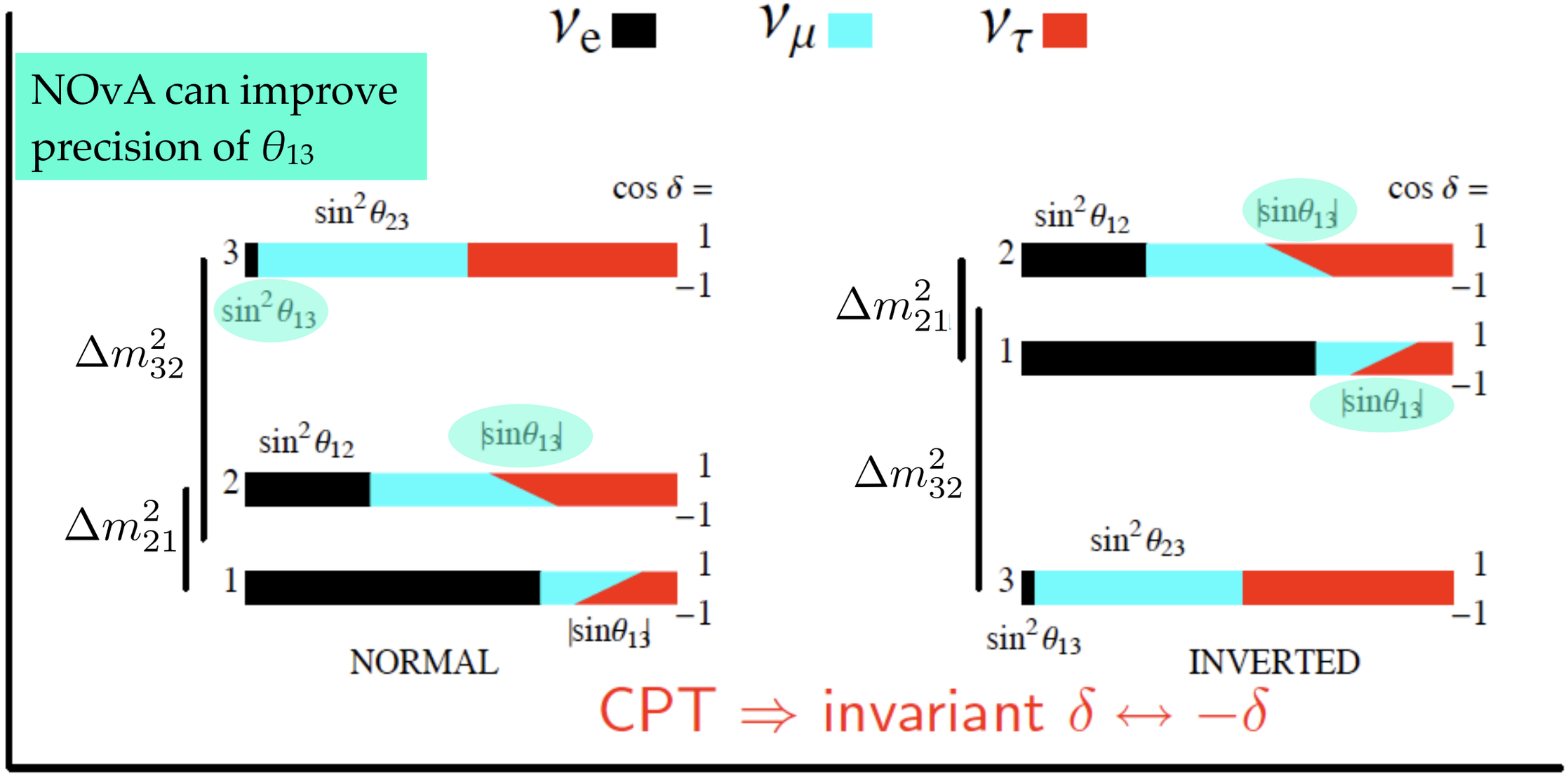


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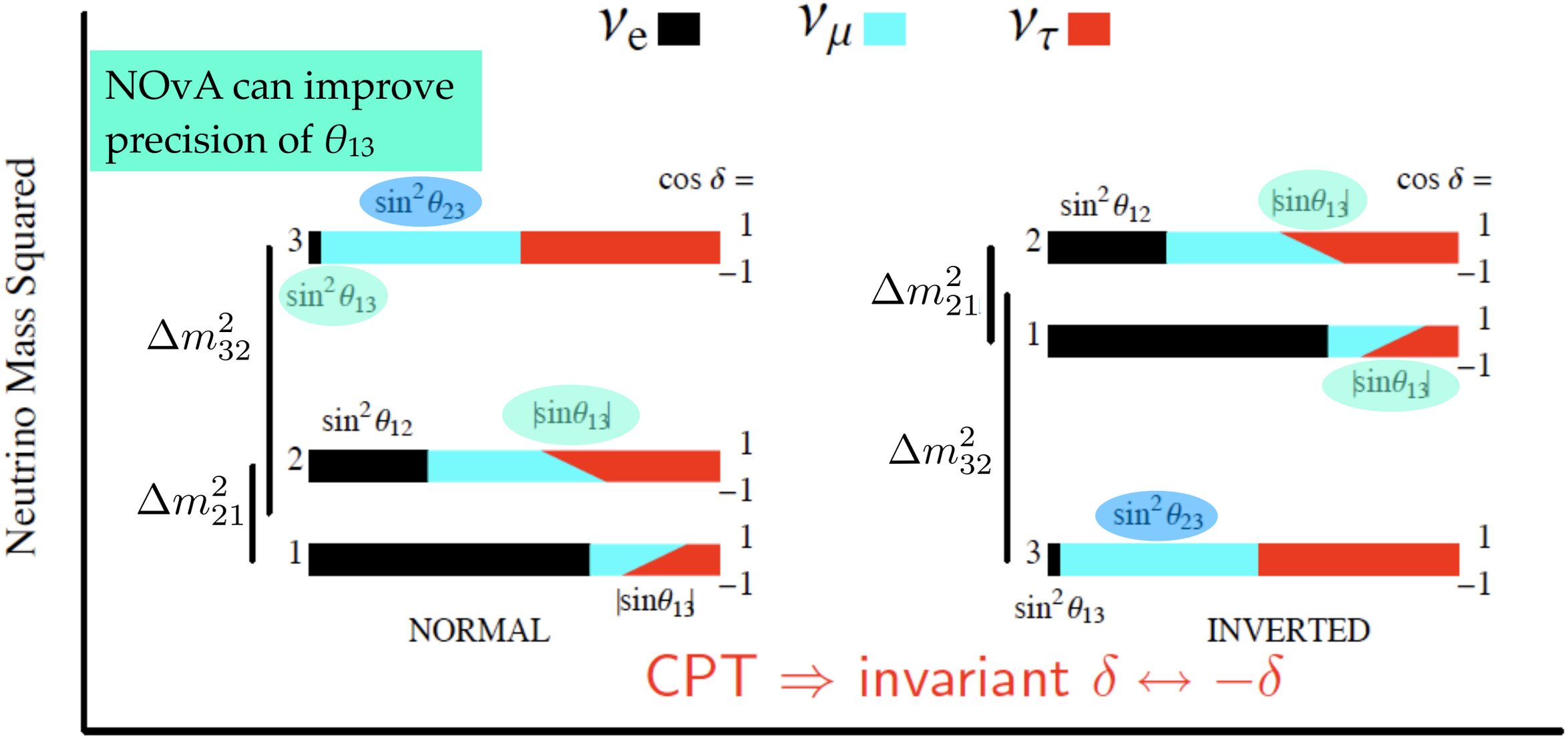


If $\sin^2(\theta_{23}) \neq 1$, NOvA might determine $\theta_{23} < 45^o$ or $> 45^o$

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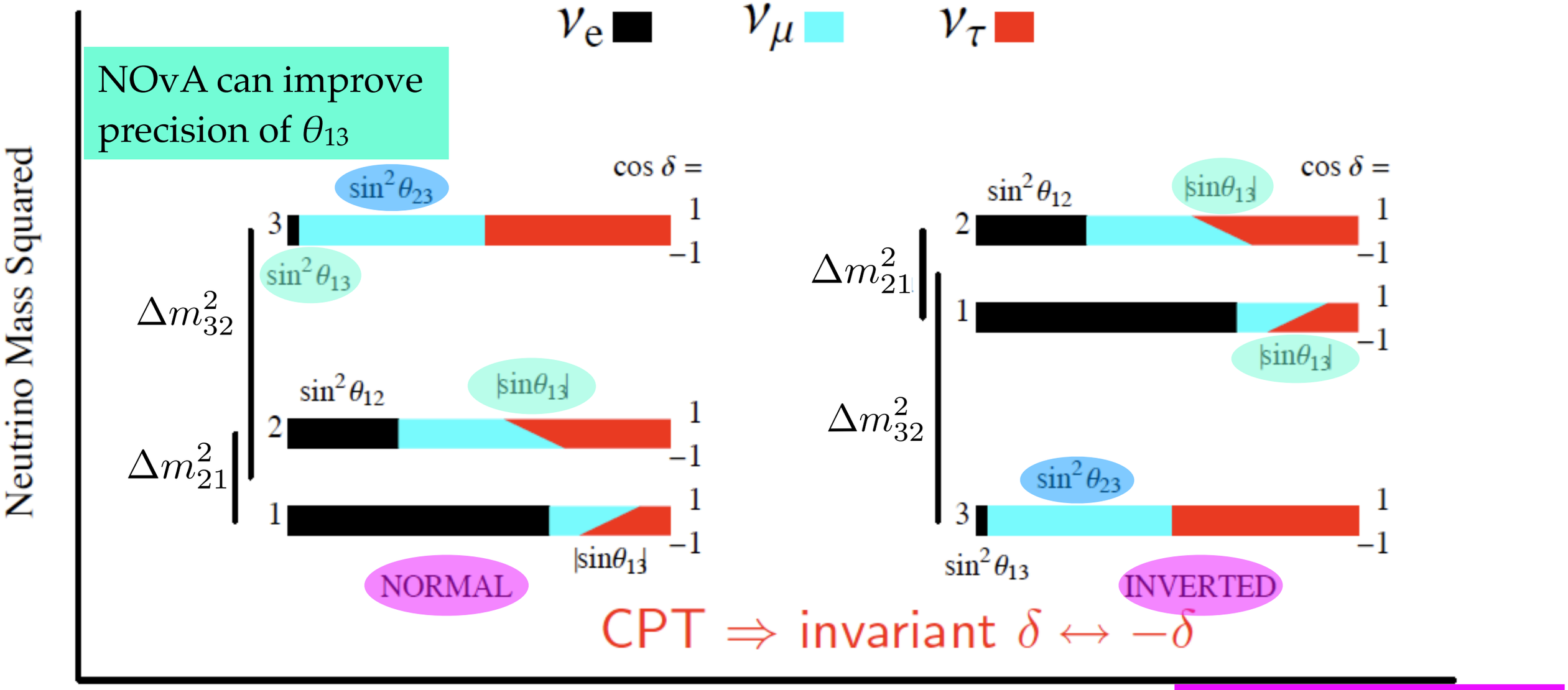


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NOvA's long baseline provides sensitivity to the hierarchy

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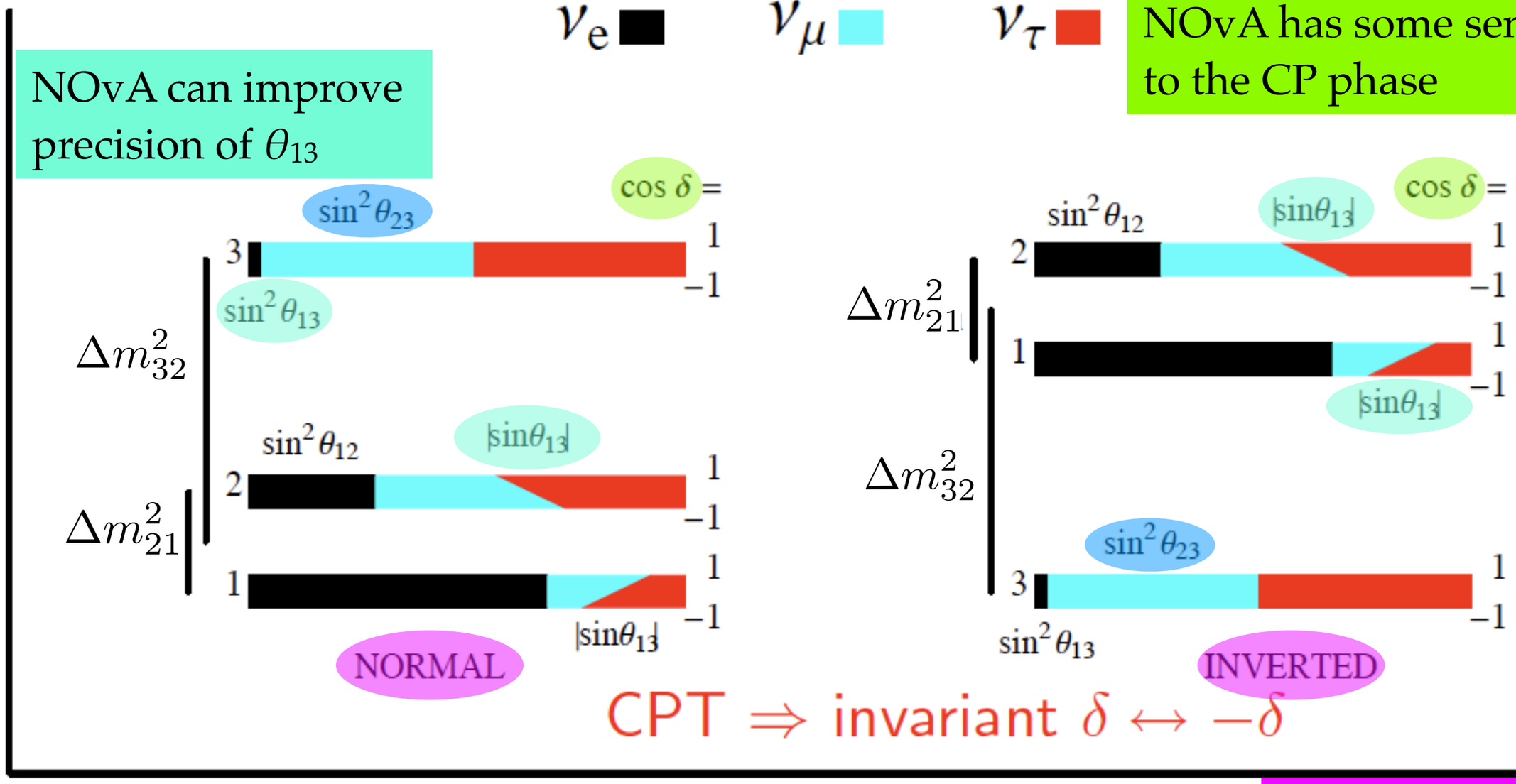
$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\alpha j} e^{-\frac{i m_j^2 t}{2E}} U_{j\beta}^* \right|^2$$

In concert with complimentary experiments, NOvA has some sensitivity to the CP phase

NOvA can improve precision of $\theta_{13}$

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NOvA's long baseline provides sensitivity to the hierarchy

# How do we find out?

$$P(\nu_\mu \to \nu_e) = \left| \sum_j U_{\mu j} e^{-\frac{i m_j^2 t}{2E}} U_{je}^* \right|^2$$

V. Barger, *et al. Phys Rev. D* **22**:2718 (1980)
Nunokawa, Parke, and Valle, *Prog. Part. Nucl. Phys.* **60** (2008) 338-402

$$\approx P_{\rm atm} + P_{\rm sol} + \sqrt{P_{\rm atm} P_{\rm sol}} (\cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta)$$

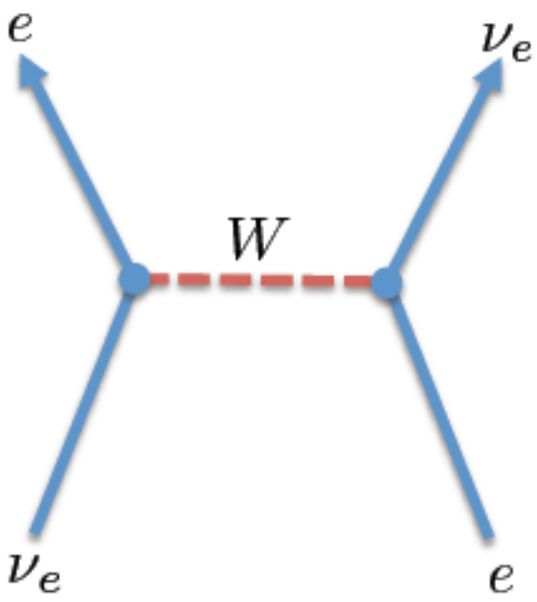
+ for ν
- for $\overline{\nu}$

$$P_{\rm atm} = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

$$P_{\rm sol} = \cos^2(\theta_{23}) \cos^2(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

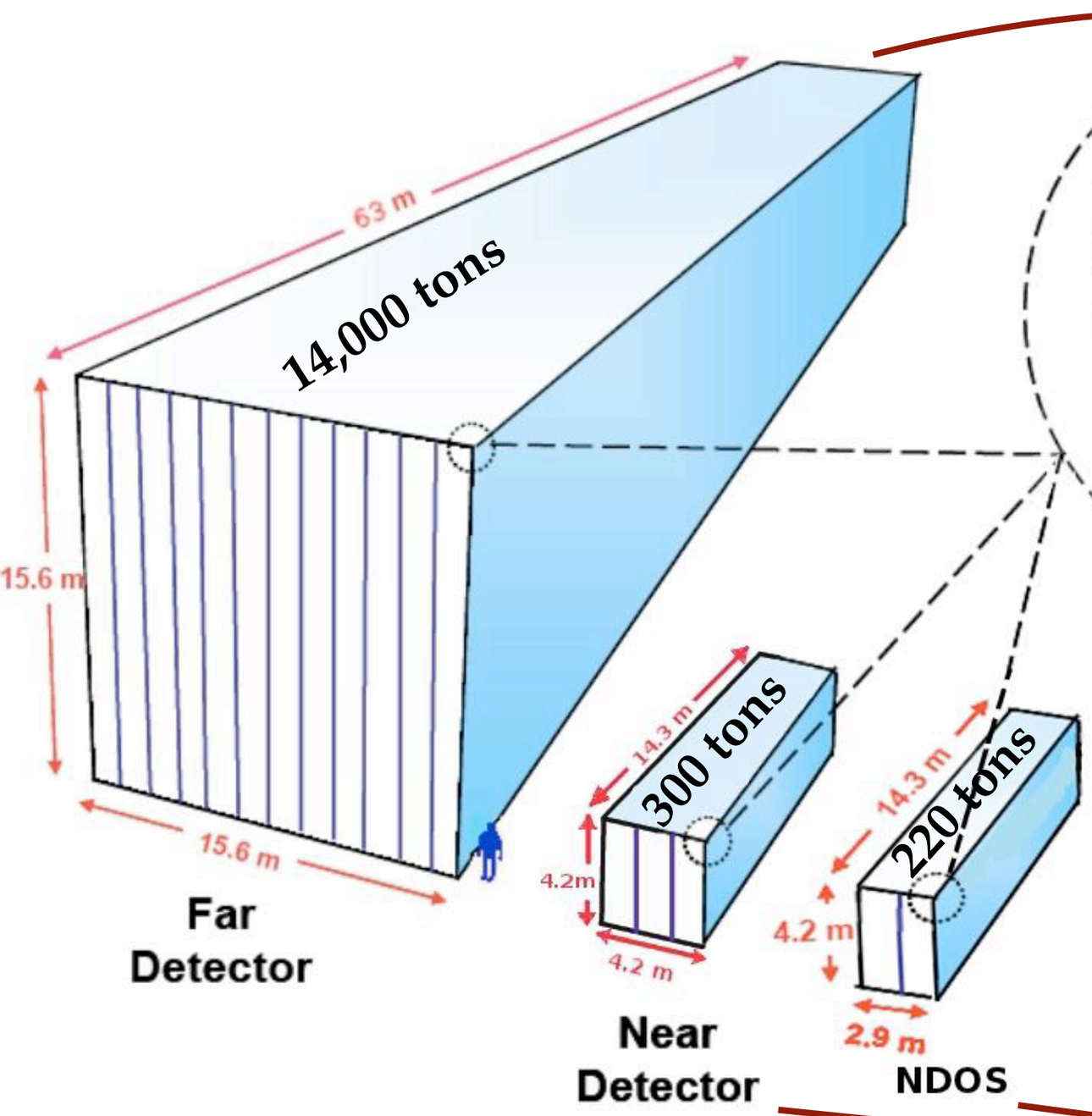
$$\Delta_{ij} = \frac{1.27 \Delta m^2_{ij} [{\rm eV}^2] L[{\rm km}]}{E[{\rm GeV}]}$$

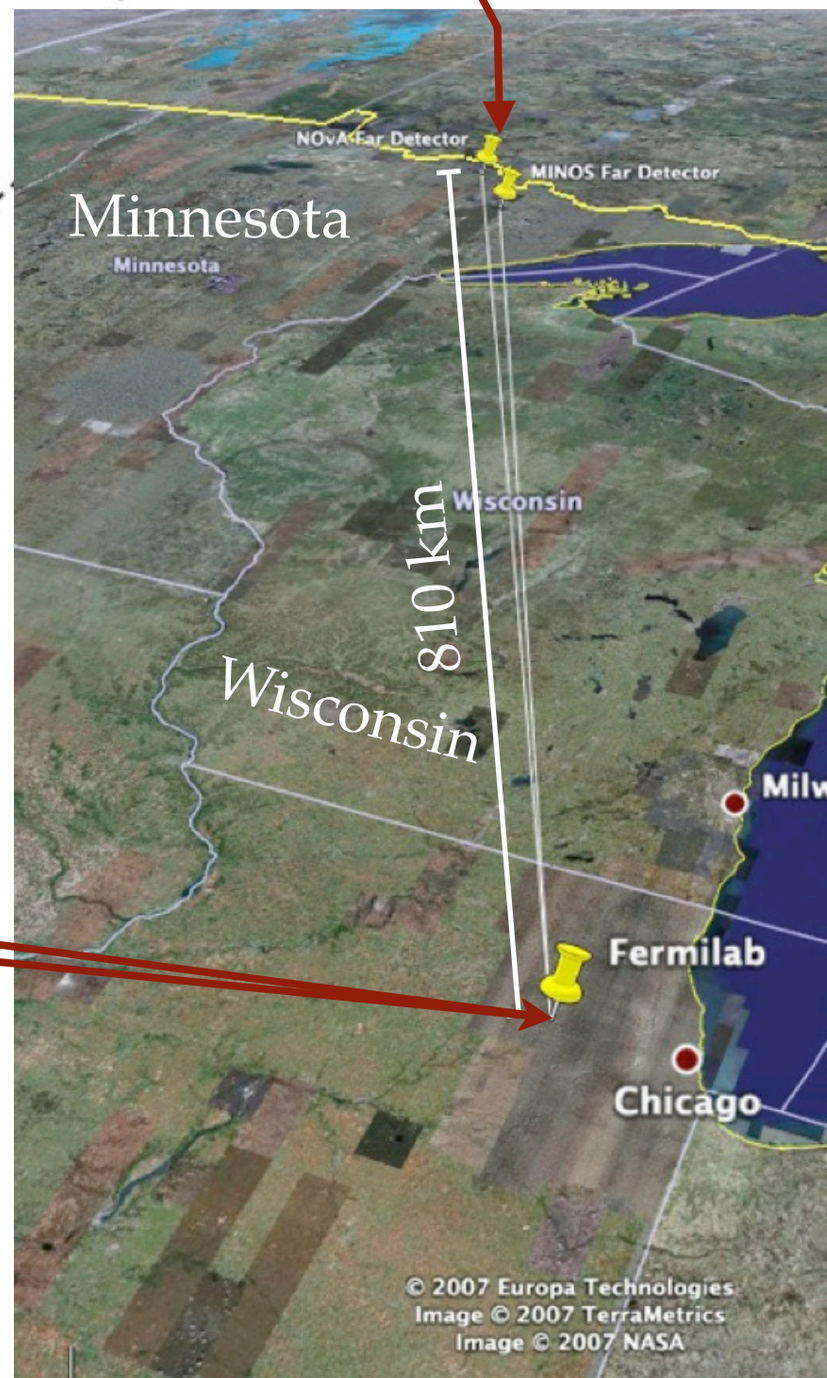
# Matter (MSW) Effect and Hierarchy




- As electron neutrinos propagate through matter, they scatter off of electrons
  - Electron anti-neutrinos do not
- The NuMI beam travels through 810 km of matter en route to the far detector
- This produces a hierarchy-dependent effect on electron neutrino appearance

$$P_{\text{matter}}(\nu_\mu \to \nu_e) \approx \left(1 + \frac{E\Delta m^2_{23}}{2\sqrt{2}G_F N_e}\right) P_{\text{vacuum}}(\nu_\mu \to \nu_e)$$

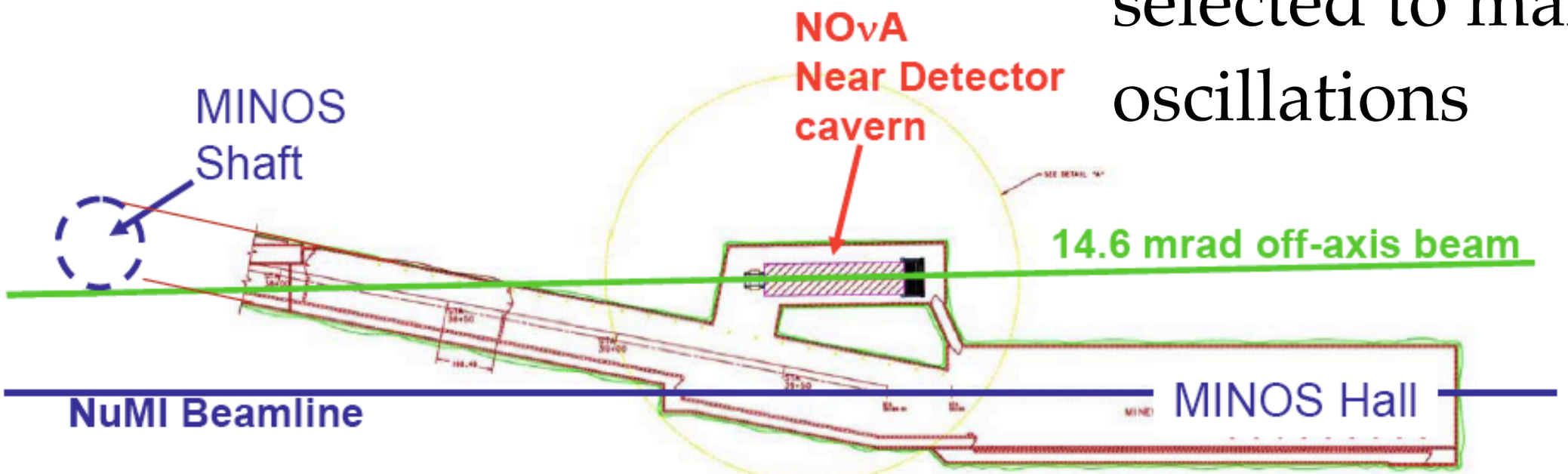


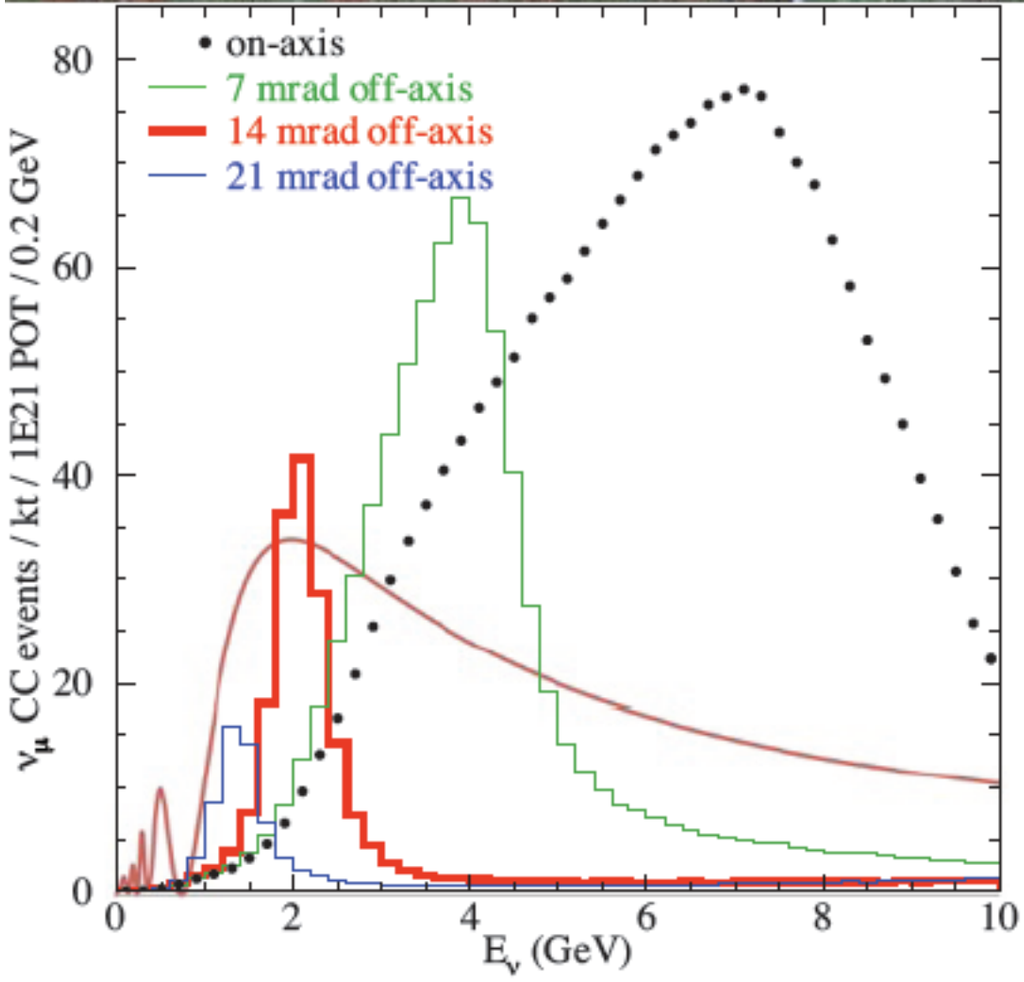



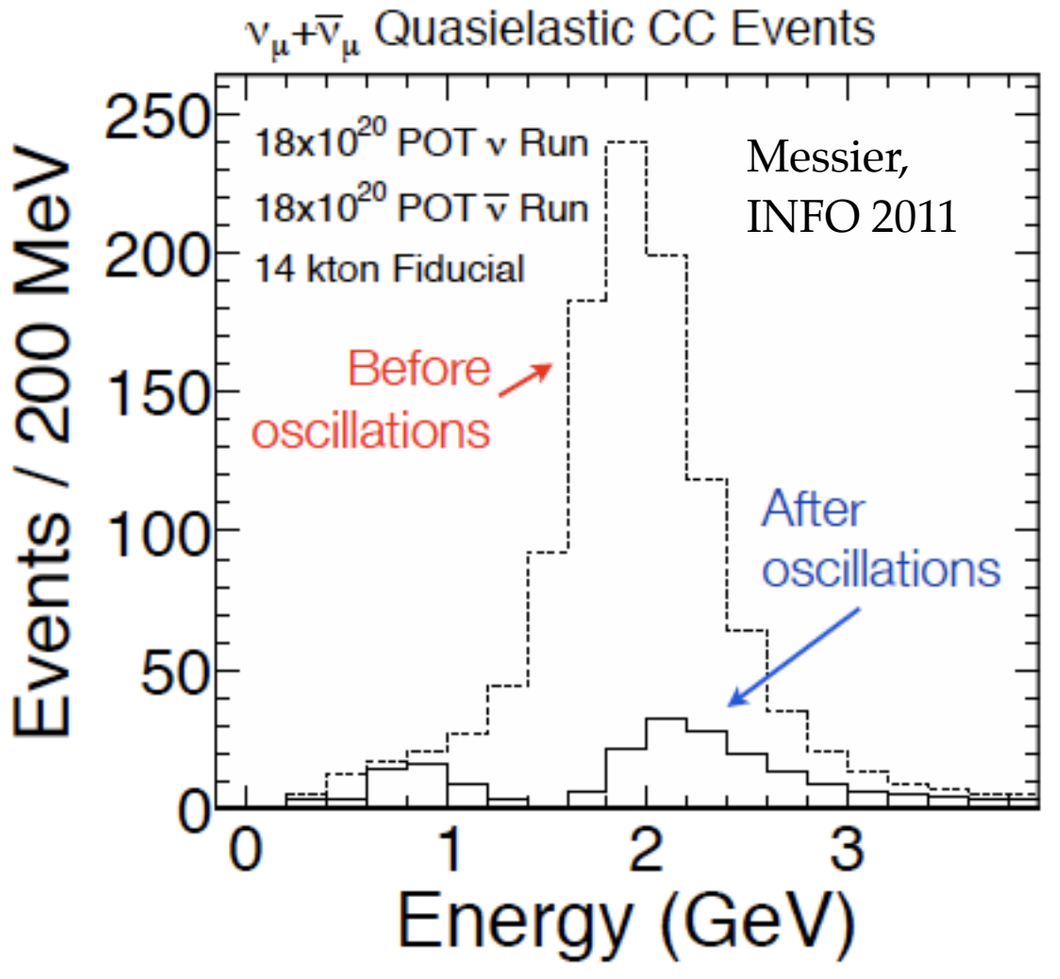

# NOvA Detectors

# Why Off-axis?

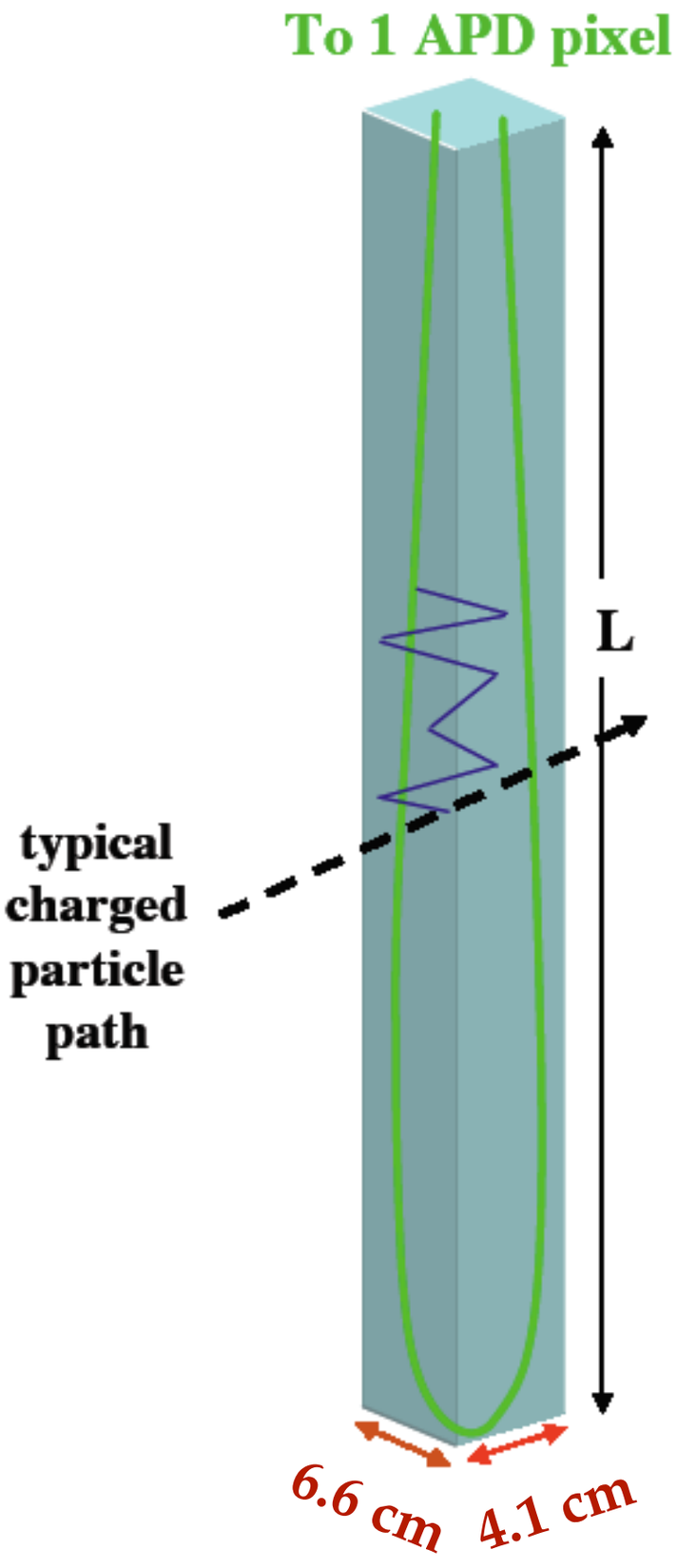
- Baseline (L) and E selected to maximize oscillations

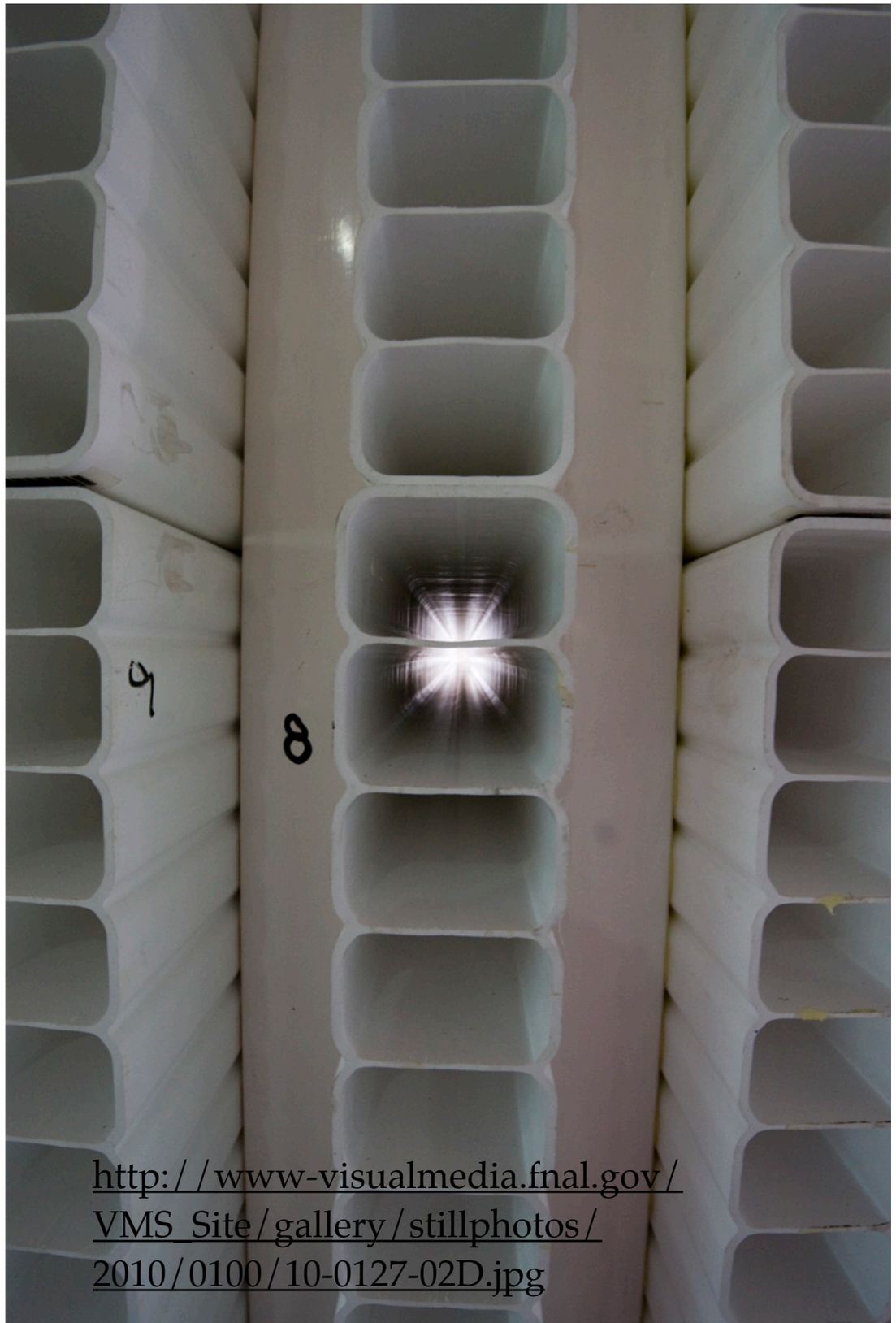


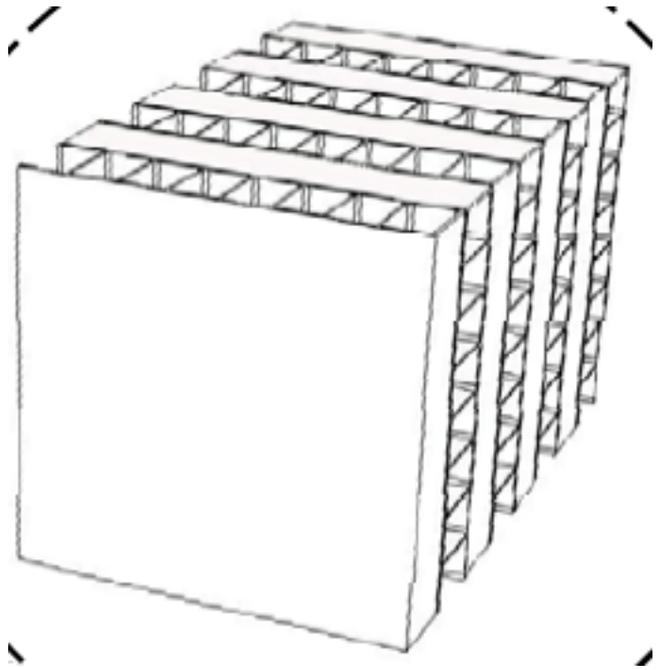
# Detector Elements



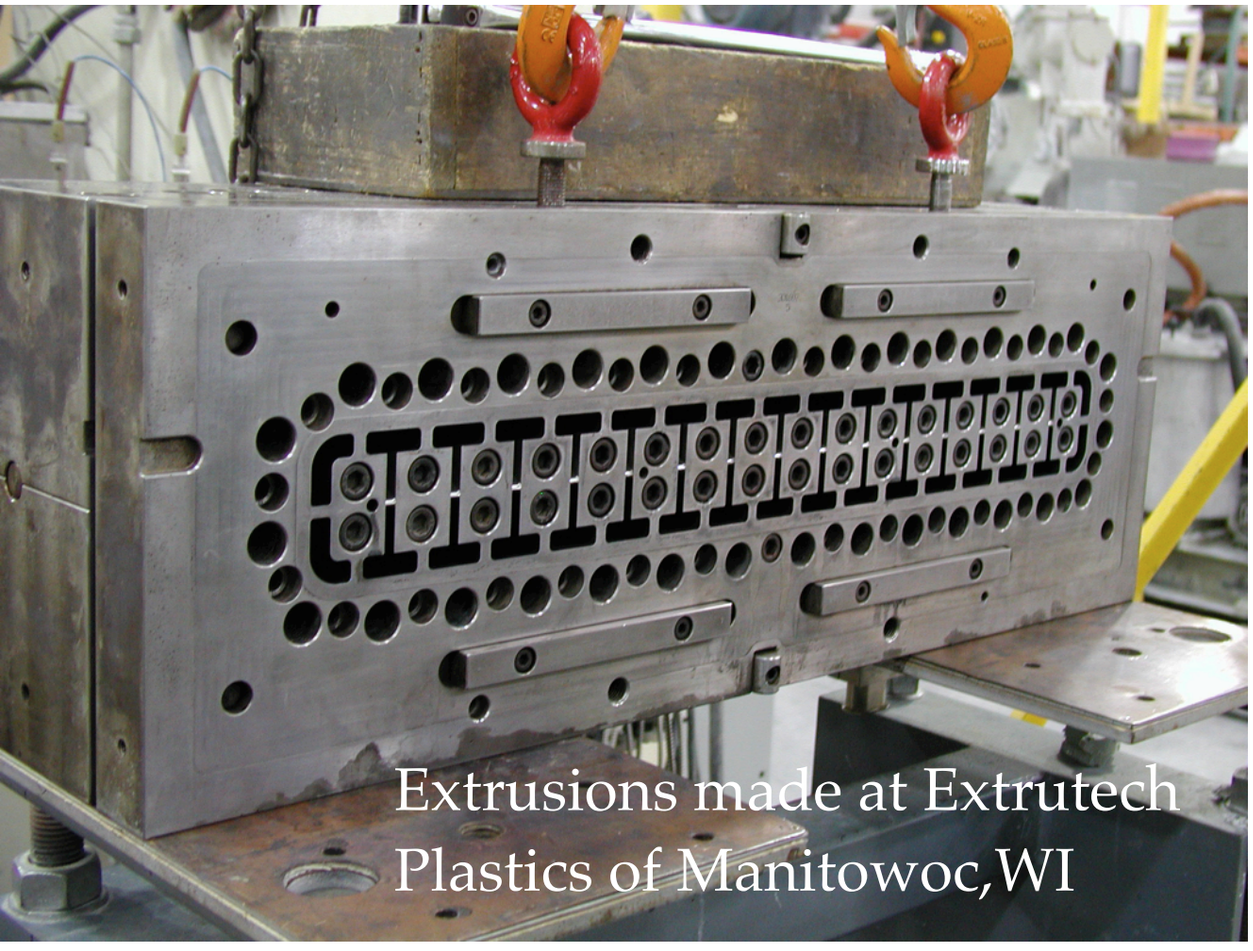




http://www-visualmedia.fnal.gov/VMS_Site/gallery/stillphotos/2010/0100/10-0127-02D.jpg

- Cells with liquid scintillator grouped into alternating planes



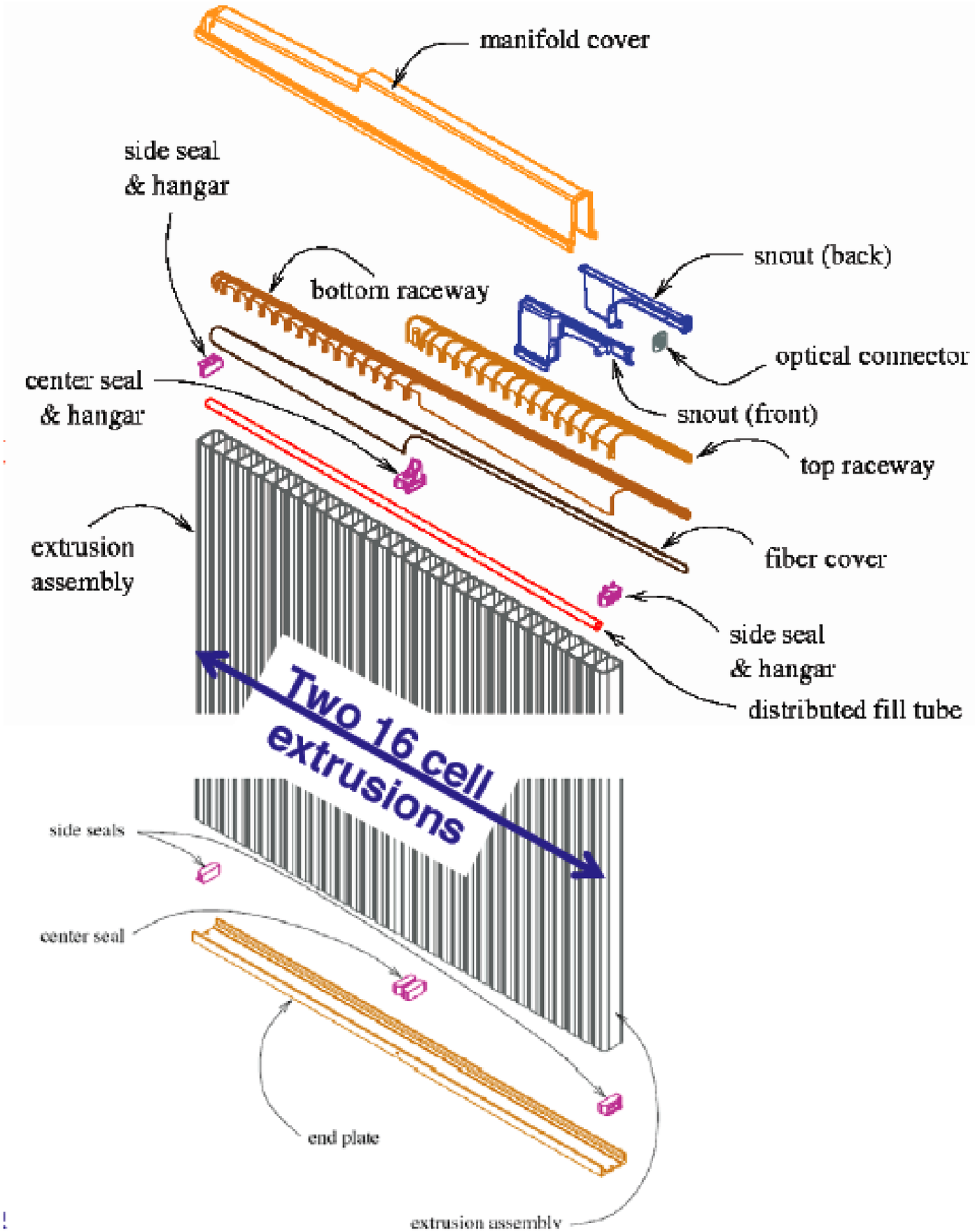
# Extrusions

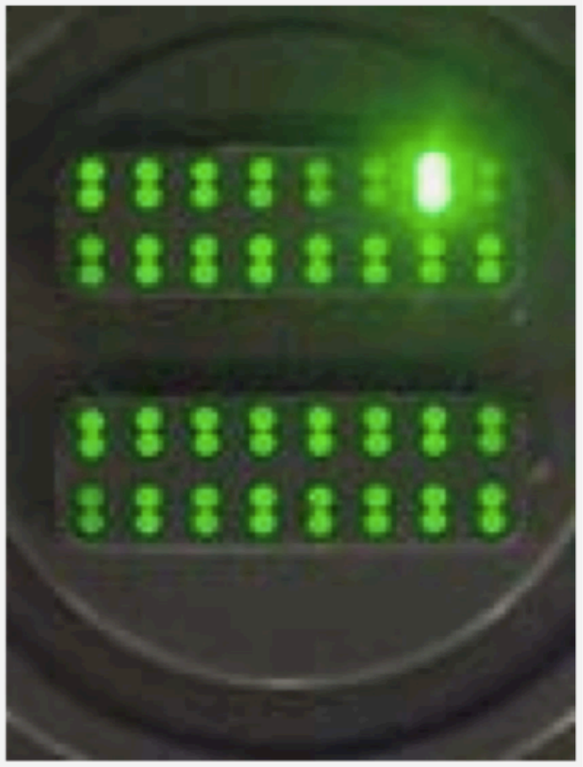


- PVC extruded through die to form 15.7m extrusions
- ~24,000 required for Far Detector.

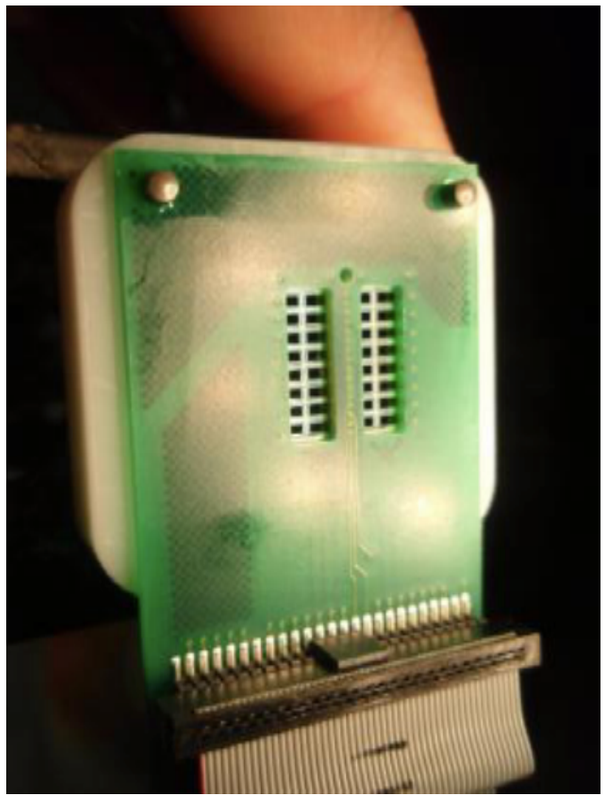
# Modules

- Many pieces must be brought together to form an active detector module
- Many undergrads working at module factory at the U of MN
- Cell interiors must be very reflective so scintillation light is not lost.





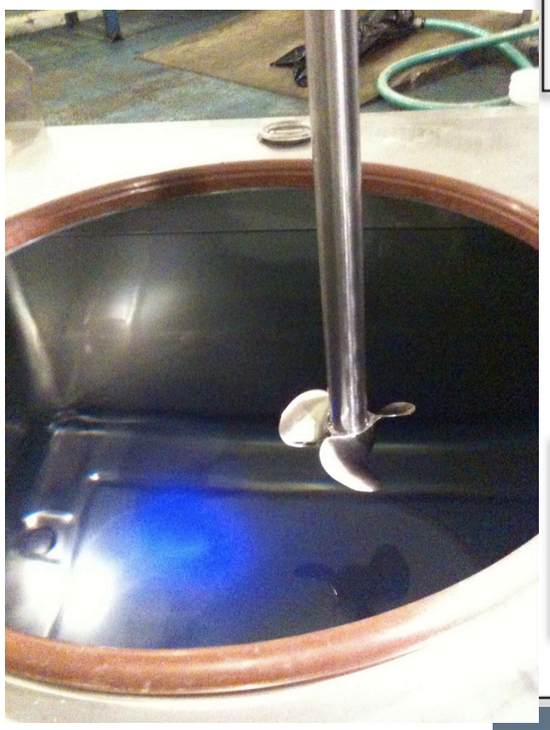
Scintillation light travels along wavelength shifting fibers to end of manifold



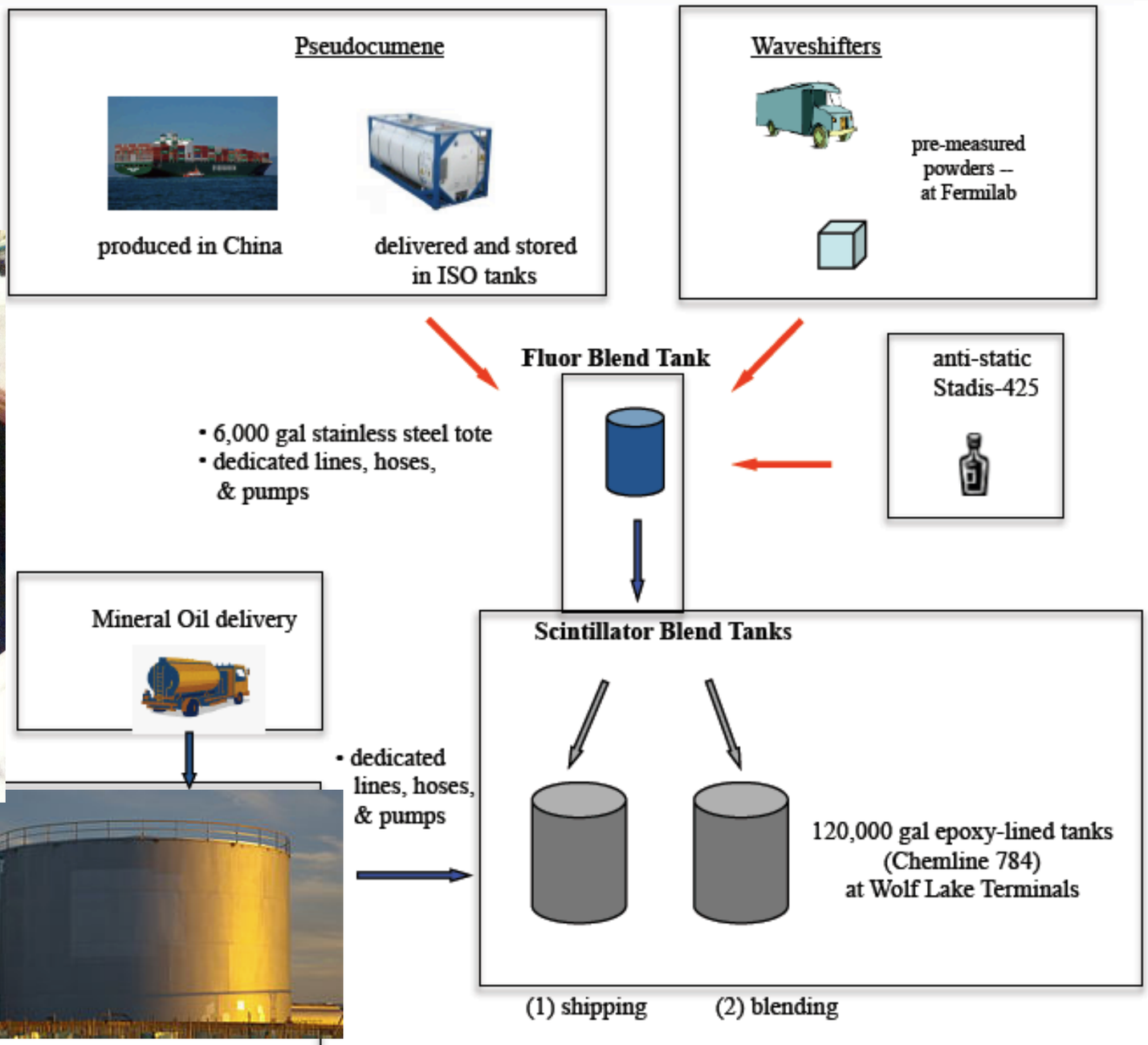
Light detected in by avalanche photodiodes (APDs) that are sealed, cooled (to -15 °C) and mated to the detector data acquisition system.

# Assembly

# Mixing The Scintillator



storage tank cleaned and holding our oil




Have enough of everything except mineral oil and pseudocumene for full far detector

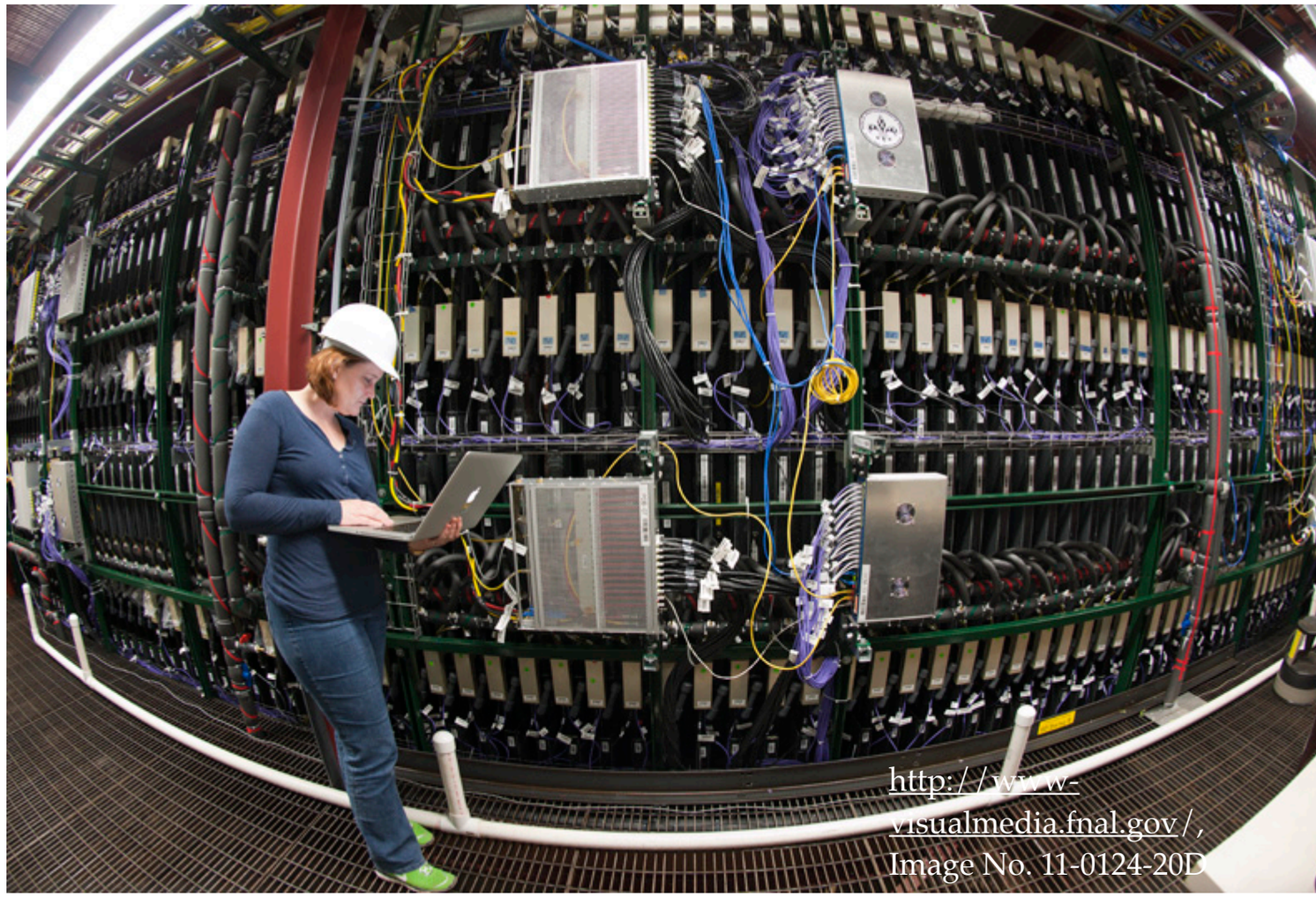
Hired private contractor (Renkert Oil) to deliver mineral oil and mix ingredients

# Filling

- NDOS is filled with high-quality scintillator
- Pumping and piping systems being installed for Far Detector
  - 6 tankers per week to FD planned
  - ~3,000,000 gallons

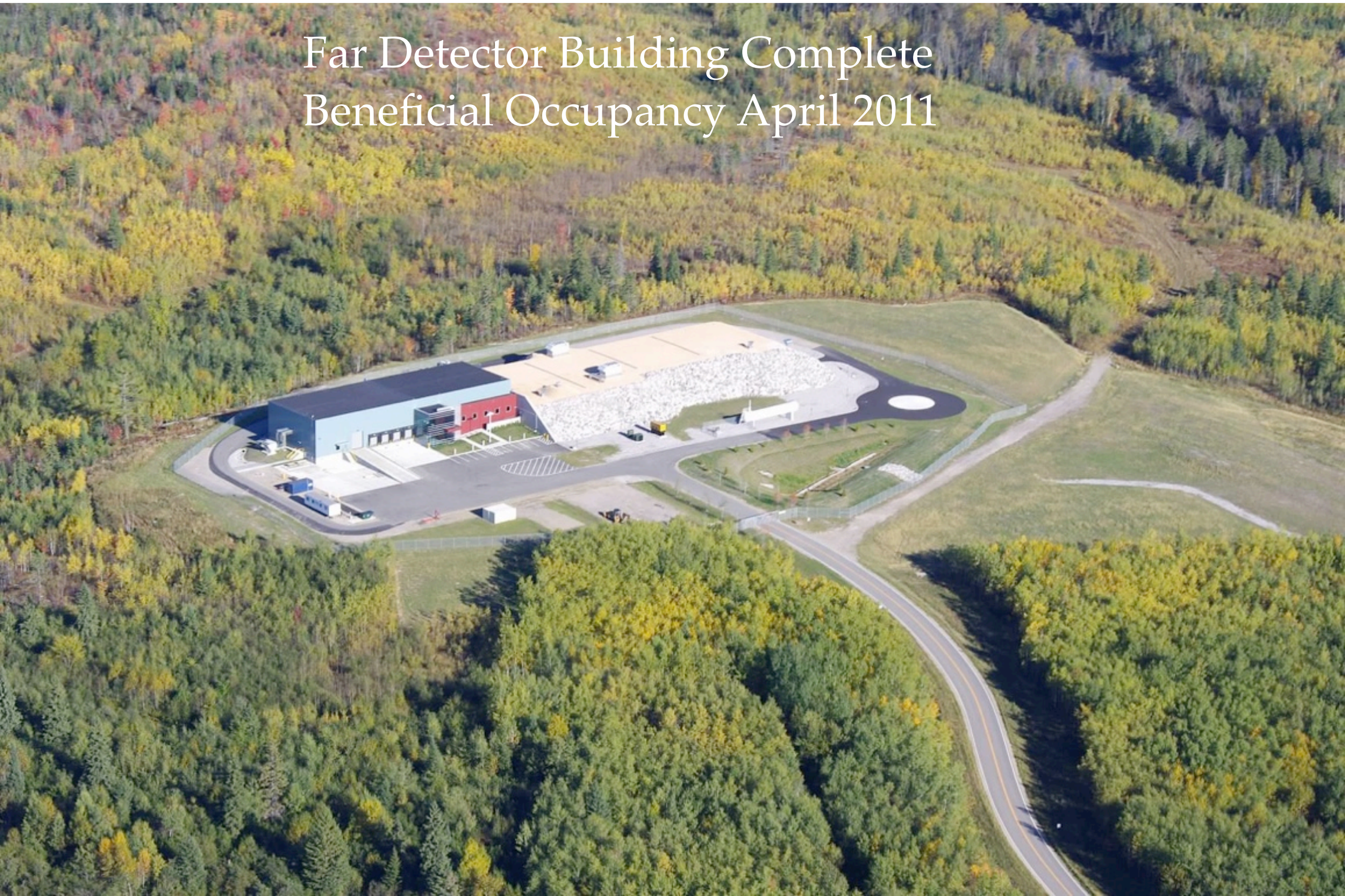
# NDOS is Built and Functioning

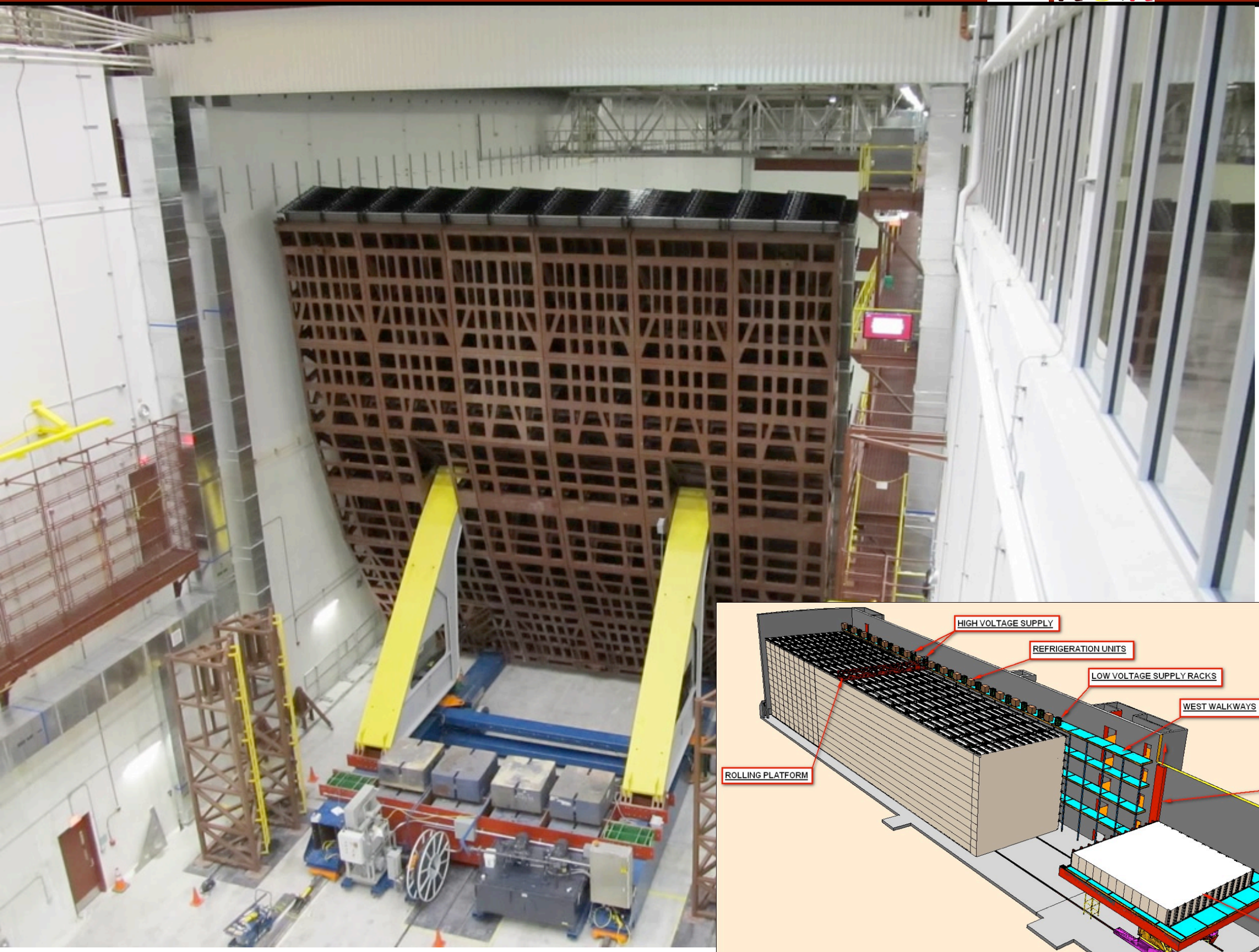
- Our prototype near detector
- It has taught us many valuable lessons for building NOvA near and far detectors.

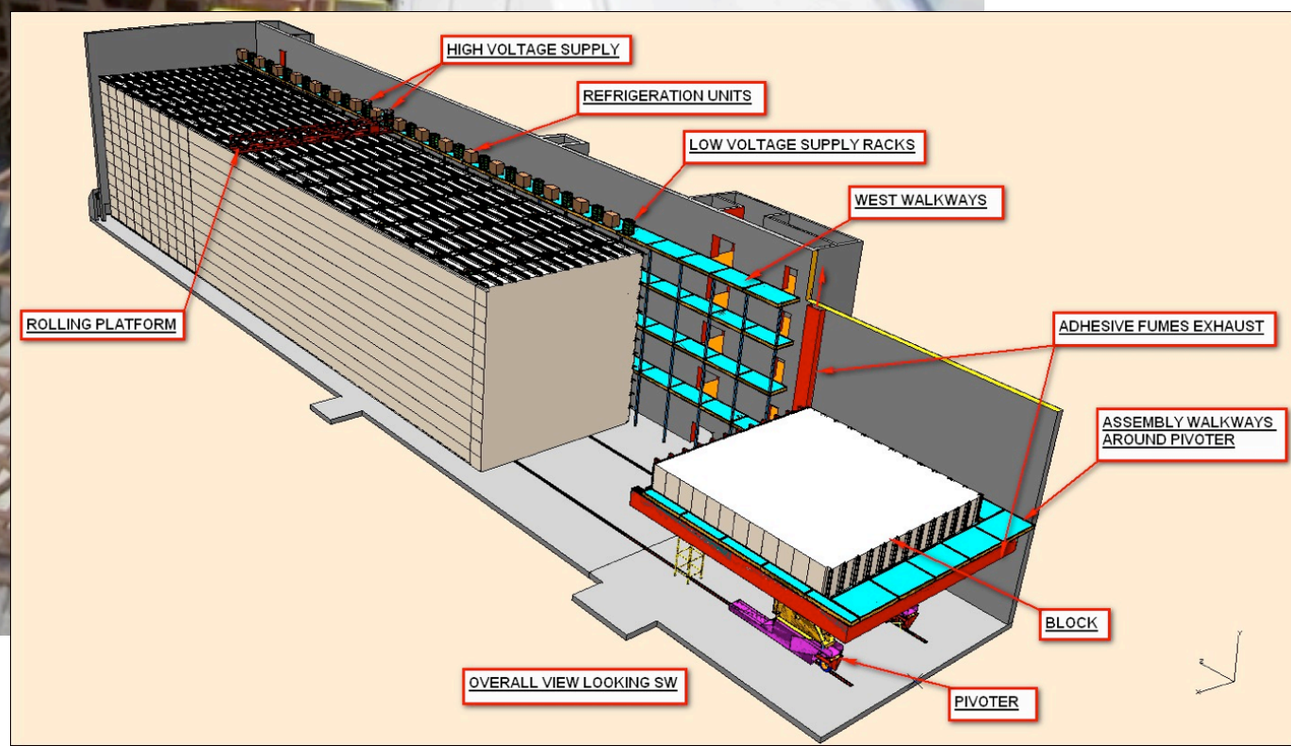


# Near Detector Excavation

# Far Detector Building Complete
# Beneficial Occupancy April 2011





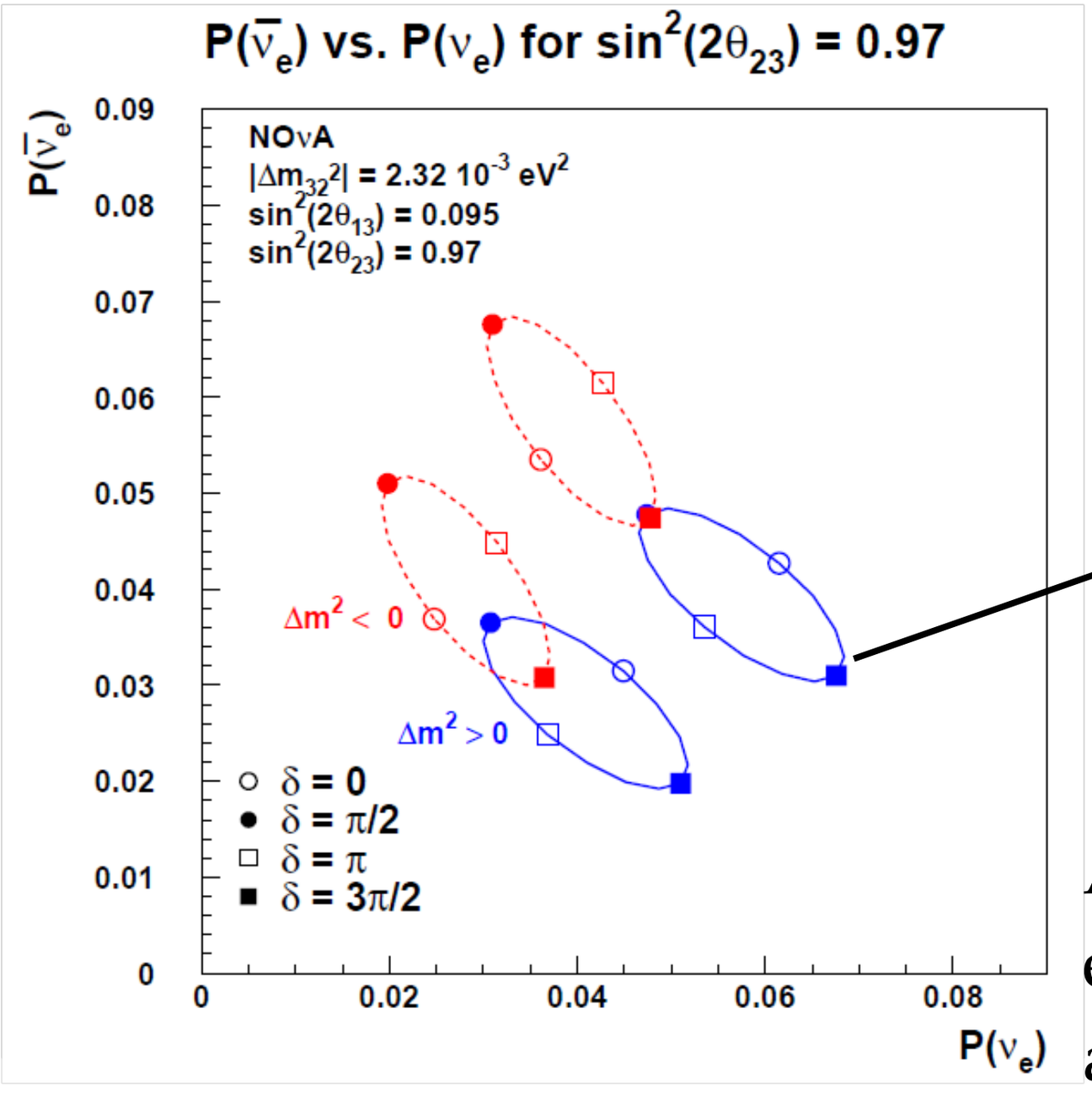

HIGH VOLTAGE SUPPLY
REFRIGERATION UNITS
LOW VOLTAGE SUPPLY RACKS
WEST WALKWAYS
ROLLING PLATFORM
ADHESIVE FUMES EXHAUST
ASSEMBLY WALKWAYS AROUND PIVOTER
BLOCK
OVERALL VIEW LOOKING SW
PIVOTER

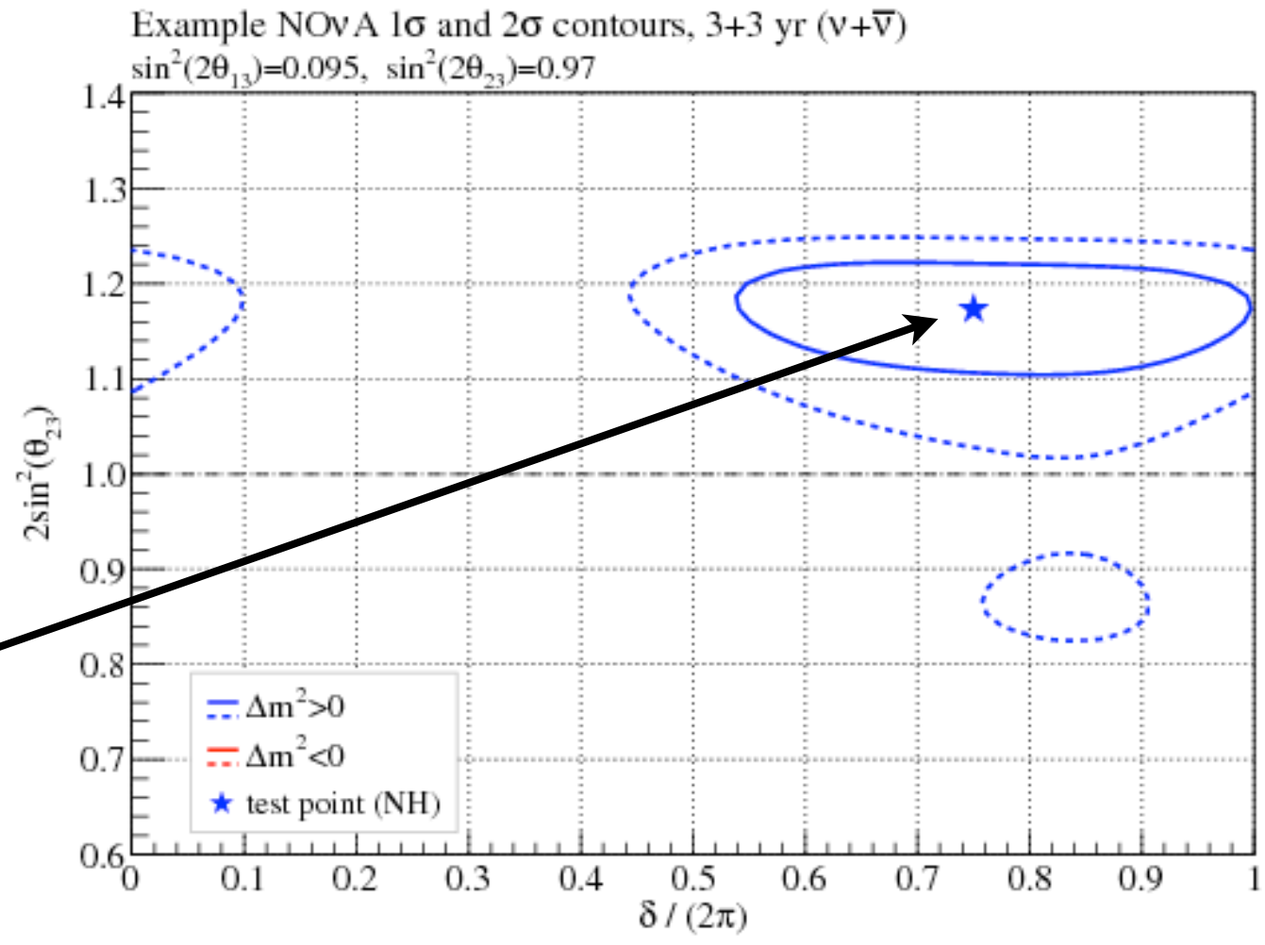
First block in place and
freestanding on Sep. 10, 2012

Second Block on Oct. 4, 2012

Only 26 more to go!

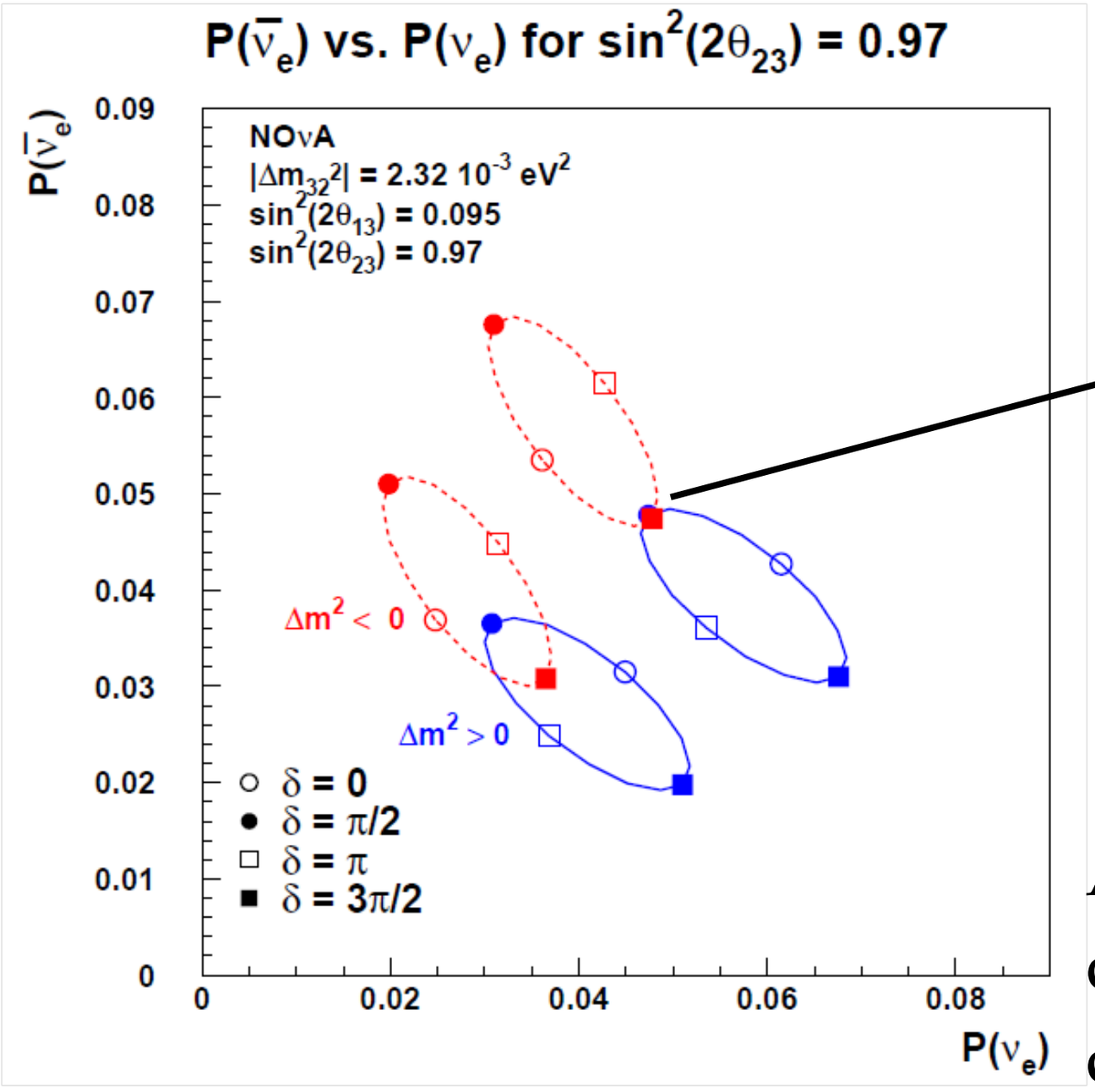
# Physics Sensitivities (if we're lucky)

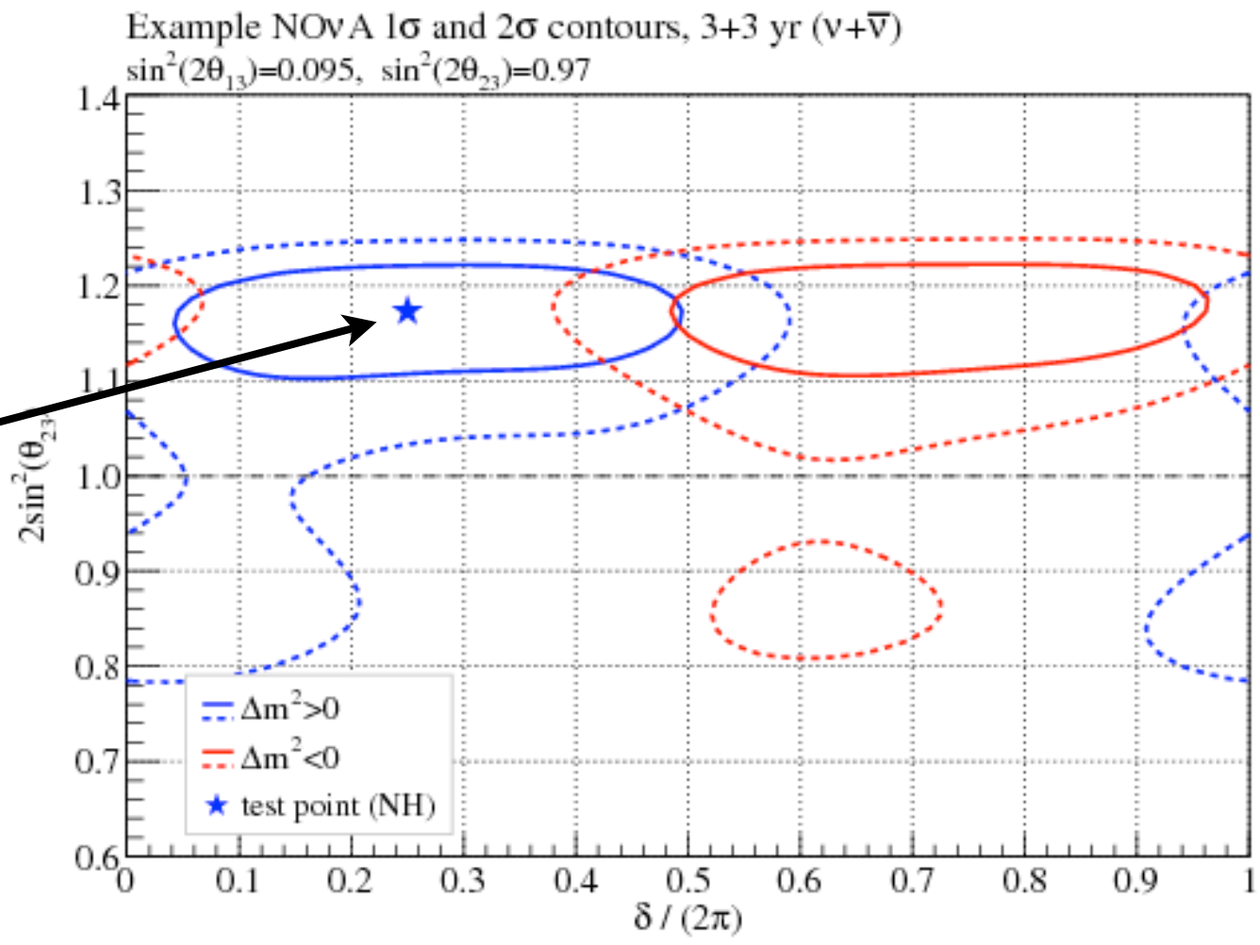



At this best-case point, we exclude the wrong hierarchy and a good fraction of $\delta_{CP}$ at $2\sigma$.

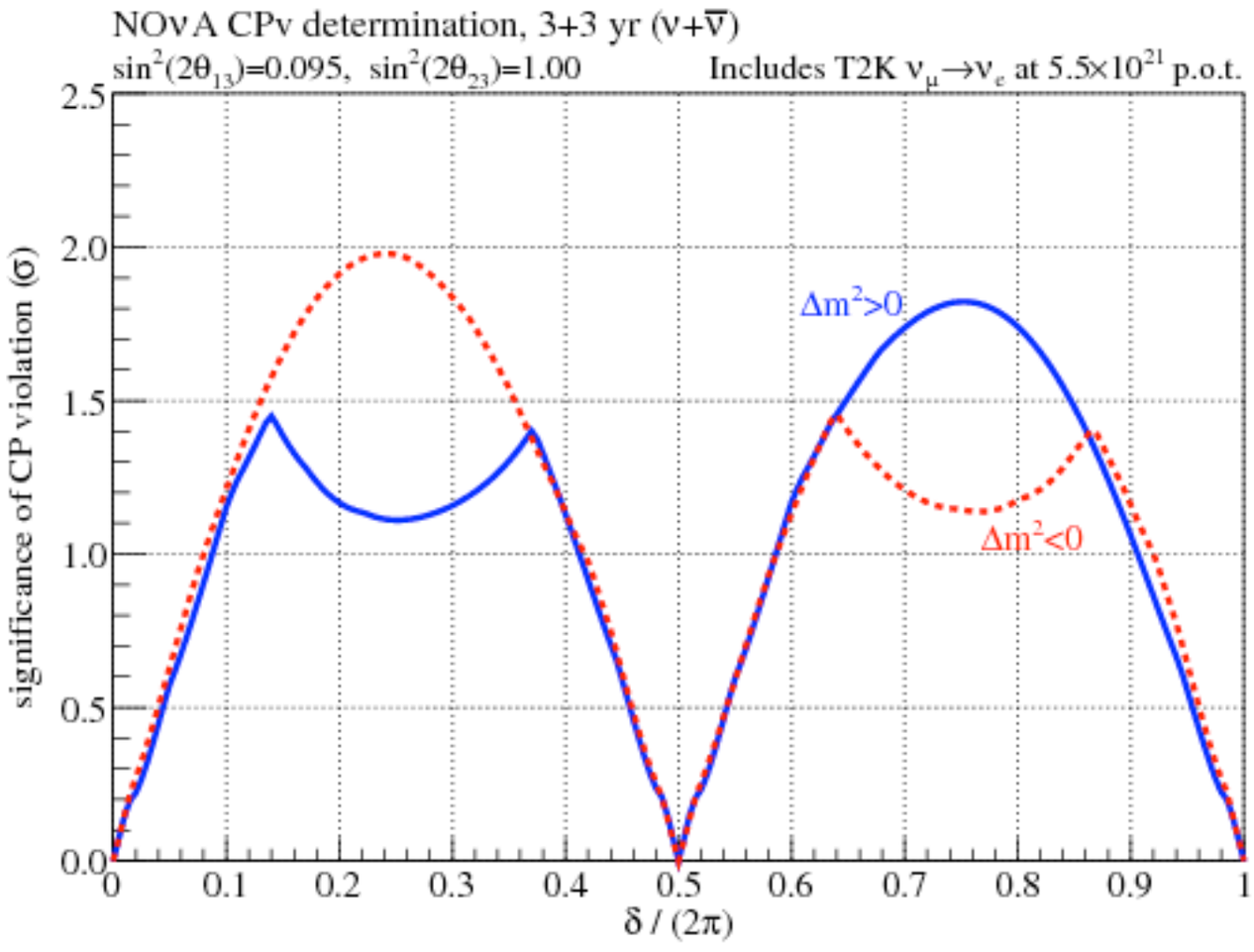
# Physics Sensitivities (if we're unlucky)




At this point, we cannot determine the hierarchy, but we can make conditional statements about it and $\delta_{CP}$. In both cases, we select $\theta_{23} > 45^o$ at 1$\sigma$

# $\delta_{CP}$ Sensitivity




- With complimentary data from T2K, we can determine $\delta_{CP}$ at $1\sigma$ over a good fraction of possible values.

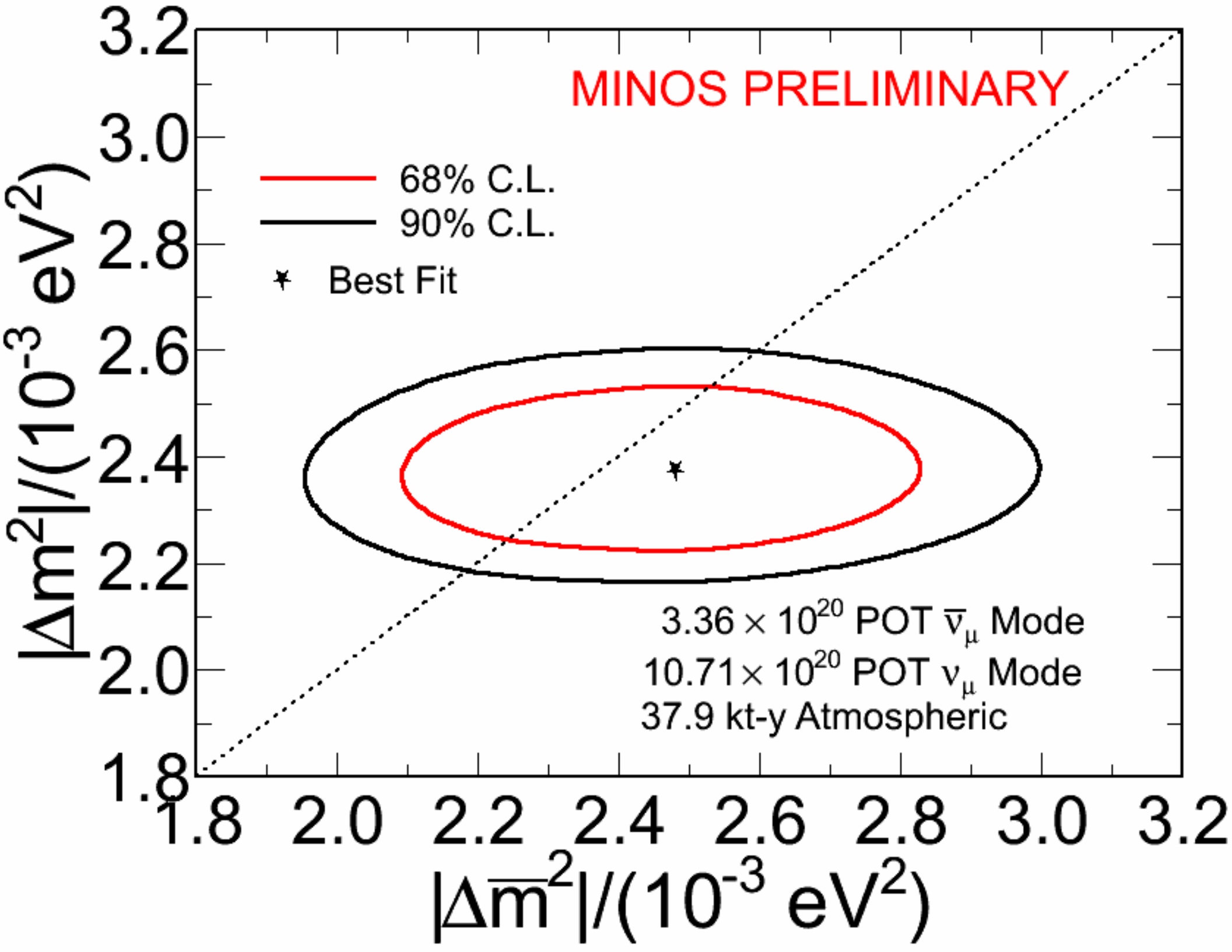
# NOvA Schedule & Outlook

- Filling of first block scheduled to begin in Nov.
- Beam is currently off; scheduled to return next Apr.
  - FD should have 5 kt in place
- ND & FD scheduled to be complete by the end of 2014
- The NOvA project is building, growing, and heading for an exciting future
- Thanks to my collaborators, especially those from whose talks I lifted material for this seminar!
- Thank you!

www.twitter.com/NOvANuz

www.facebook.com/novaexperiment

# Backup


MINOS PRELIMINARY
68% C.L.
90% C.L.
Best Fit
3.36 × 10^20 POT ν̄_μ Mode
10.71 × 10^20 POT ν_μ Mode
37.9 kt-y Atmospheric
|Δm²|/(10⁻³ eV²)
|Δm̄²|/(10⁻³ eV²)
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2

## Liquid Scintillator

94.91% food grade mineral oil
4.98% pseudocumene (scintillant)
0.110% parts PPO (powder, wave shifter)
0.00153% bis-MSB (powder, wave shifter)
0.0010% Stadis-425 (anti-static)
0.0010% Vitamin E (antioxidant)

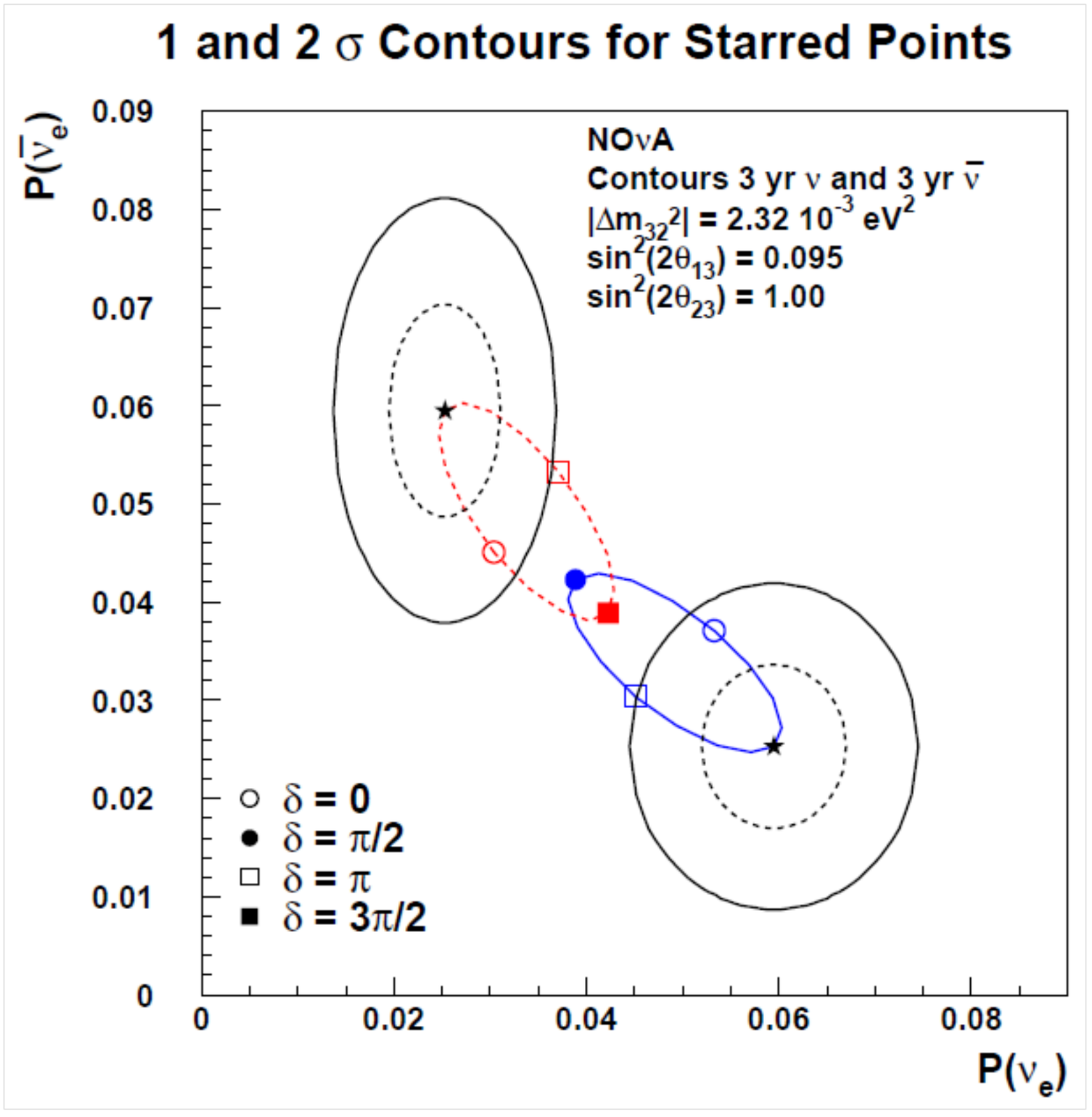
1. Mix PPO, bis-MSB, Stadis-425, and Vitamin E into pseudocumene to produce fluor blend.

2. Mix fluor blend into mineral oil to produce NOvA liquid scintillator

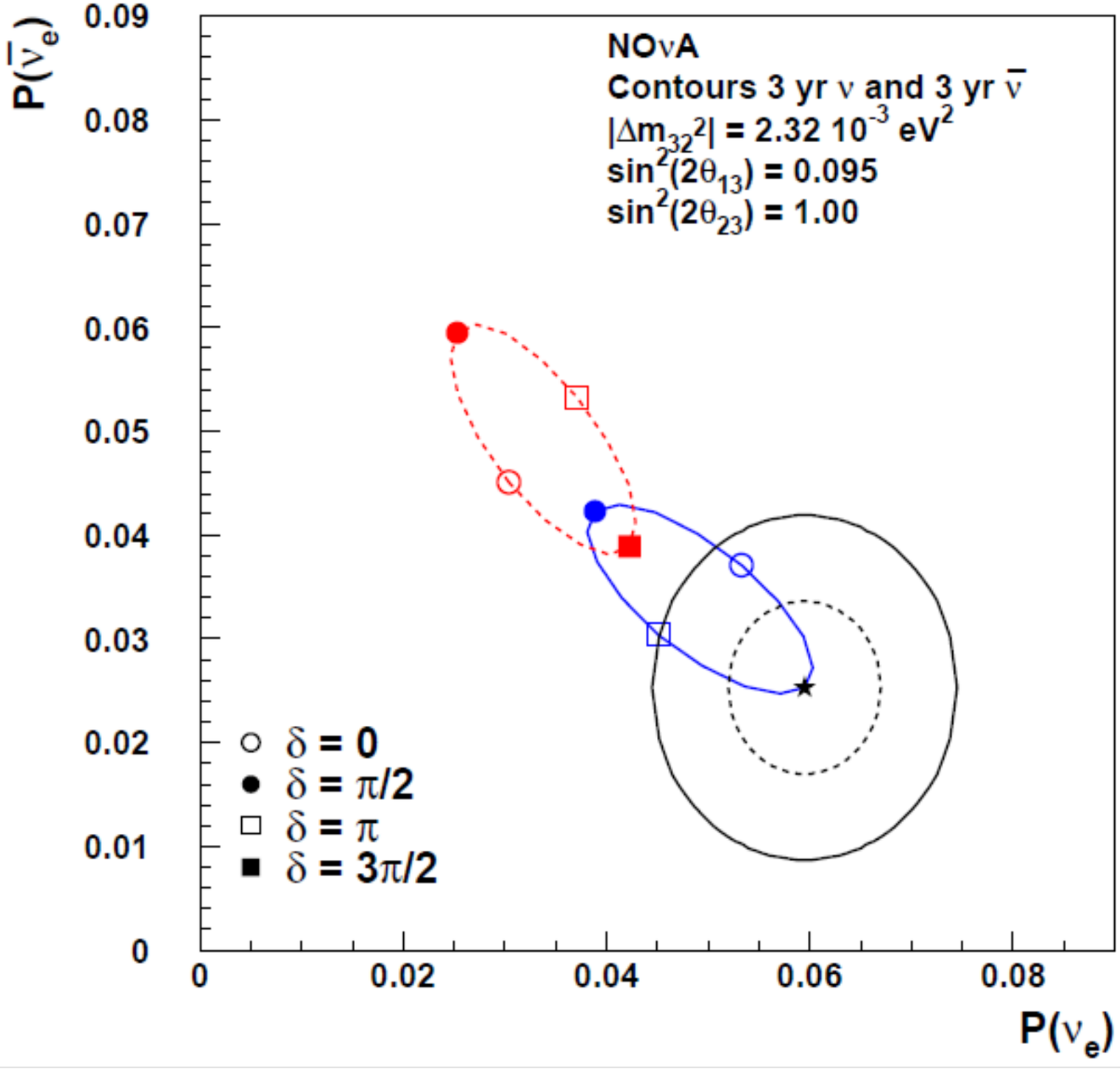
# Quality Control

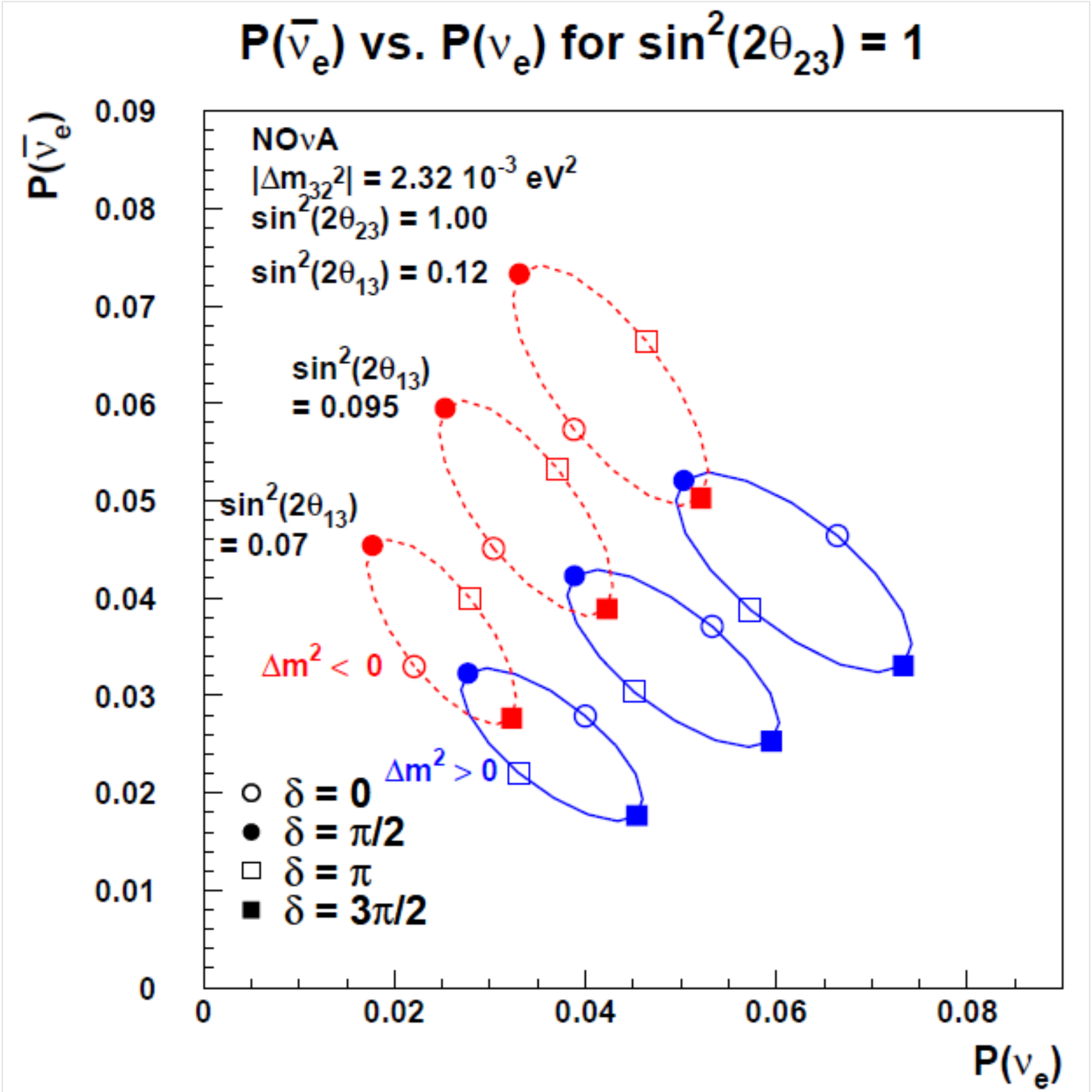
- Light Yield
  - Use radioactive sources to verify sufficient scintillator light
- Chemistry
  - Verify correct chemical composition.
- Clarity (15 m long far detector cells)
  - Use a “tintometer”
  - Maintaining cleanliness critical at every stage!

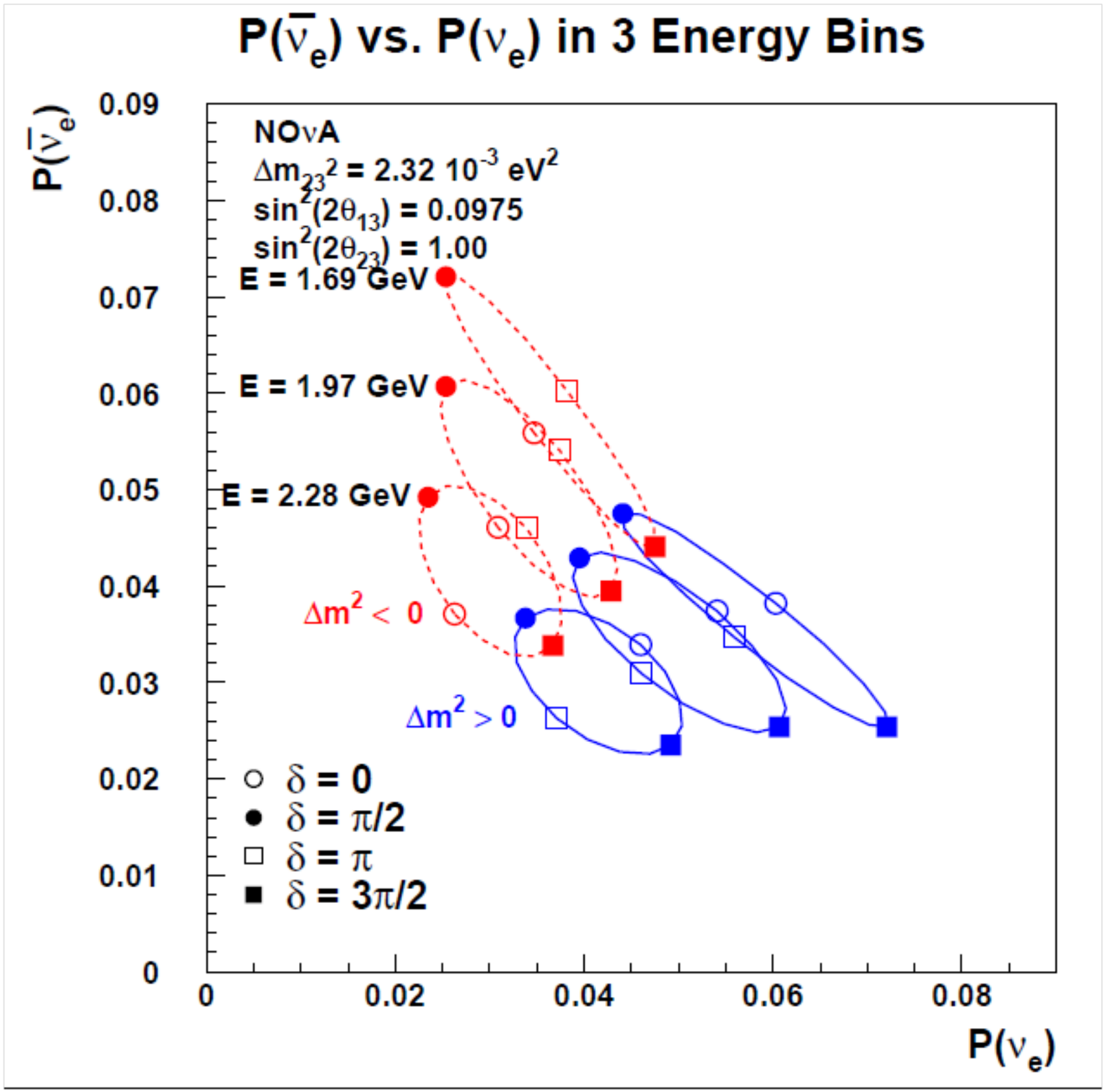
This is what we found when we looked inside of one of the fluor blending totes for the NDOS. The green substance was not identified (my guess was Mountain Dew). It was thoroughly cleaned by the blending company before any scintillator components were added.

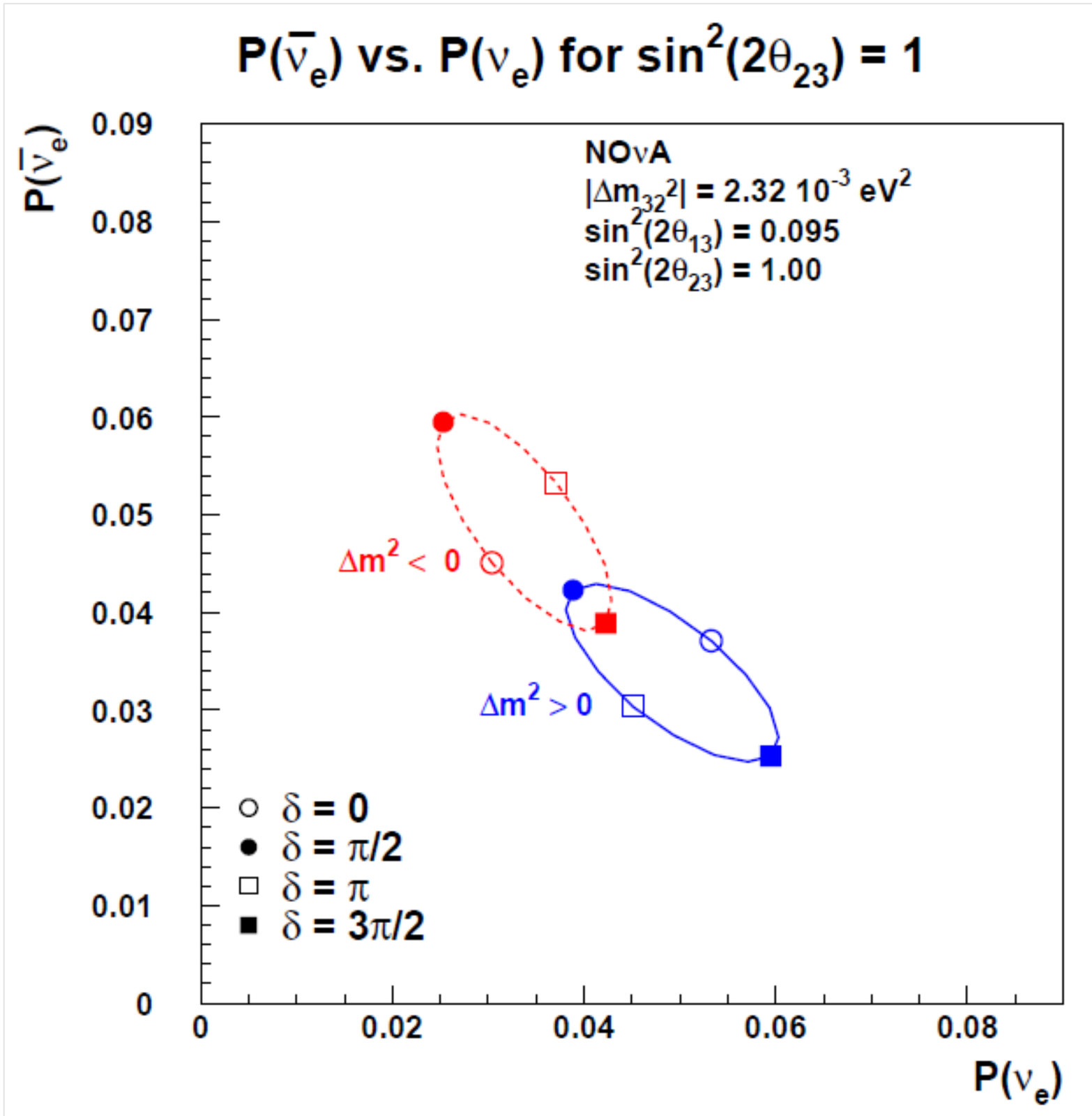

1 and 2 σ Contours for Starred Points
NOνA
Contours 3 yr ν and 3 yr ν̄
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 1.00
δ = 0
δ = π/2
δ = π
δ = 3π/2
P(ν̄e)
P(νe)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0
0.02
0.04
0.06
0.08

# 1 and 2 σ Contours for Starred Point

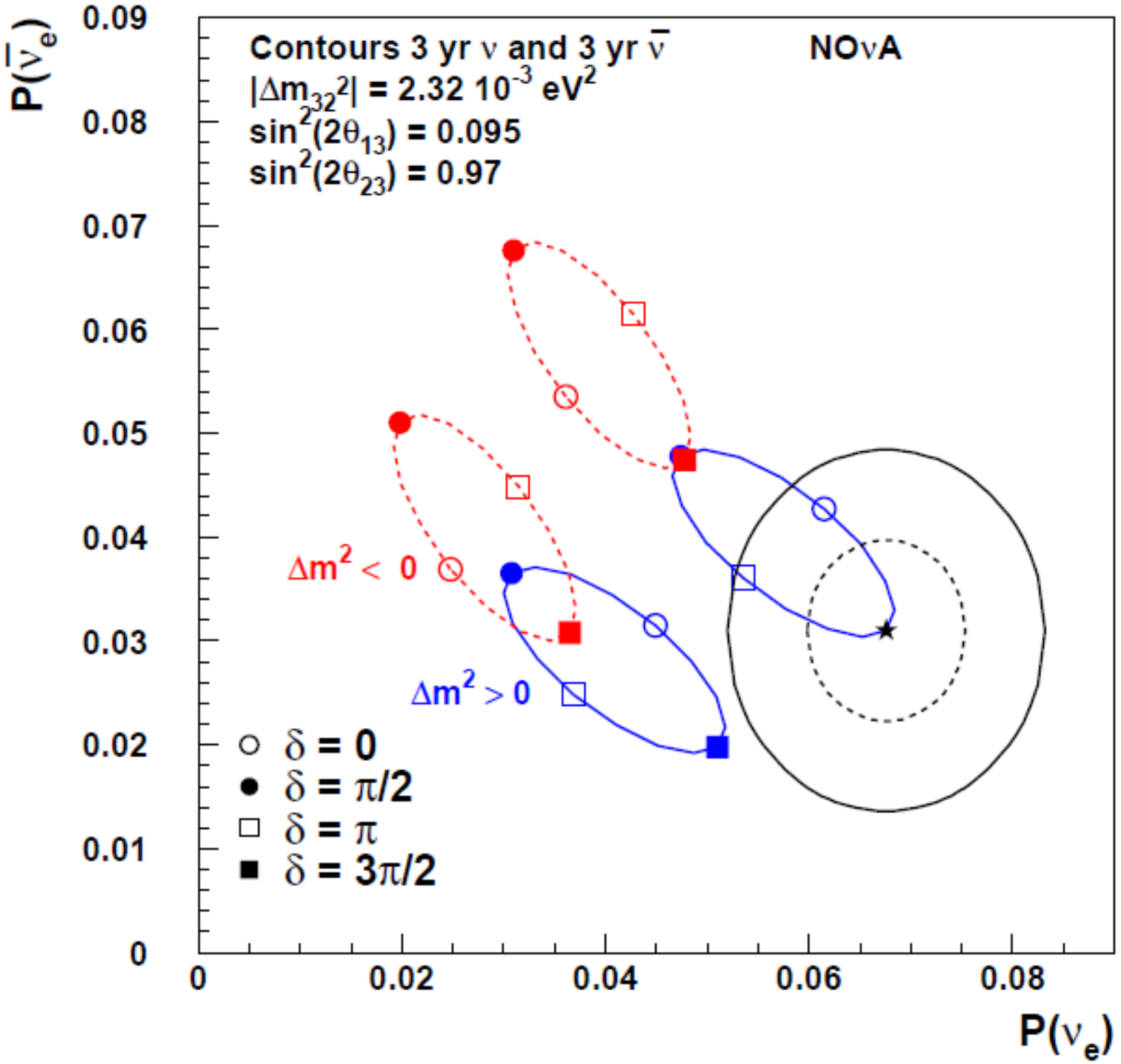


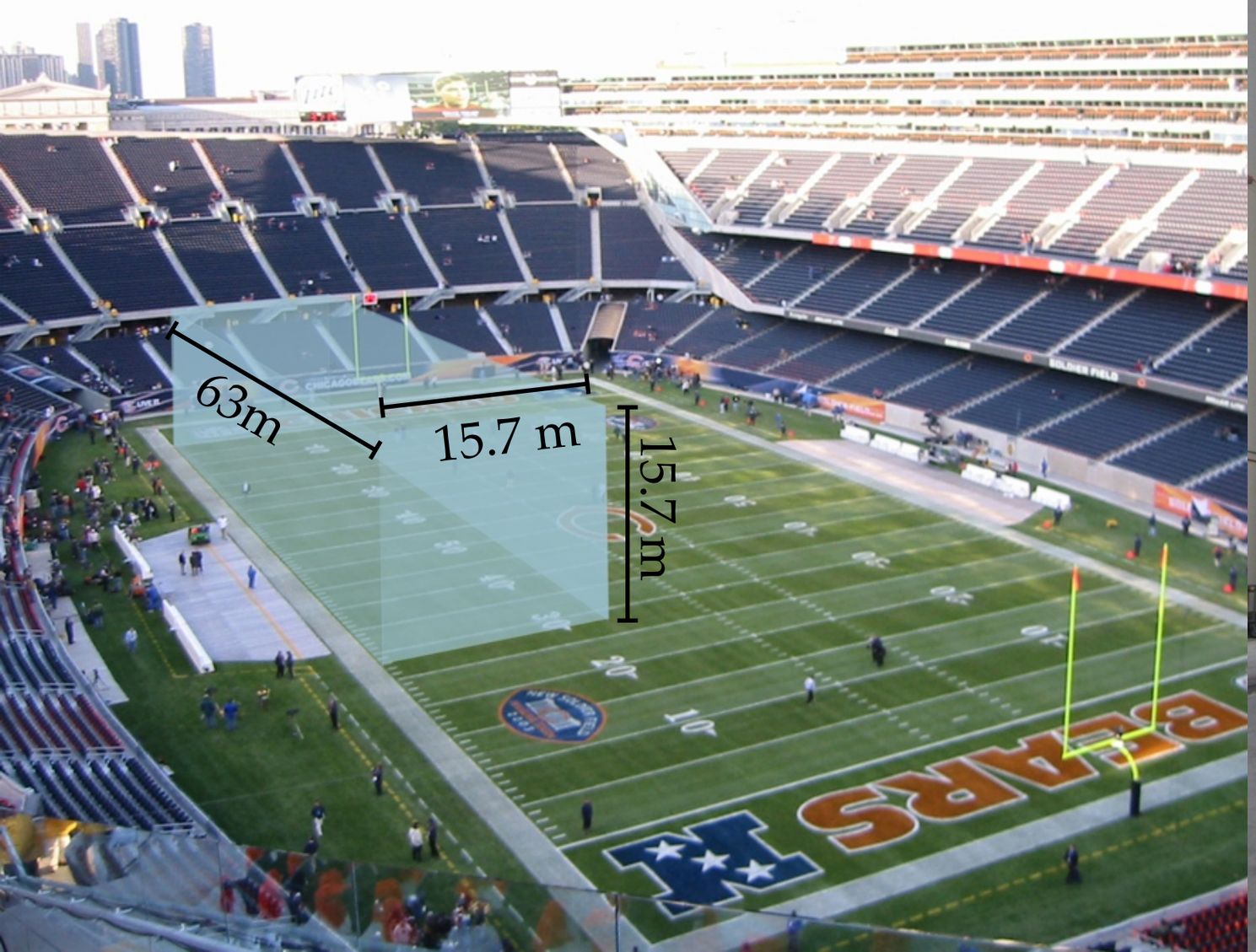

P(ν̄e) vs. P(νe) for sin²(2θ23) = 1
P(ν̄e)
P(νe)
NOνA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ23) = 1.00
sin²(2θ13) = 0.12
sin²(2θ13) = 0.095
sin²(2θ13) = 0.07
Δm² < 0
Δm² > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.02
0.04
0.06
0.08


P($\bar{\nu}_e$) vs. P($\nu_e$) in 3 Energy Bins
NOνA
$\Delta m_{23}^2 = 2.32\ 10^{-3}\ eV^2$
$\sin^2(2\theta_{13}) = 0.0975$
$\sin^2(2\theta_{23}) = 1.00$
E = 1.69 GeV
E = 1.97 GeV
E = 2.28 GeV
$\Delta m^2 < 0$
$\Delta m^2 > 0$
δ = 0
δ = π/2
δ = π
δ = 3π/2
P($\bar{\nu}_e$)
P($\nu_e$)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.02
0.04
0.06
0.08


P(ν̄e) vs. P(νe) for sin²(2θ23) = 1
P(ν̄e)
P(νe)
NOνA
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 1.00
Δm² < 0
Δm² > 0
δ = 0
δ = π/2
δ = π
δ = 3π/2
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0
0.02
0.04
0.06
0.08

# 1 and 2 σ Contours for Starred Point



# Far Detector

- 14,000 tons
- Will detected oscillated beam