Catching Ghost Partilcles in Iron, Plastic & Oil

The MINOS and NOvA Experiments

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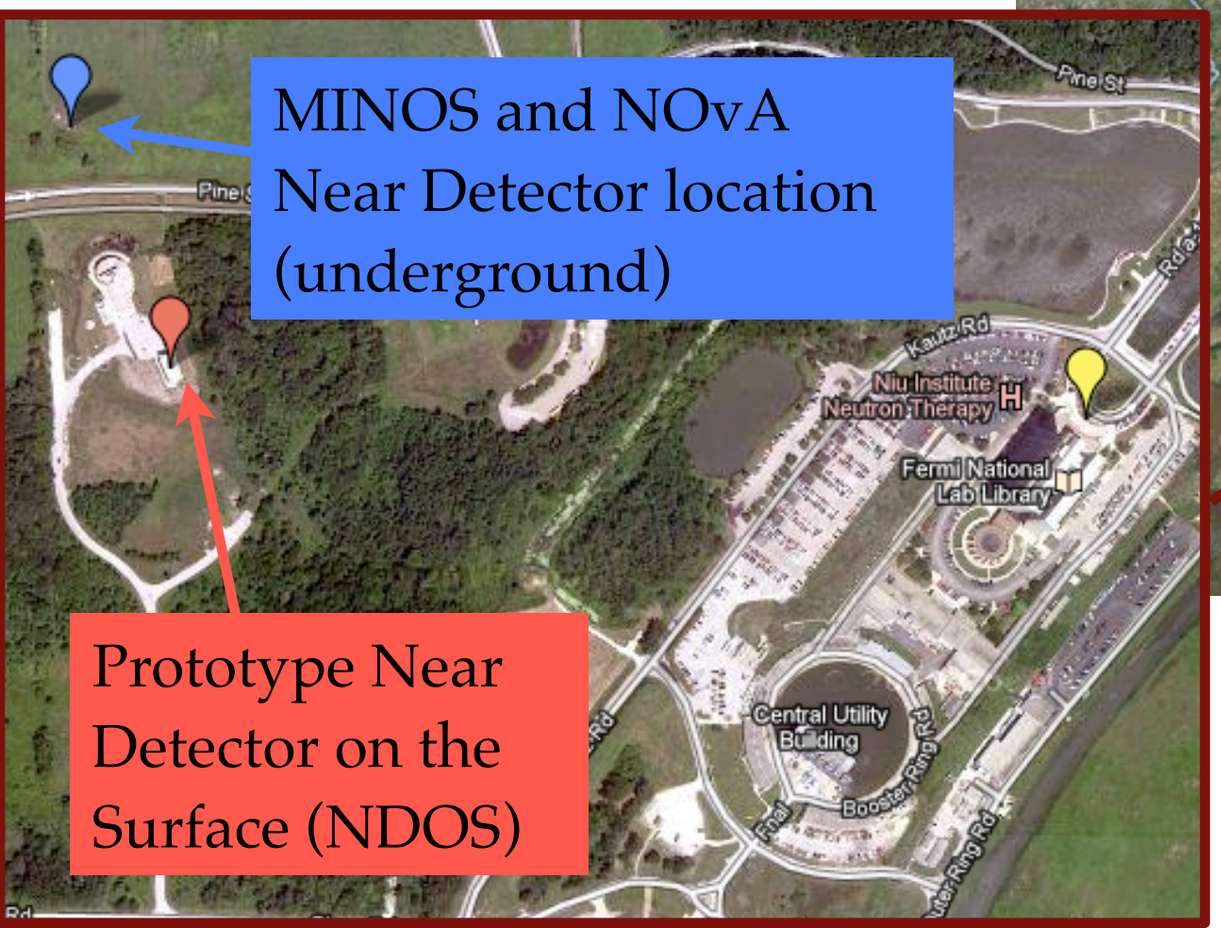
The Ohio State University High Energy Physics Seminar
2012 October 8

Outline

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

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

Entrance to Soudan Mine, home of the MINOS Far Detector



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
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ 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 (ν_e,ν_μ,ν_τ) & mass (ν_1,ν_2,ν_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.

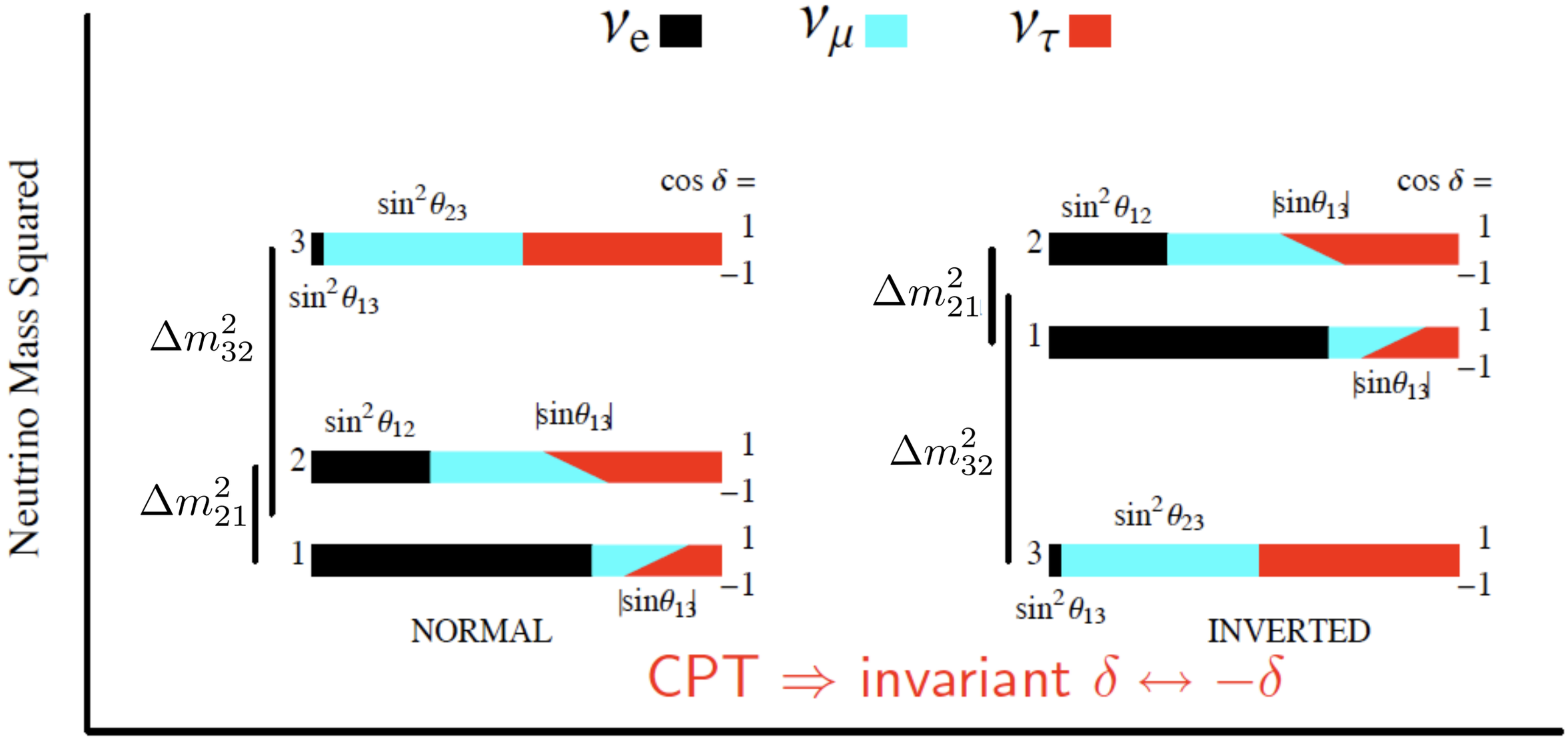
Measured Neutrino Parameters

- Mixing angles now all measured
  - $\sin^2(2\theta_{13}) = 0.095 \pm 0.010 \ (\theta_{13} = 9.0^\circ)$ (R. Patterson, NOvA)
  - $\sin^2(2\theta_{12}) = 0.857 \pm 0.024 \ (\theta_{12} = 33.9^\circ)$ (PDG 2012)
  - $\sin^2(2\theta_{23}) \approx 0.957^{+0.035}_{-0.036}$ (MINOS)*
    - Note that ambiguity remains in the value of θ_{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 θ_{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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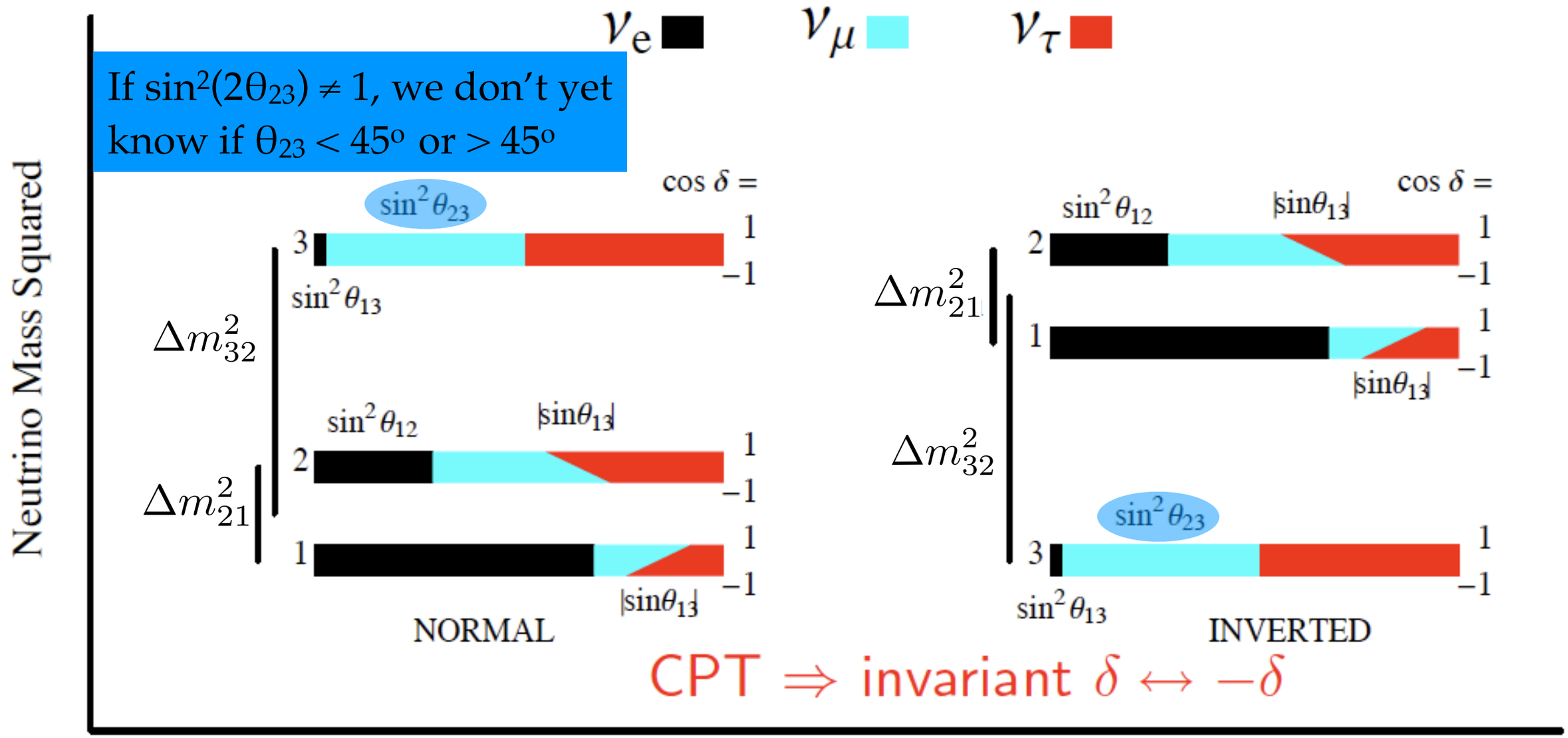

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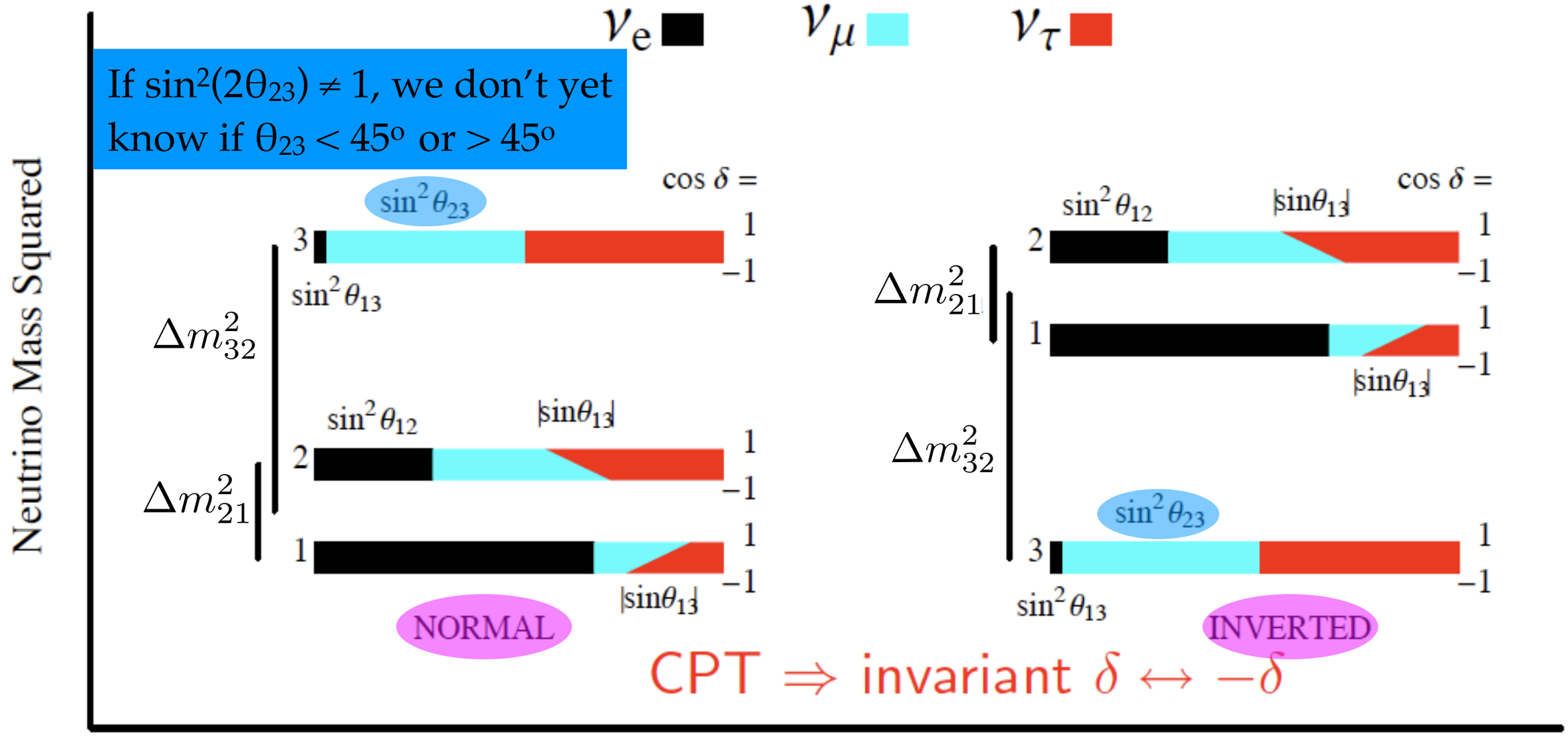

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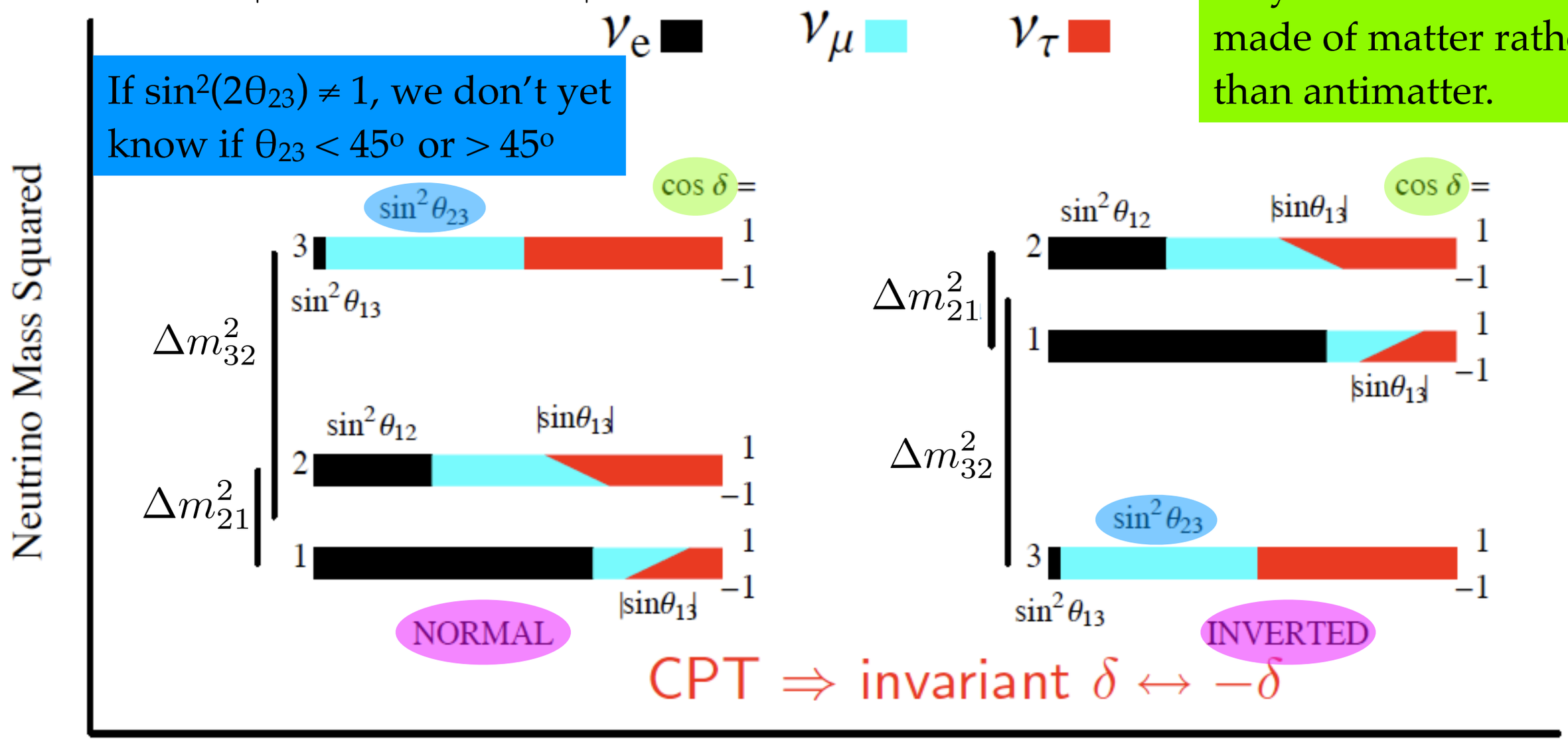
Mass Hierarchy. Is ν_3 heaviest or lightest?

The Final Unmeasured SM Parameters

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

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

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



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Mass Hierarchy. Is ν_3 heaviest or lightest?

Oscillations (Beer Analogy)

ν_μ Source

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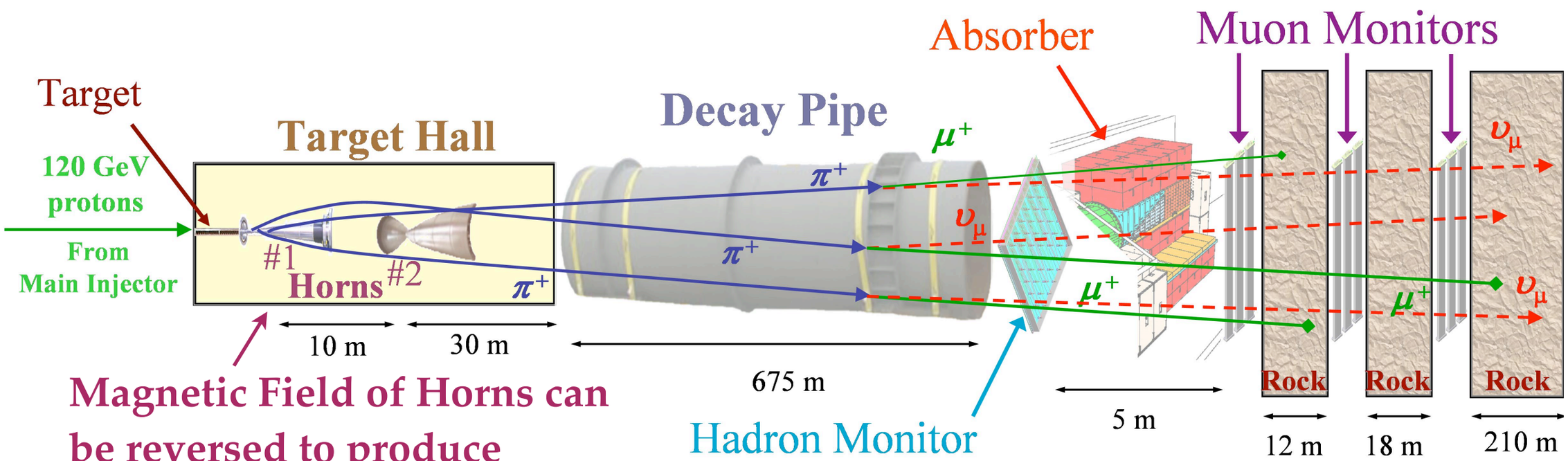
The NuMI Beam



- 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

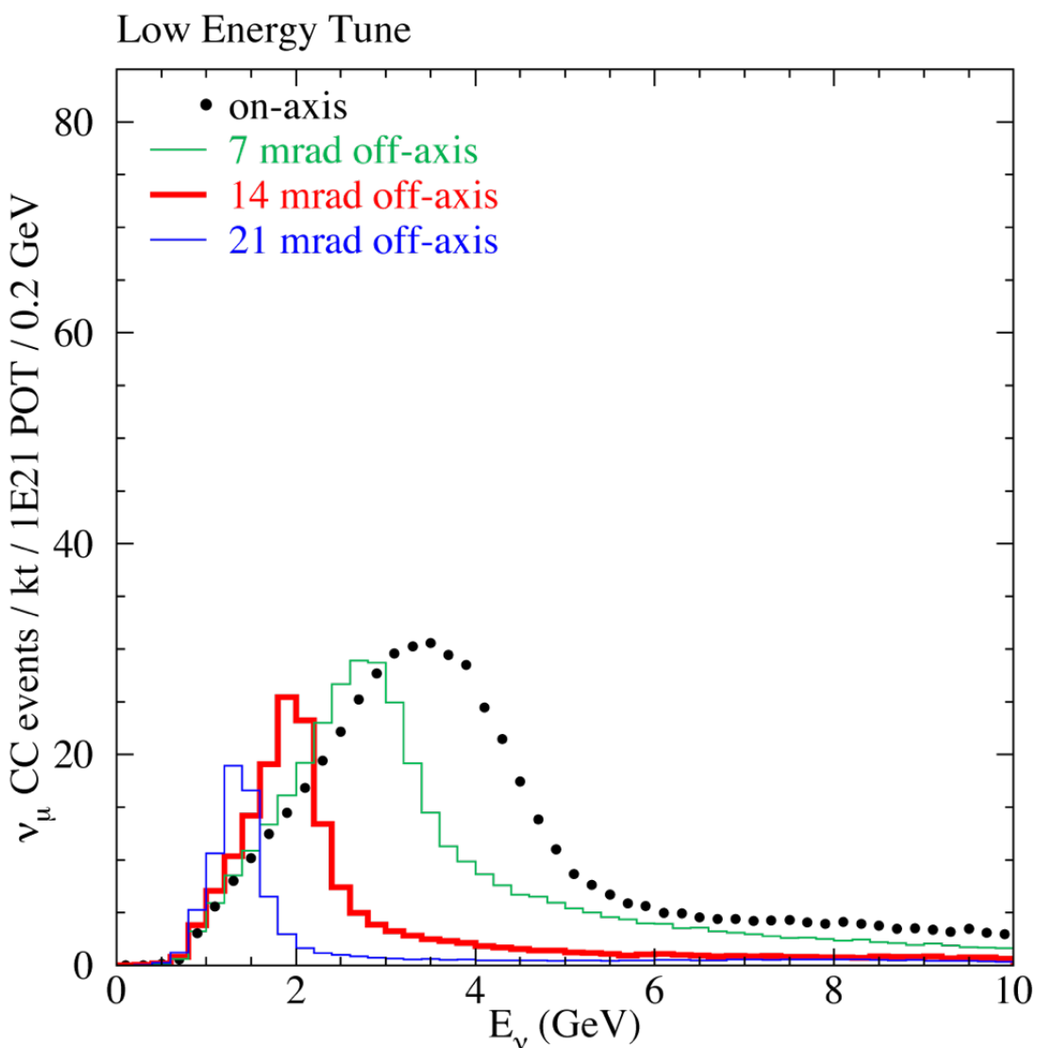
MINOS (Low Energy) Beam

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



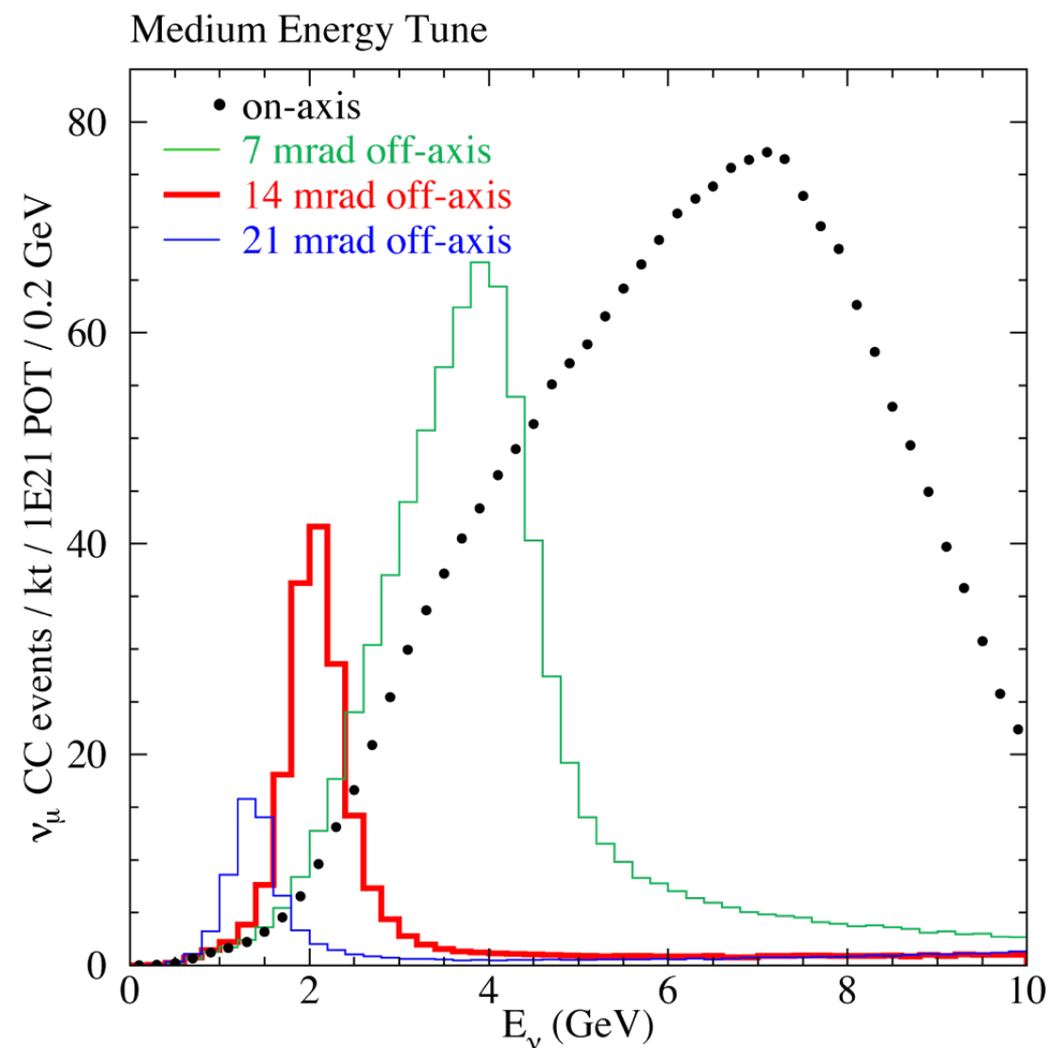
NOvA (Medium Energy) Beam

Horn 2 at 19m from start of Horn 1

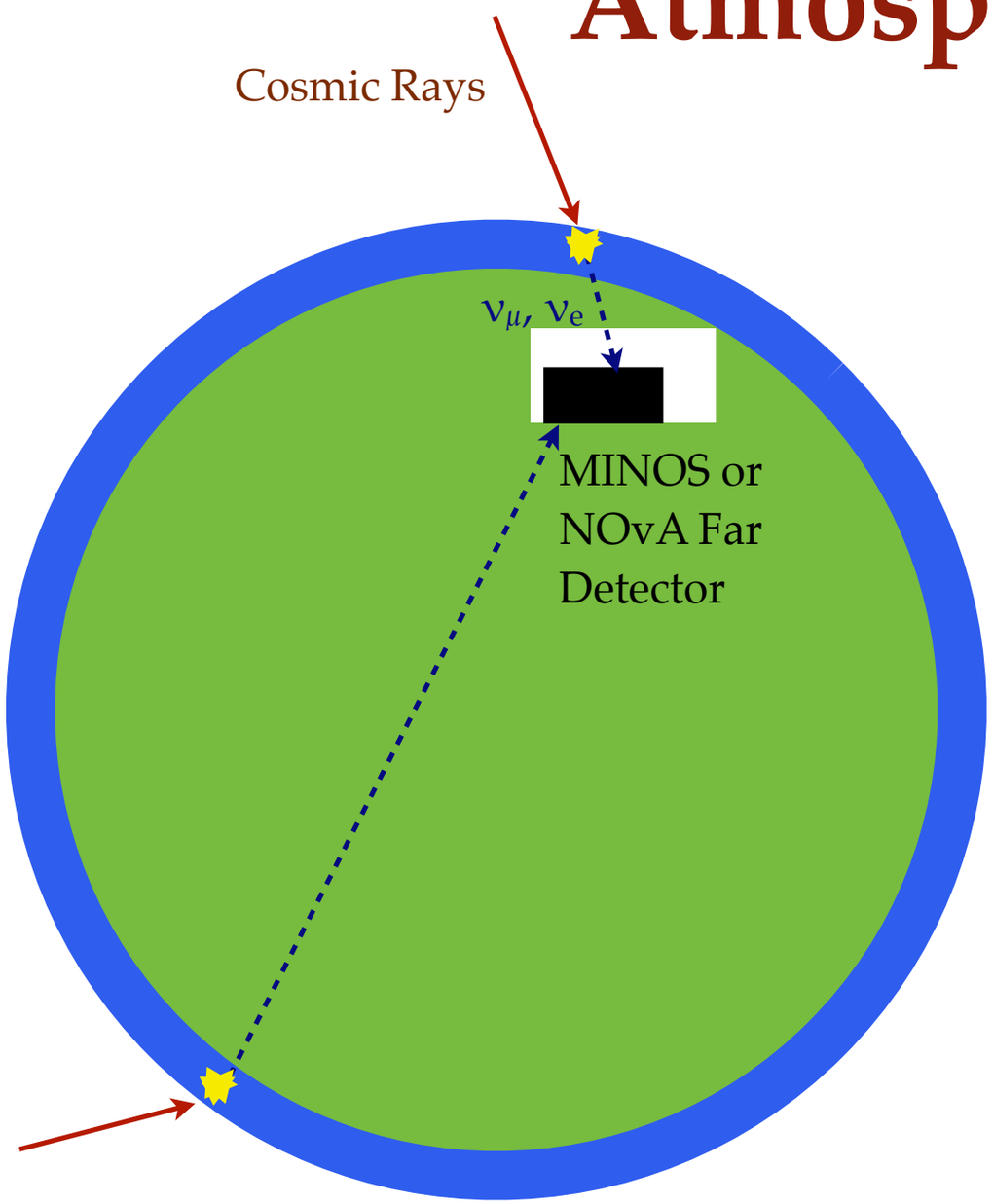
Horn Current 200 kA

Beam Power 700 kW

Downstream Target End 20 cm upstream of start of Horn 1



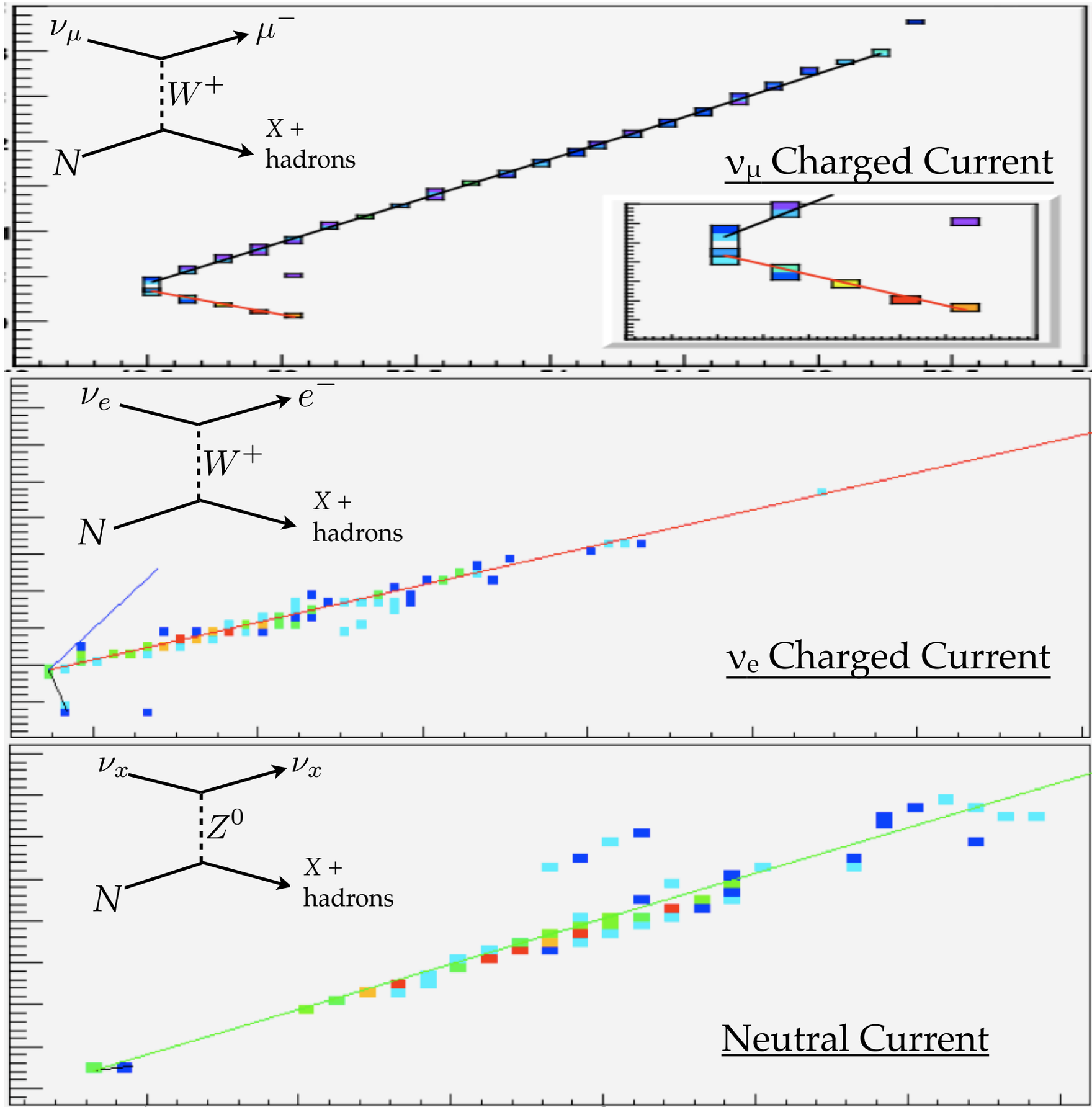
Atmospheric Neutrinos



- 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 ν_μ and $\bar{\nu}_\mu$ are detected in MINOS

Neutrino Interactions

- Simulated events for NOvA
- MINOS is denser less granular; ν_e CC events are much less distinct

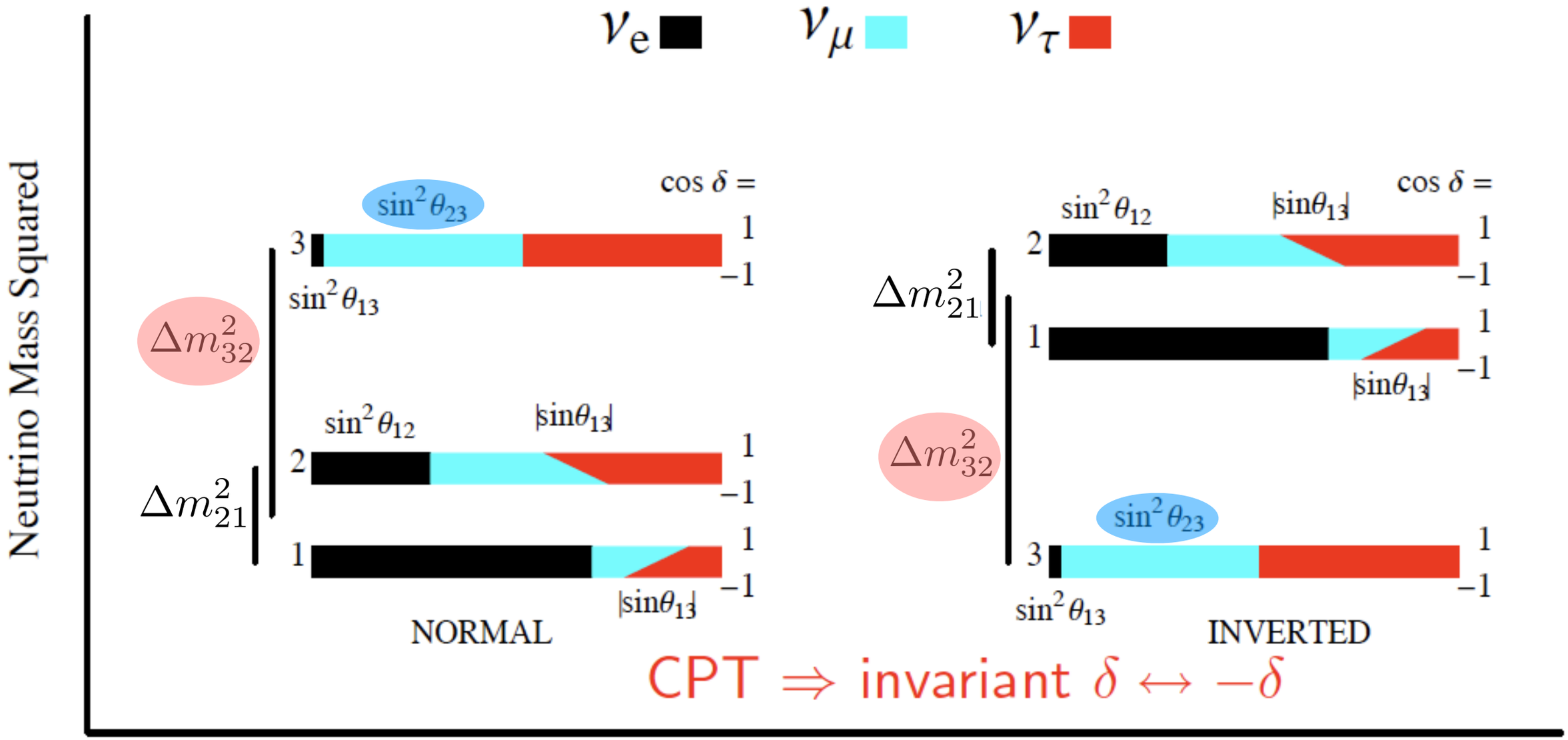


MINOS

"Catching Neutrinos in Iron & Plastic"

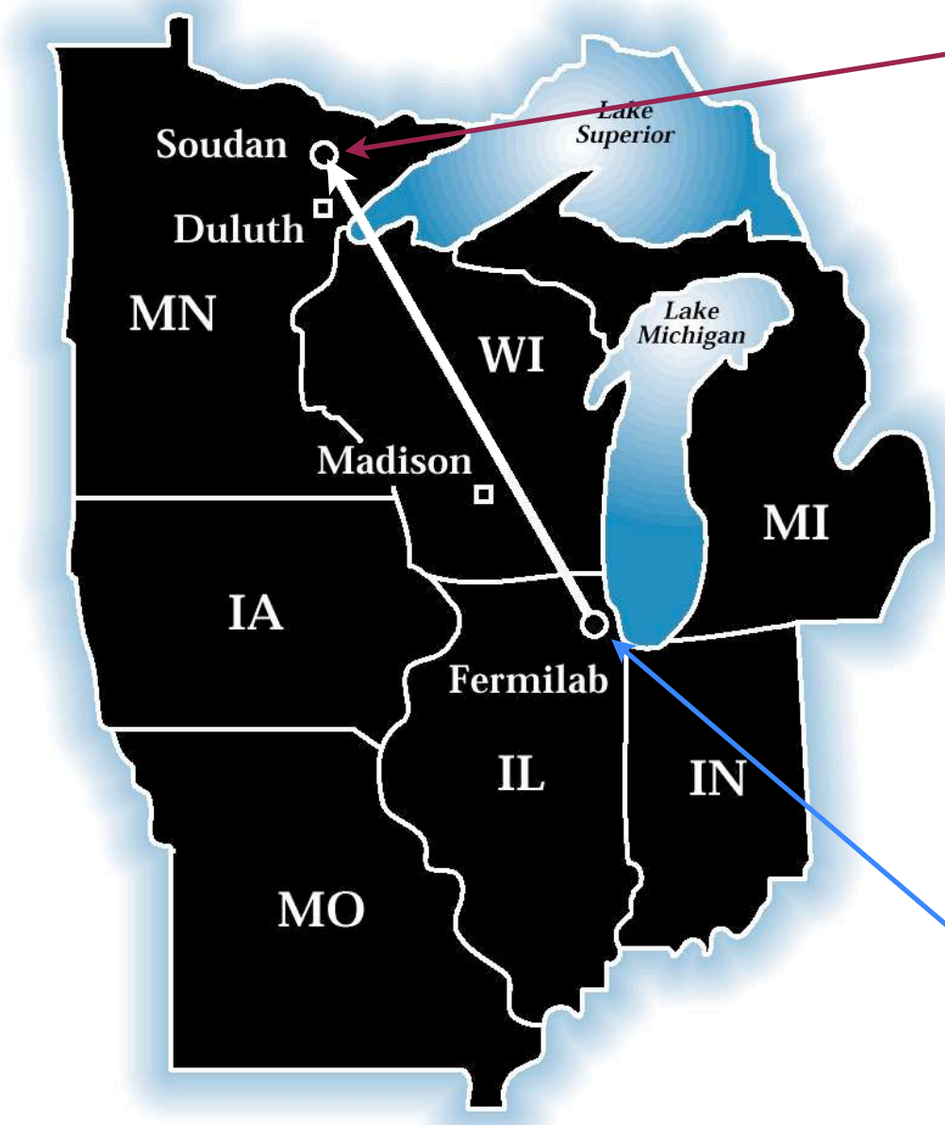
What MINOS Studies

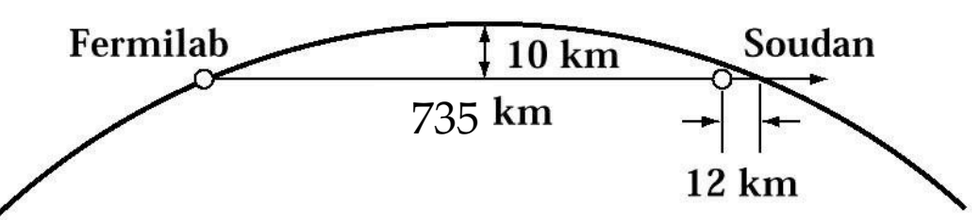
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \times \Delta m^2_{32}/\mathrm{eV} \times L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



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

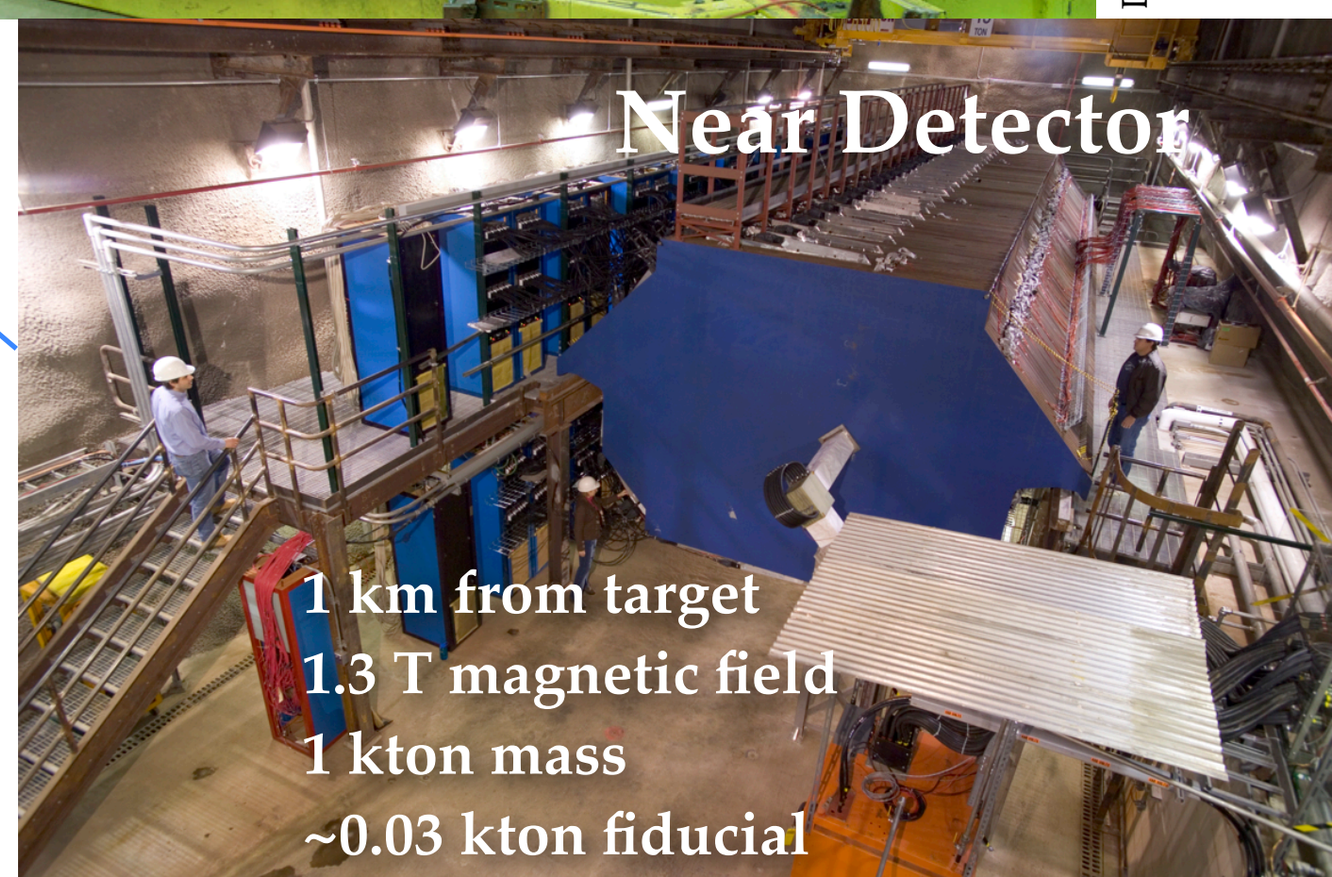
http://www.hep.ucl.ac.uk/minos/minosmap.jpg

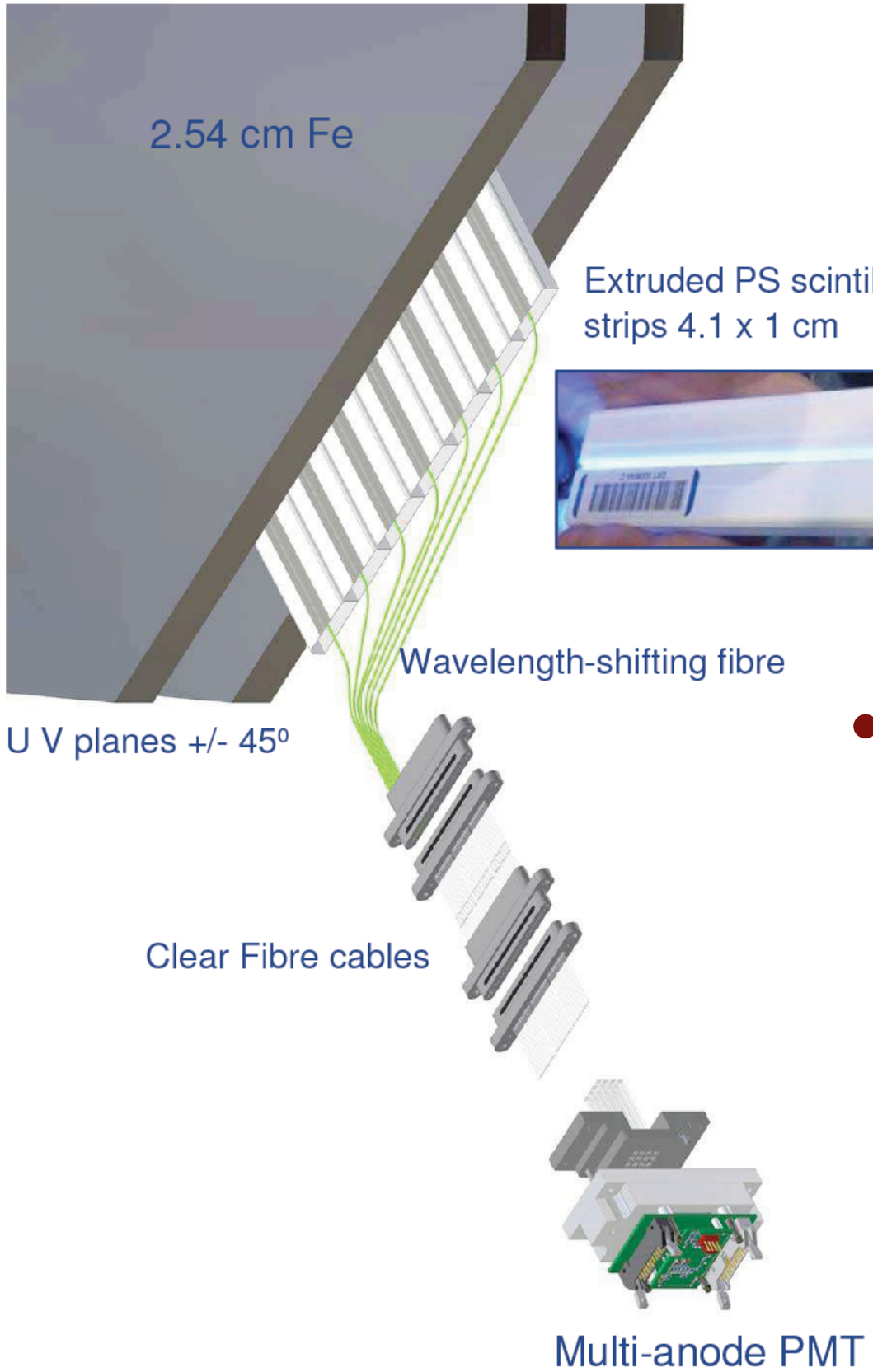


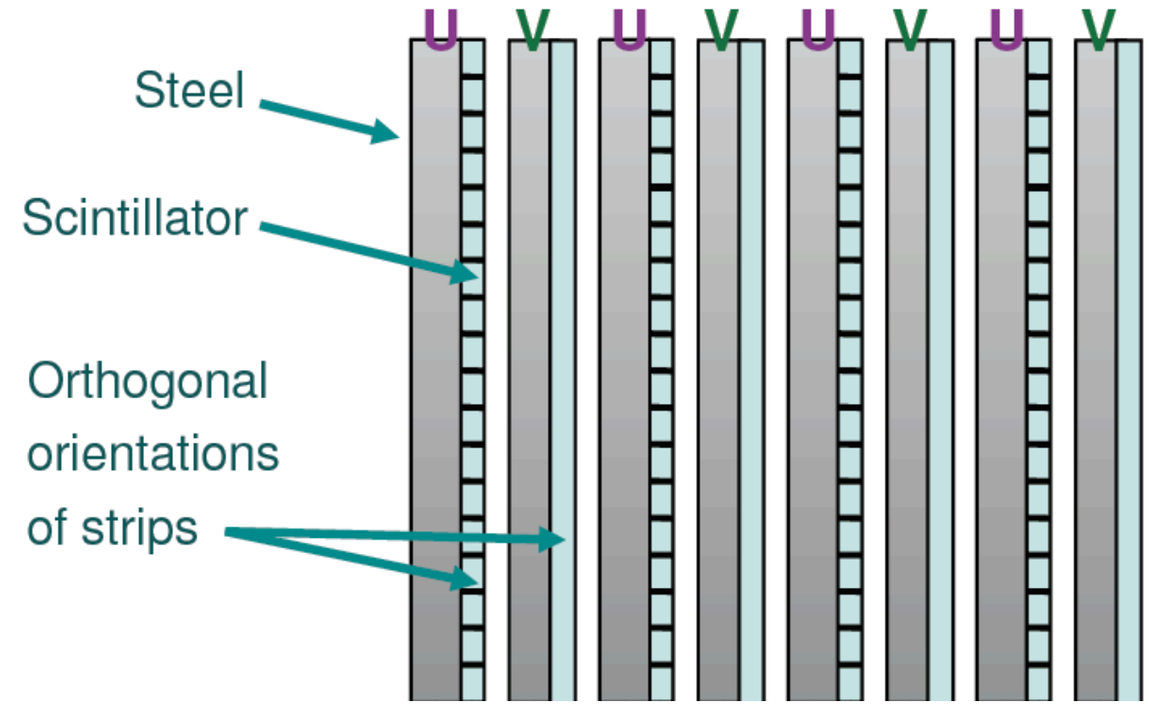


Detectors

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

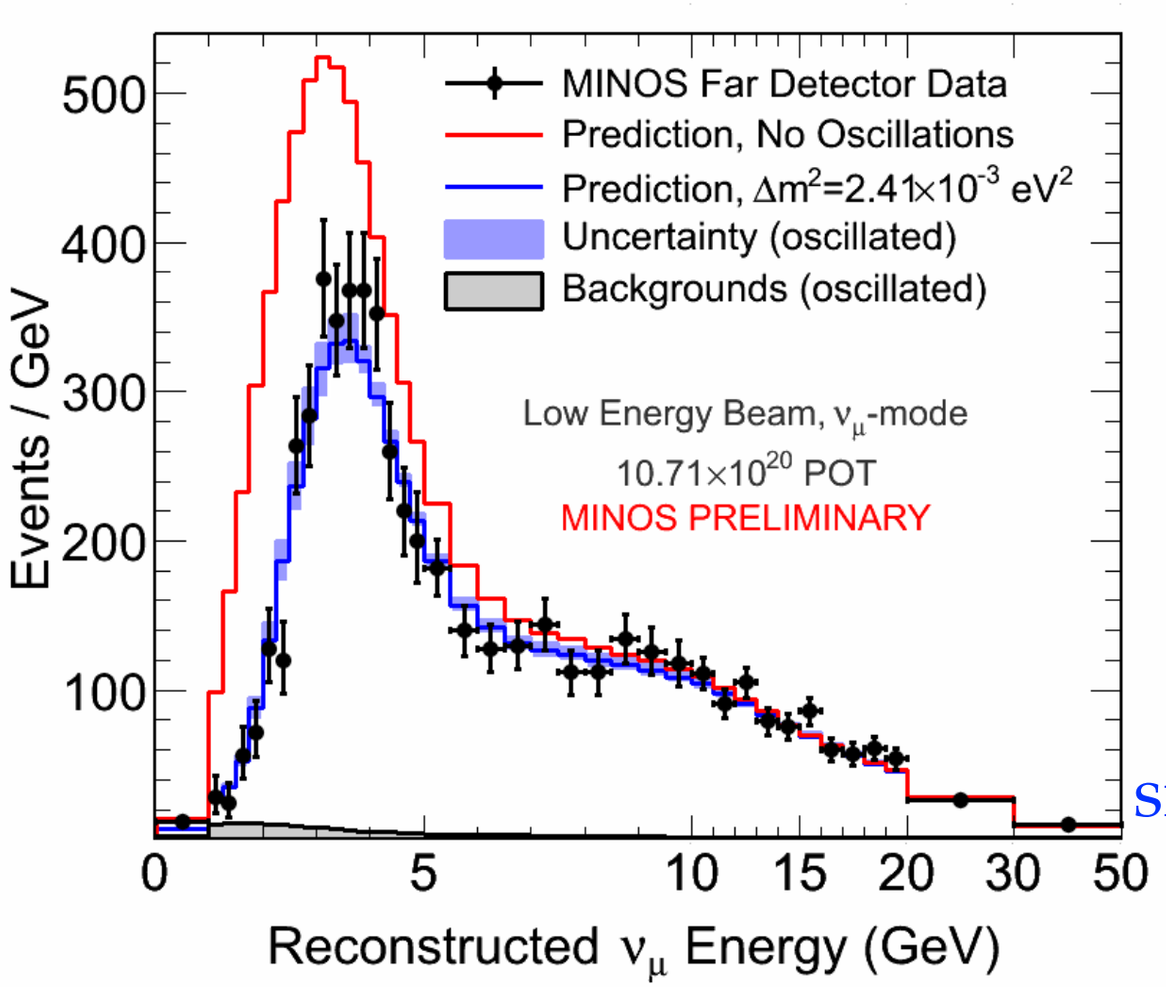


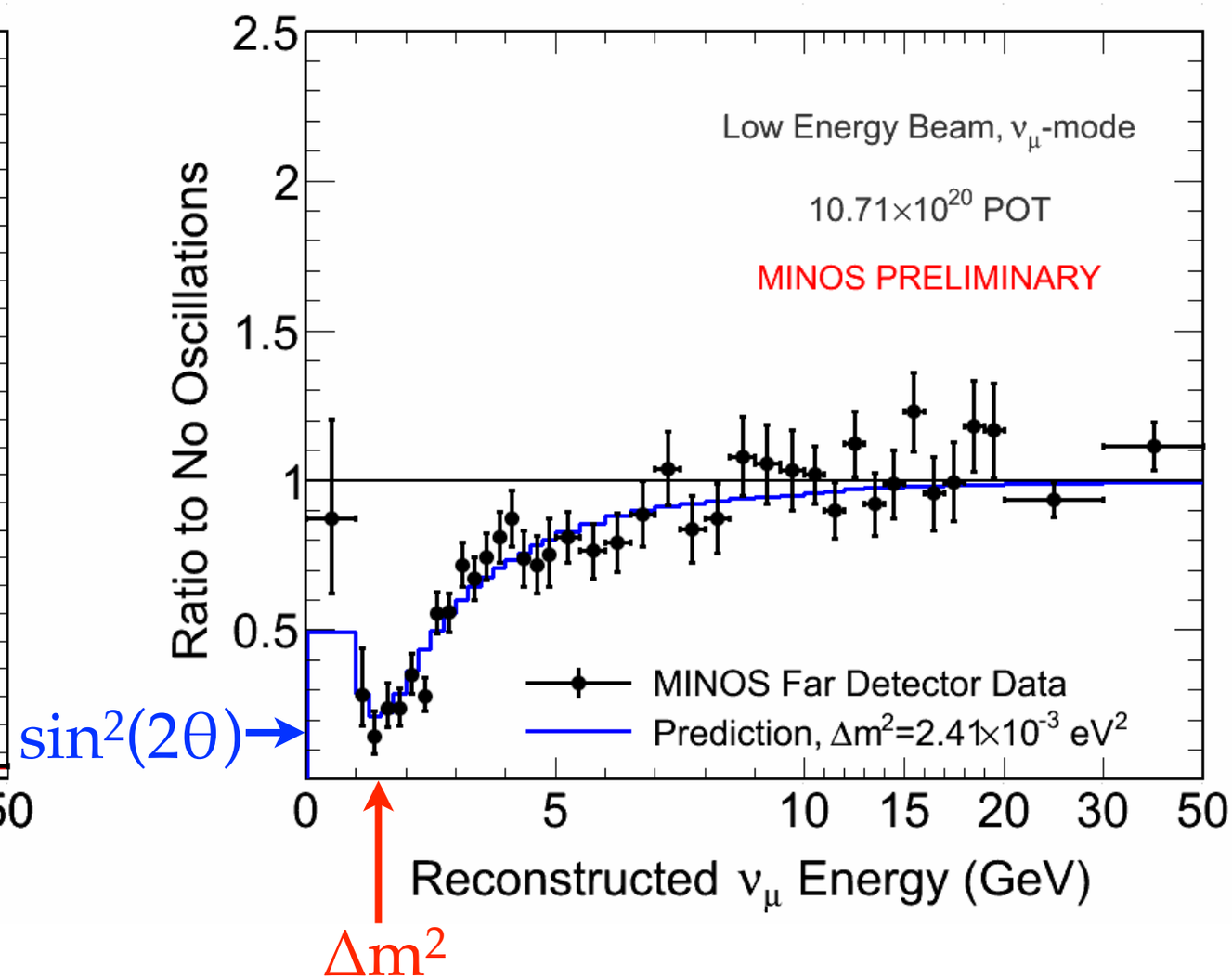




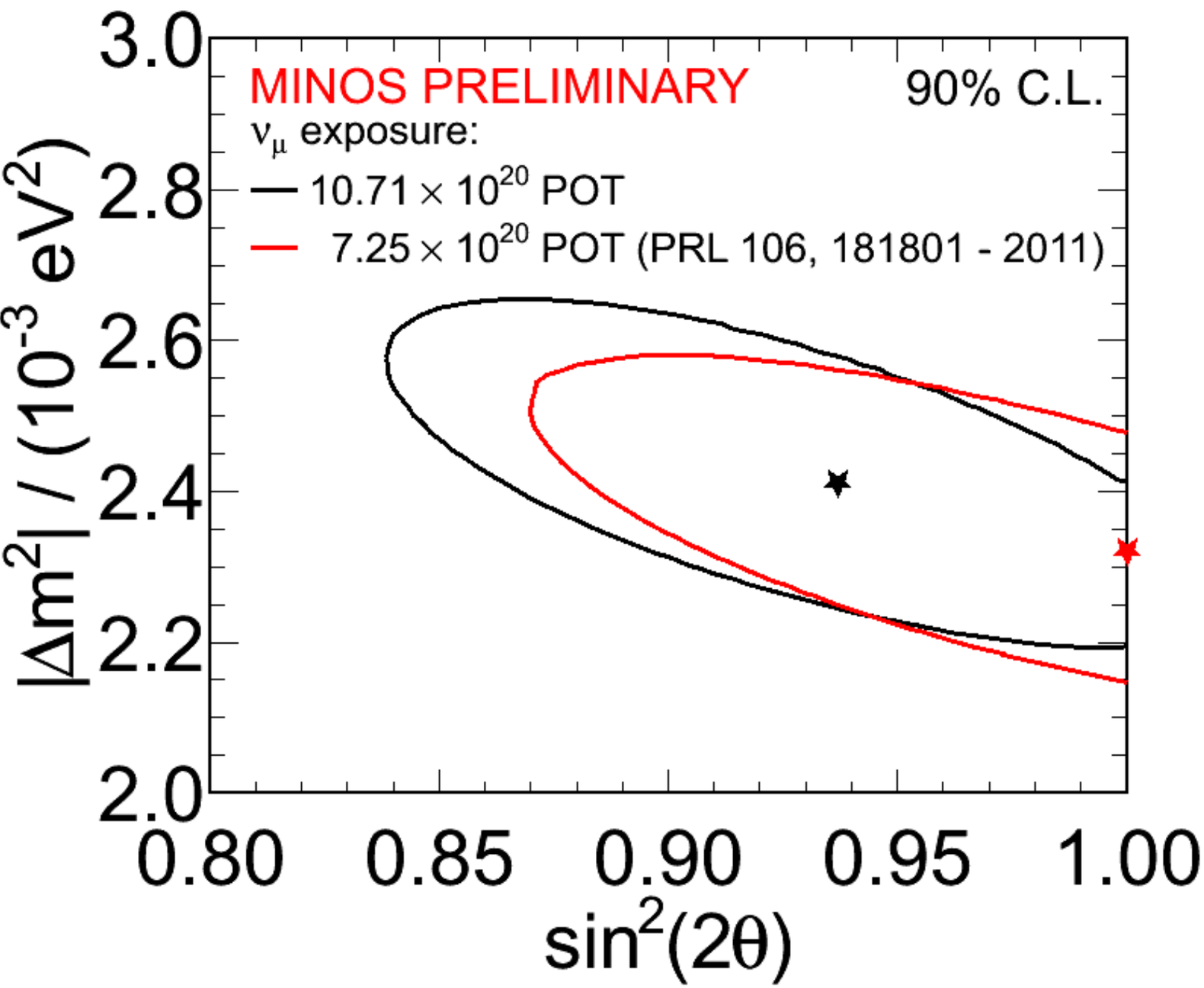
- Functionally Identical Detectors
  - Same iron and scintillator
  - Magnetic fields as similar as possible
  - Allows cancellation of systematic errors when using both detectors

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



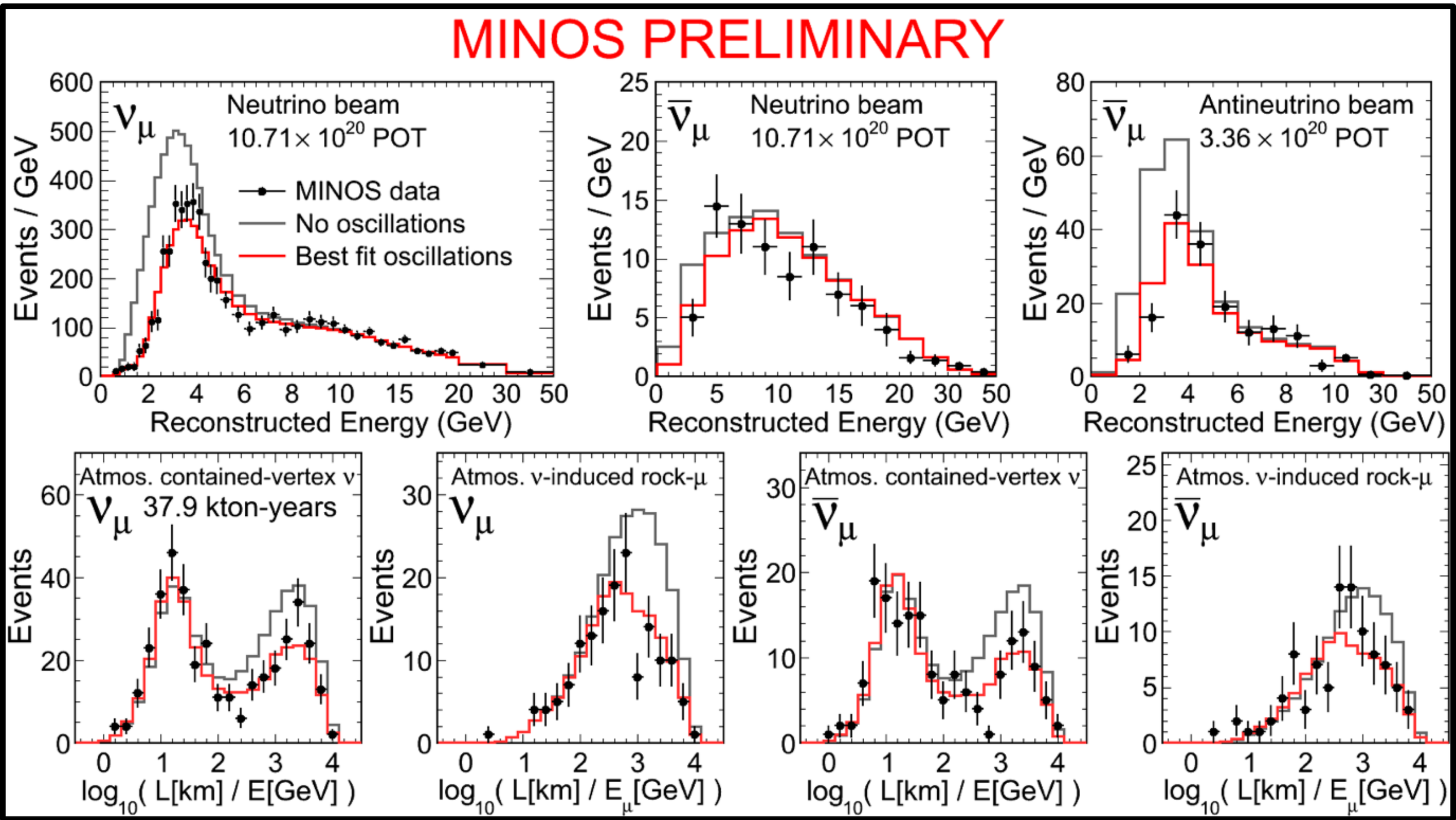


Resulting Contour

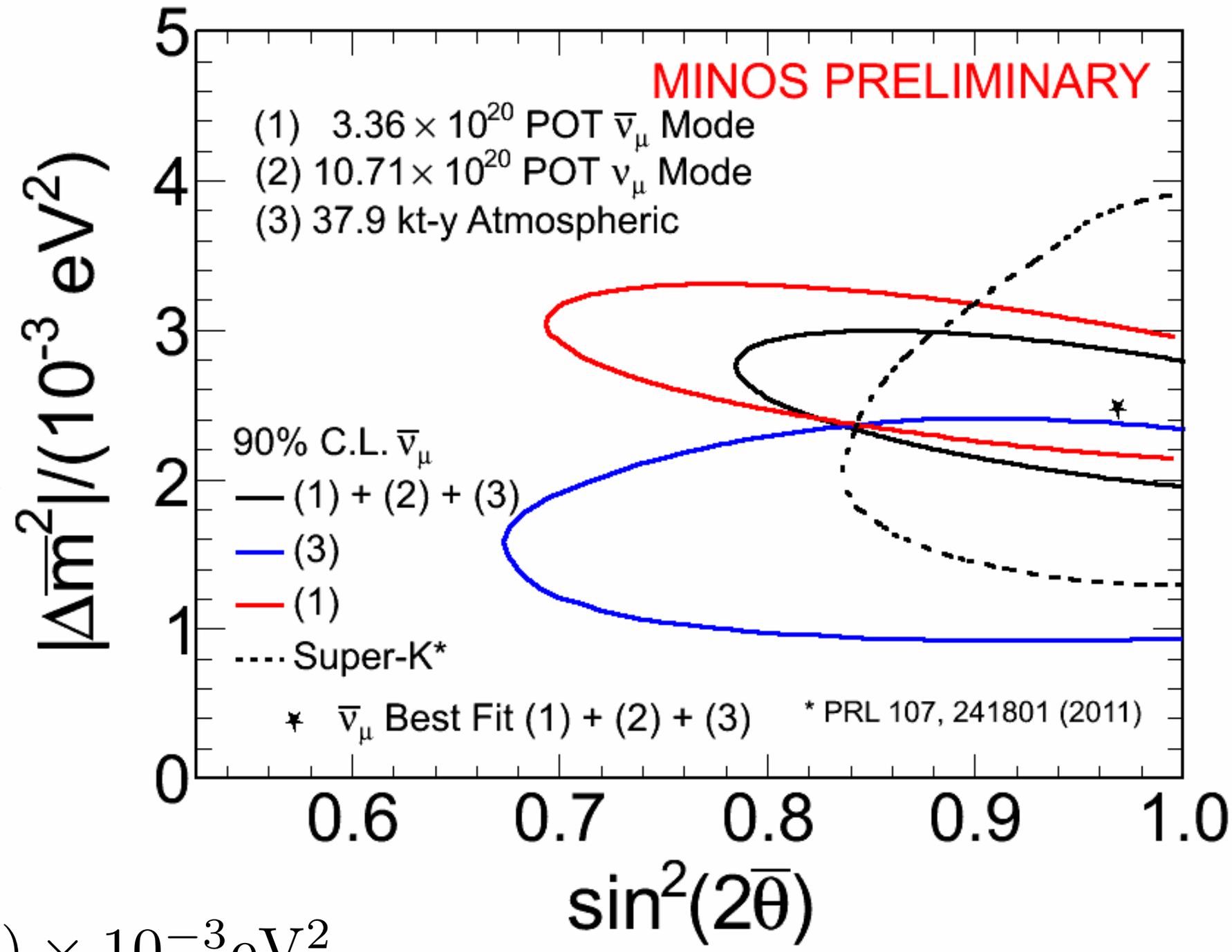


- Fit to the neutrino spectrum is translated into likelihood contours
- Parameter values are taken from projections of the contours onto each axis

All MINOS Data



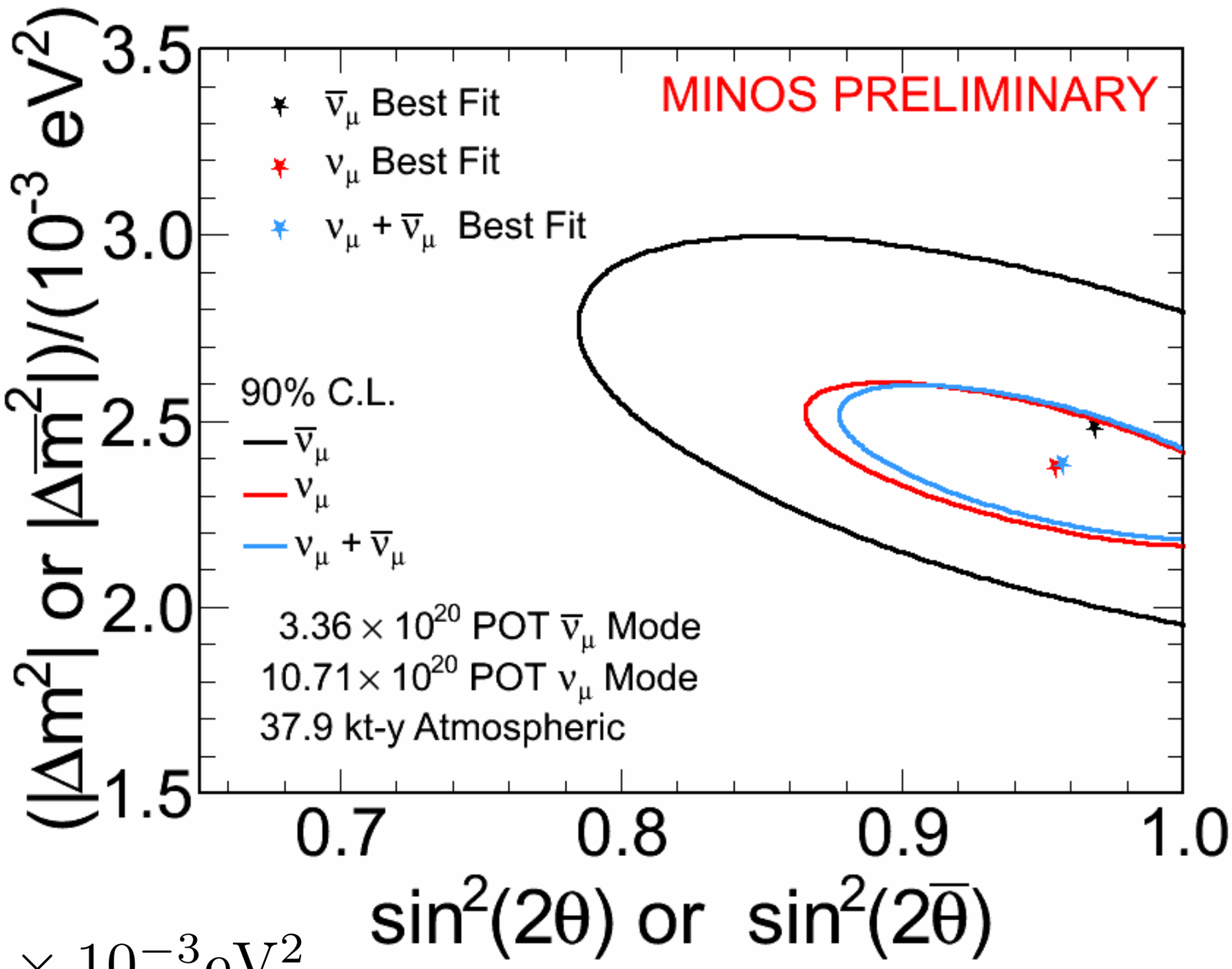
Results for Muon Antineutrinos



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

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

Results For Muon Neutrinos



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

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

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

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

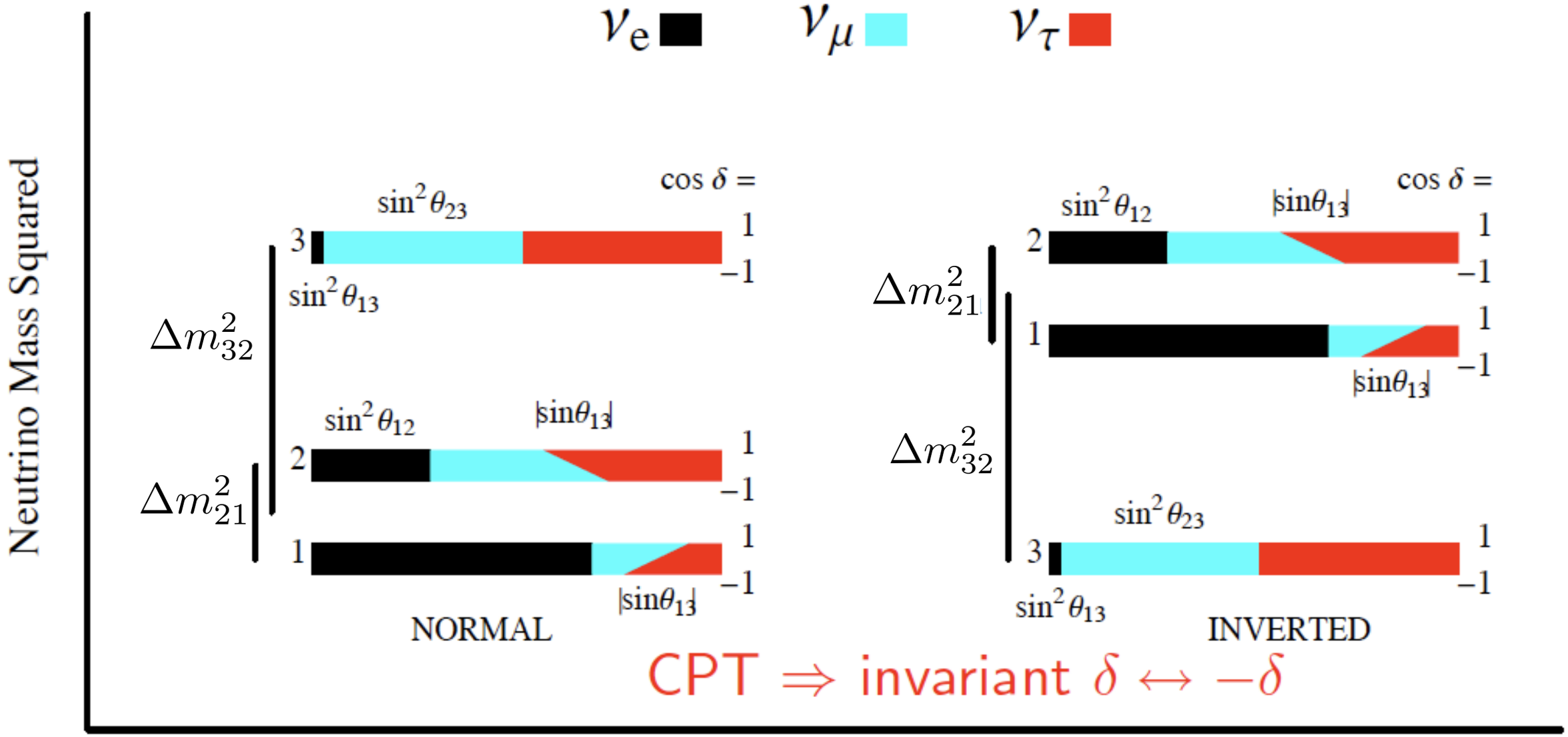
www.twitter.com/NOvANuz

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

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



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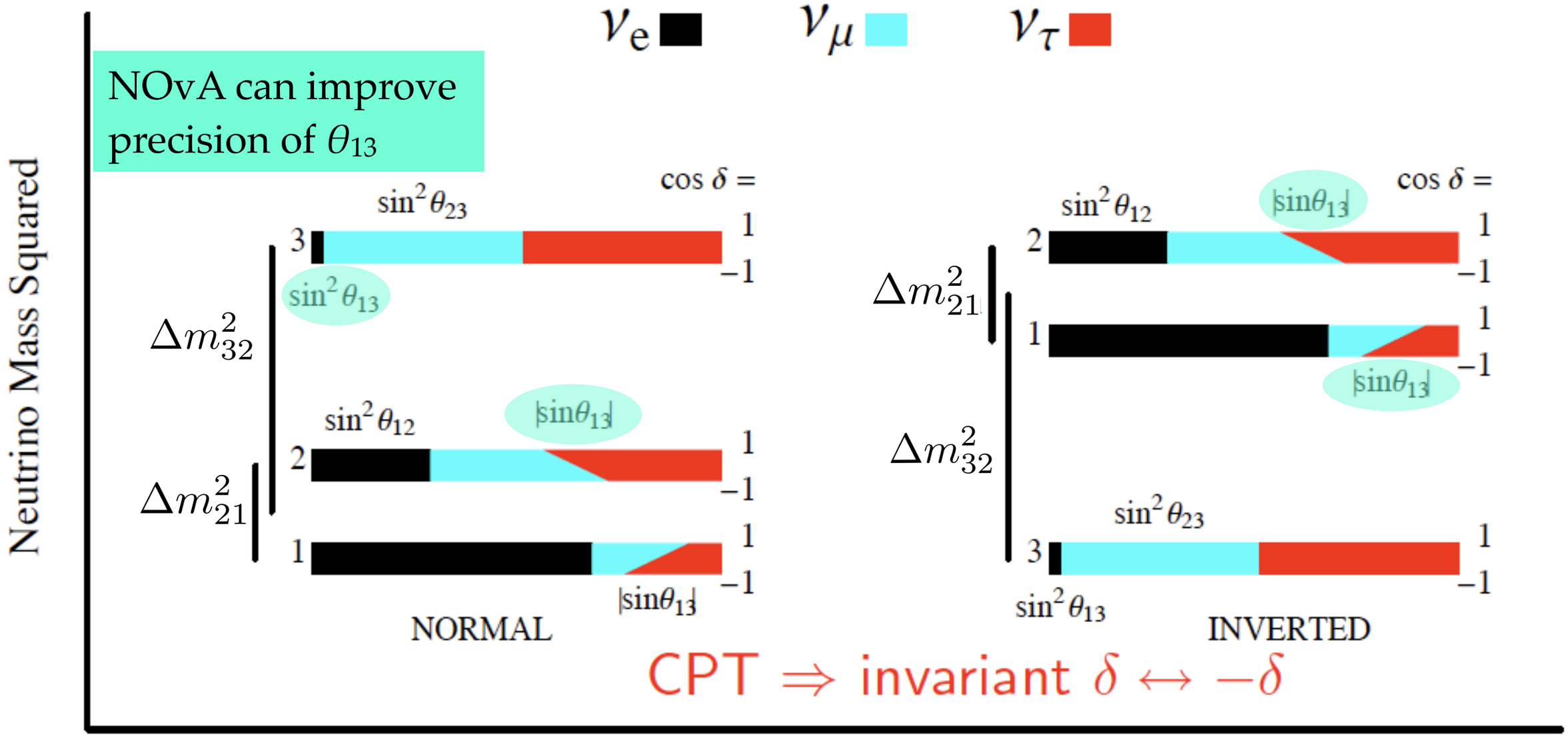

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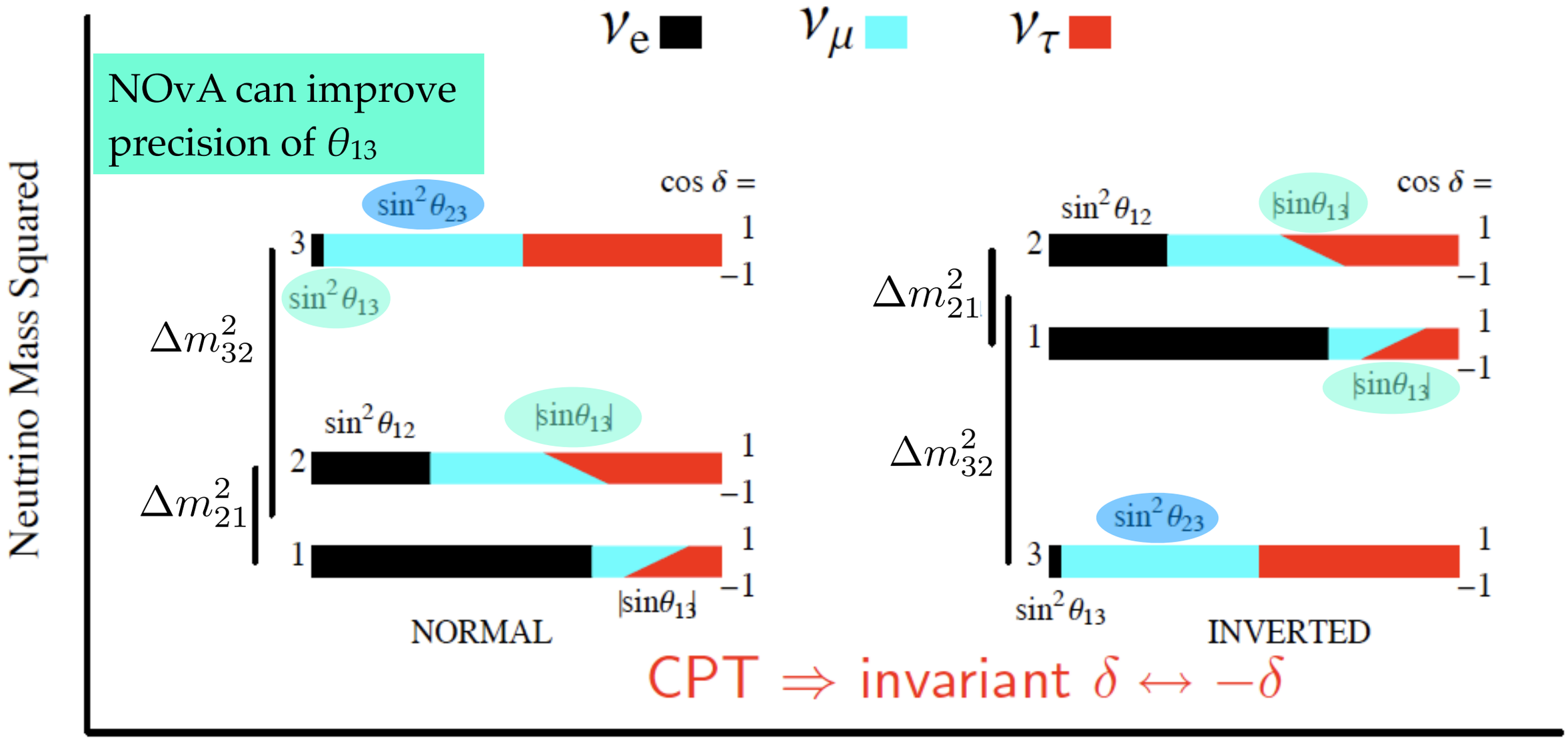

If $\sin^2(2\theta_{23}) \neq 1$, NOvA might determine $\theta_{23} < 45^o$ or $> 45^o$

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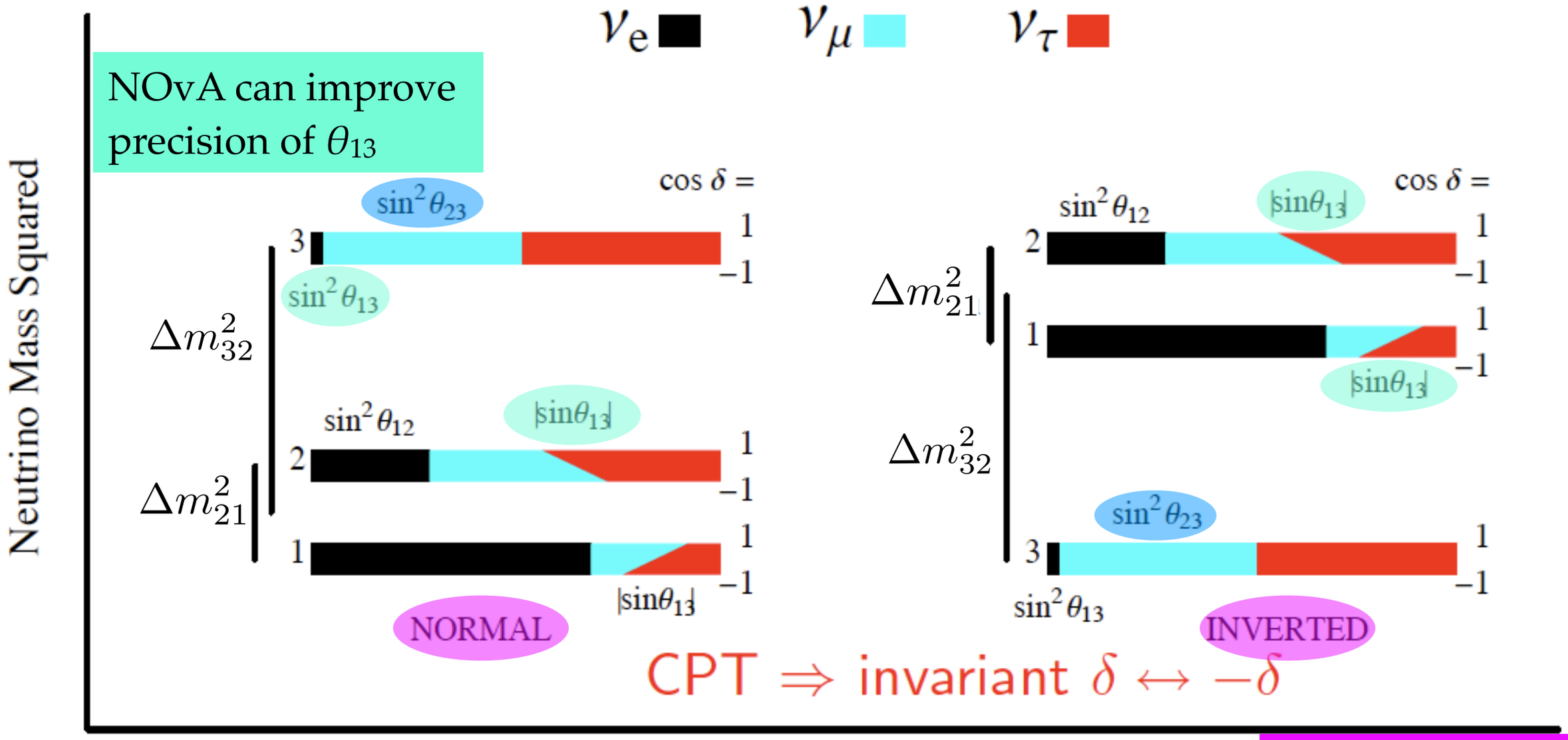

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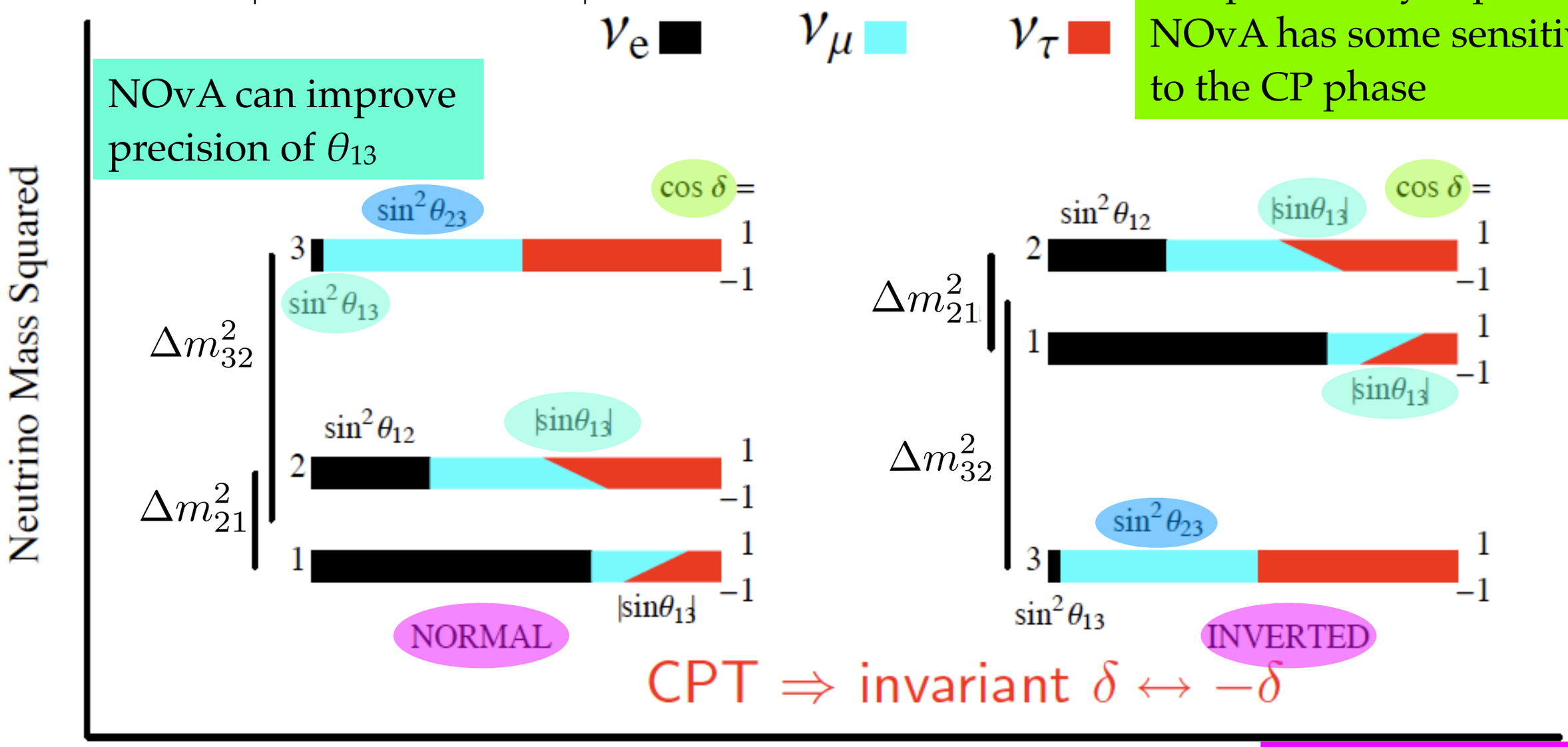
NOvA's long baseline provides sensitivity to the hierarchy

What NOvA is Designed to Study

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

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

NOvA can improve precision of θ_{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

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

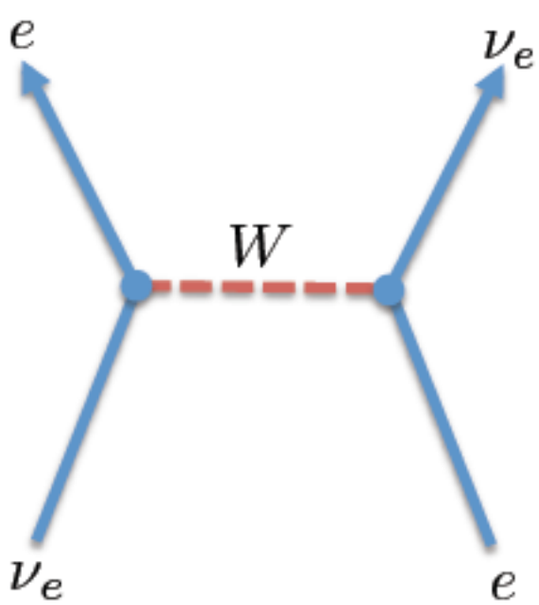
+ for ν
- for $\overline{\nu}$

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

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

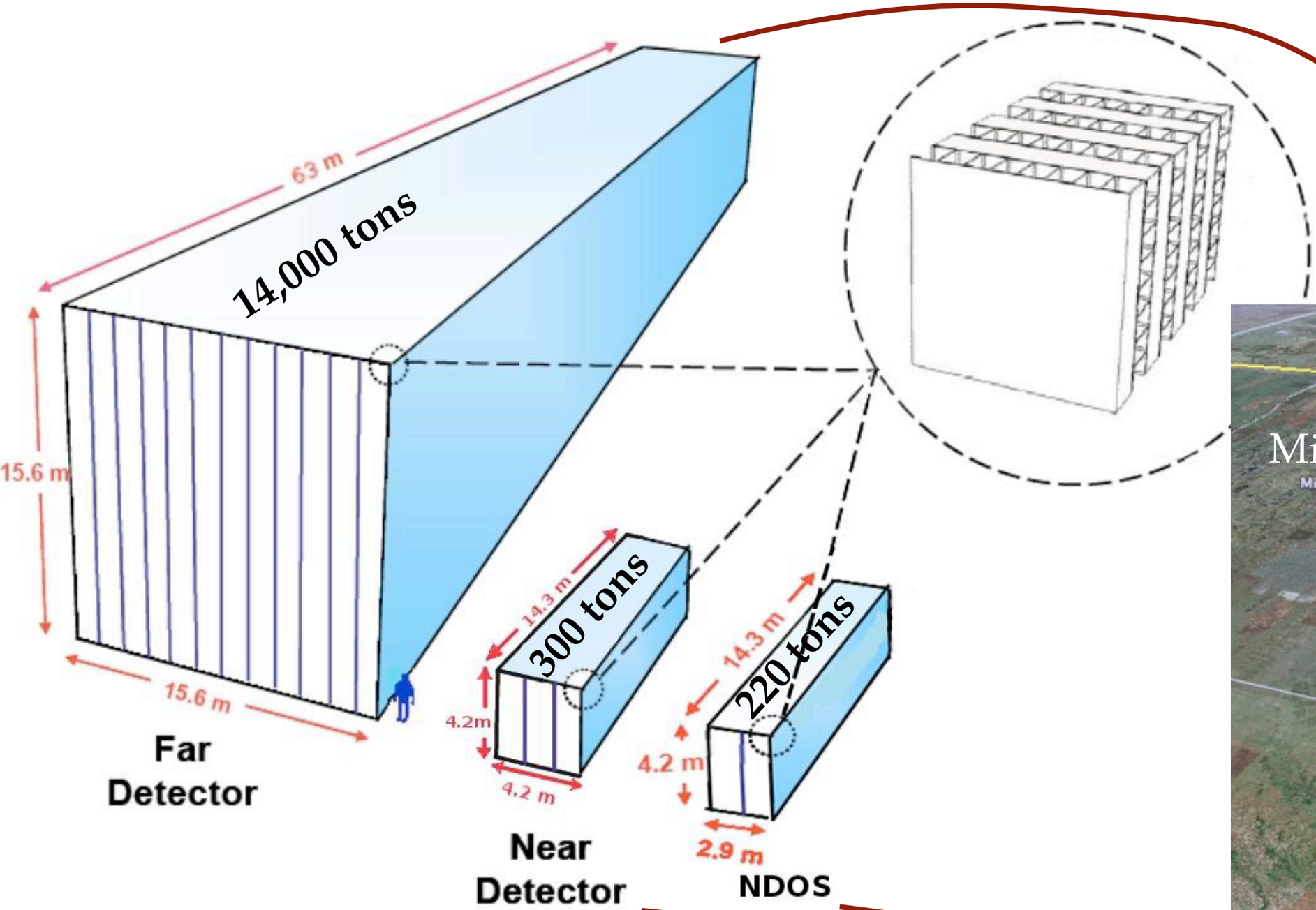
$$\Delta_{ij} = \frac{1.27 \Delta m_{ij}^2 [\mathrm{eV}^2] L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

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

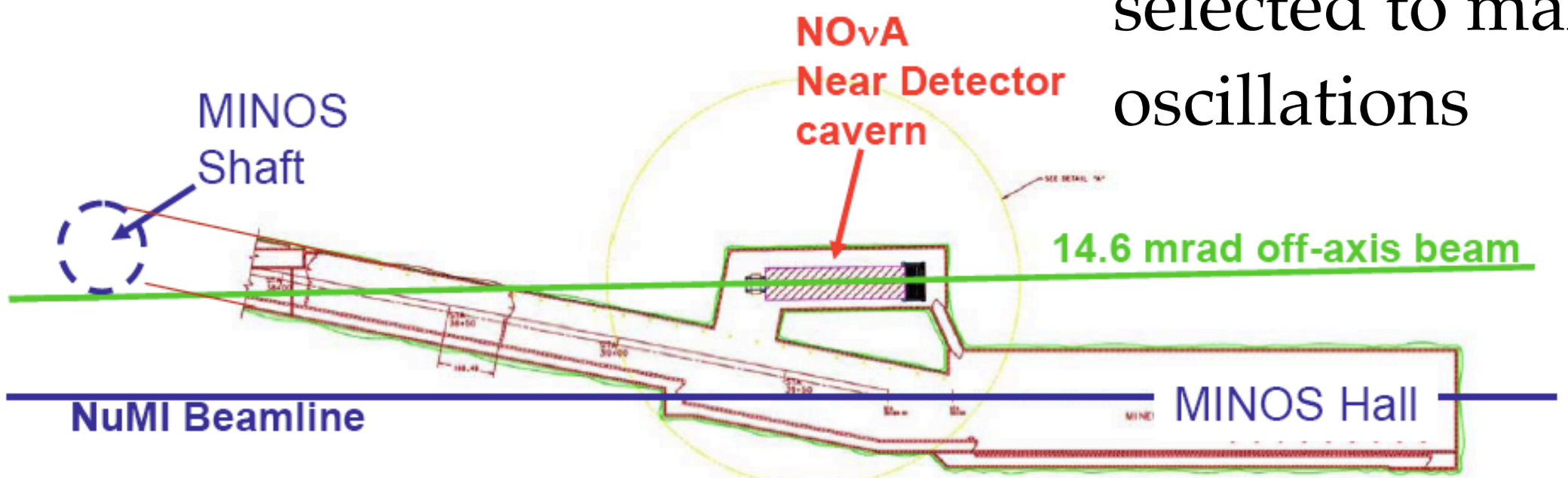
$$P_{\text{matter}}(\nu_\mu \to \nu_e) \approx \left(1 + \frac{E\Delta m^2_{23}}{2\sqrt{2}G_F N_e}\right) P_{\text{vacuum}}(\nu_\mu \to \nu_e)$$

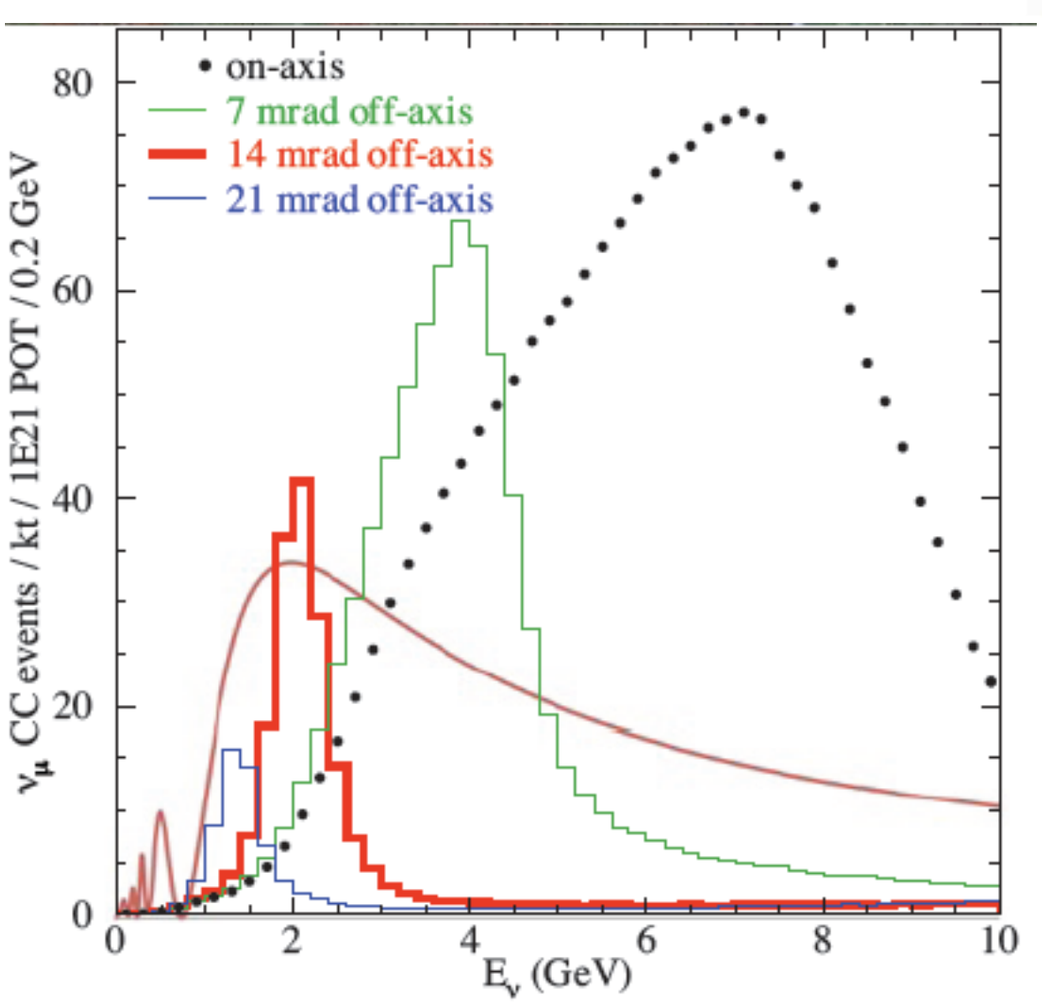


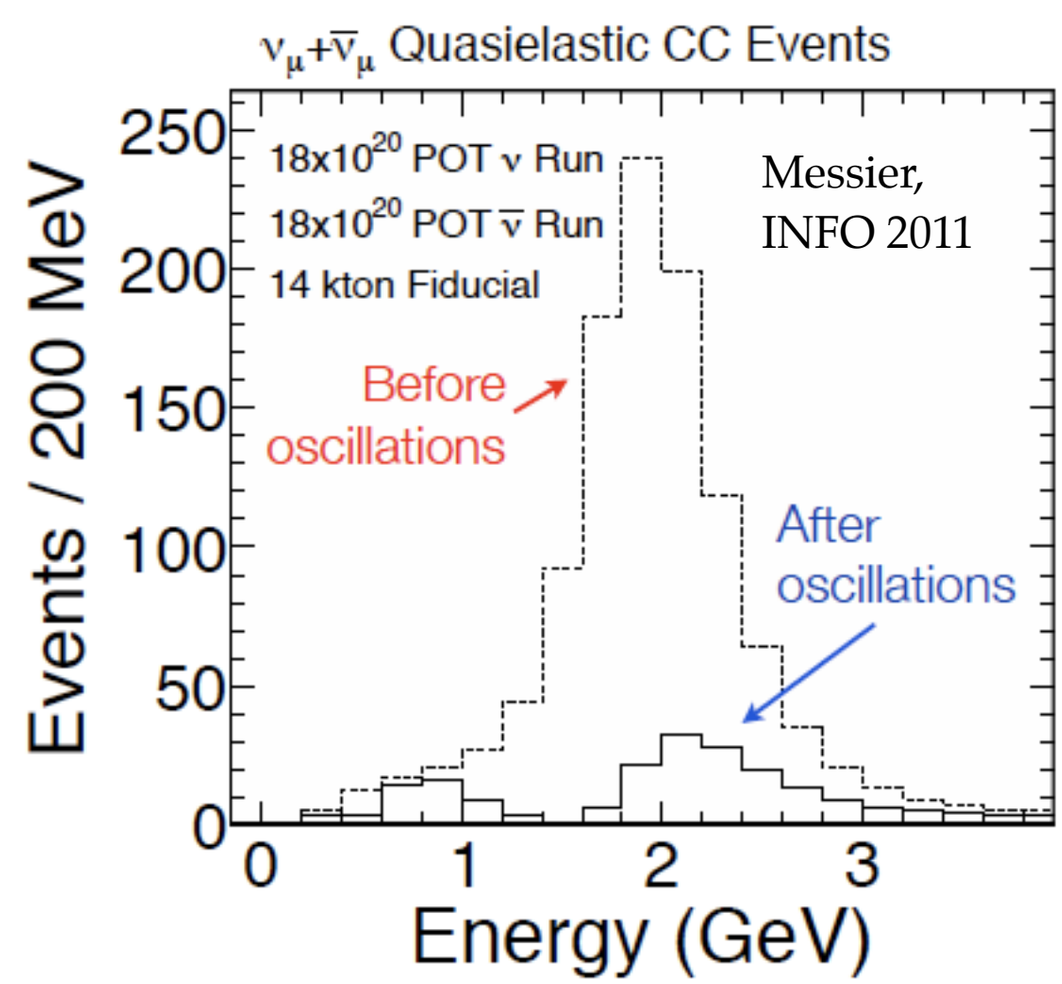
NOvA Detectors

Why Off-axis?

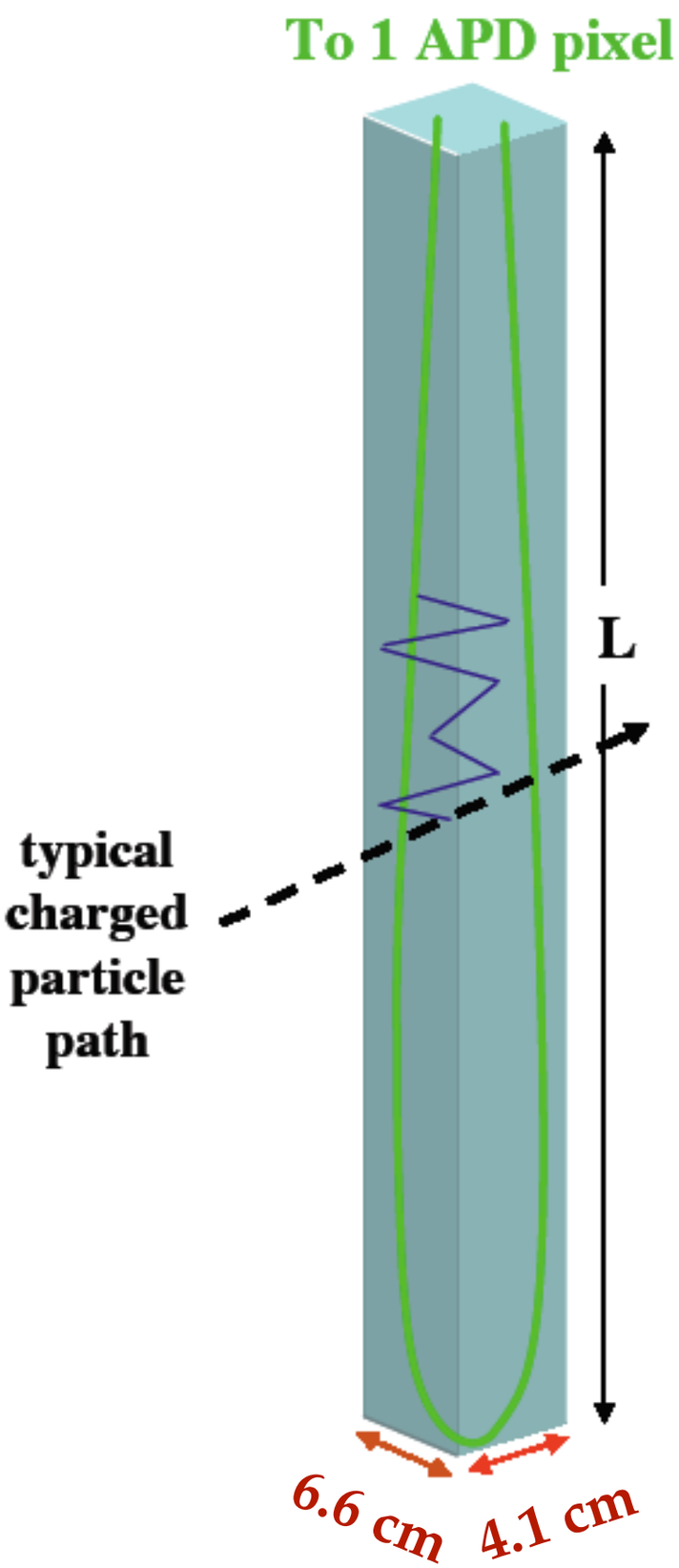
- Baseline (L) and E selected to maximize oscillations

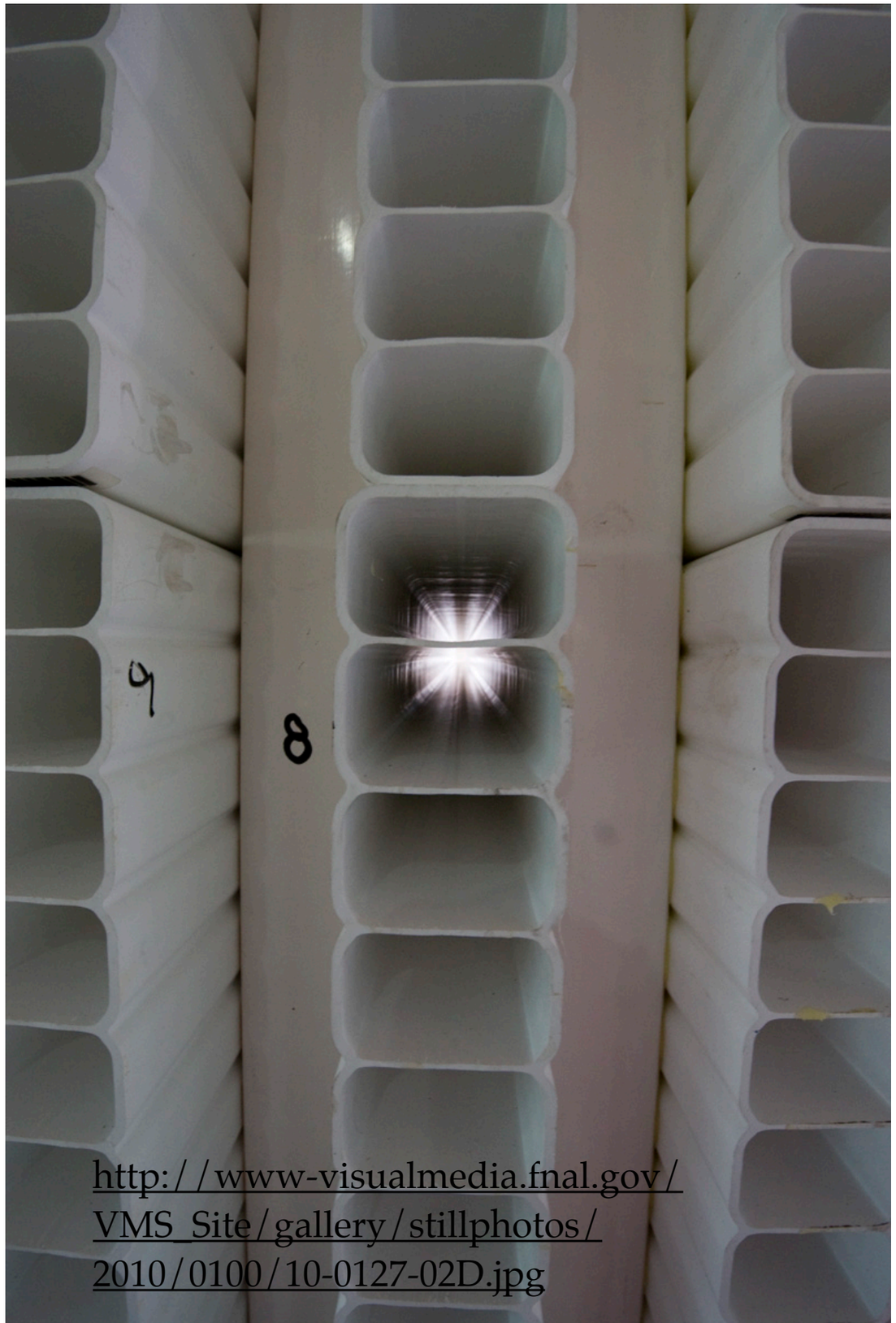






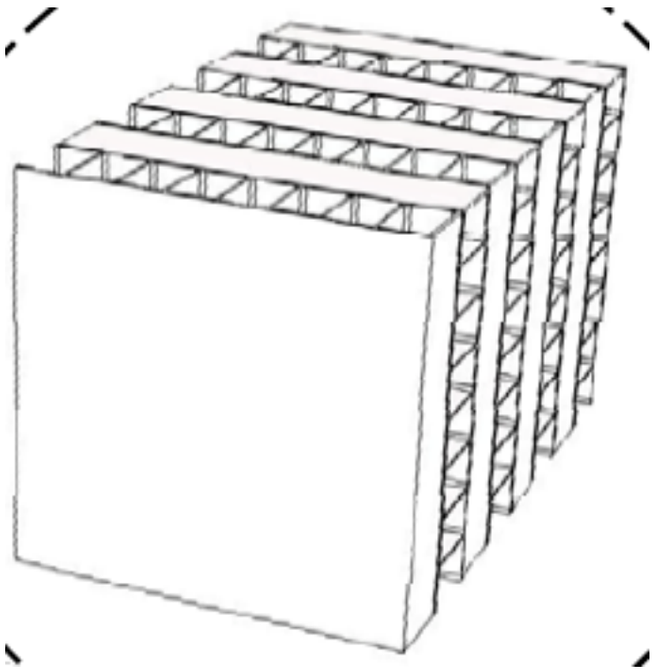
Detector Elements



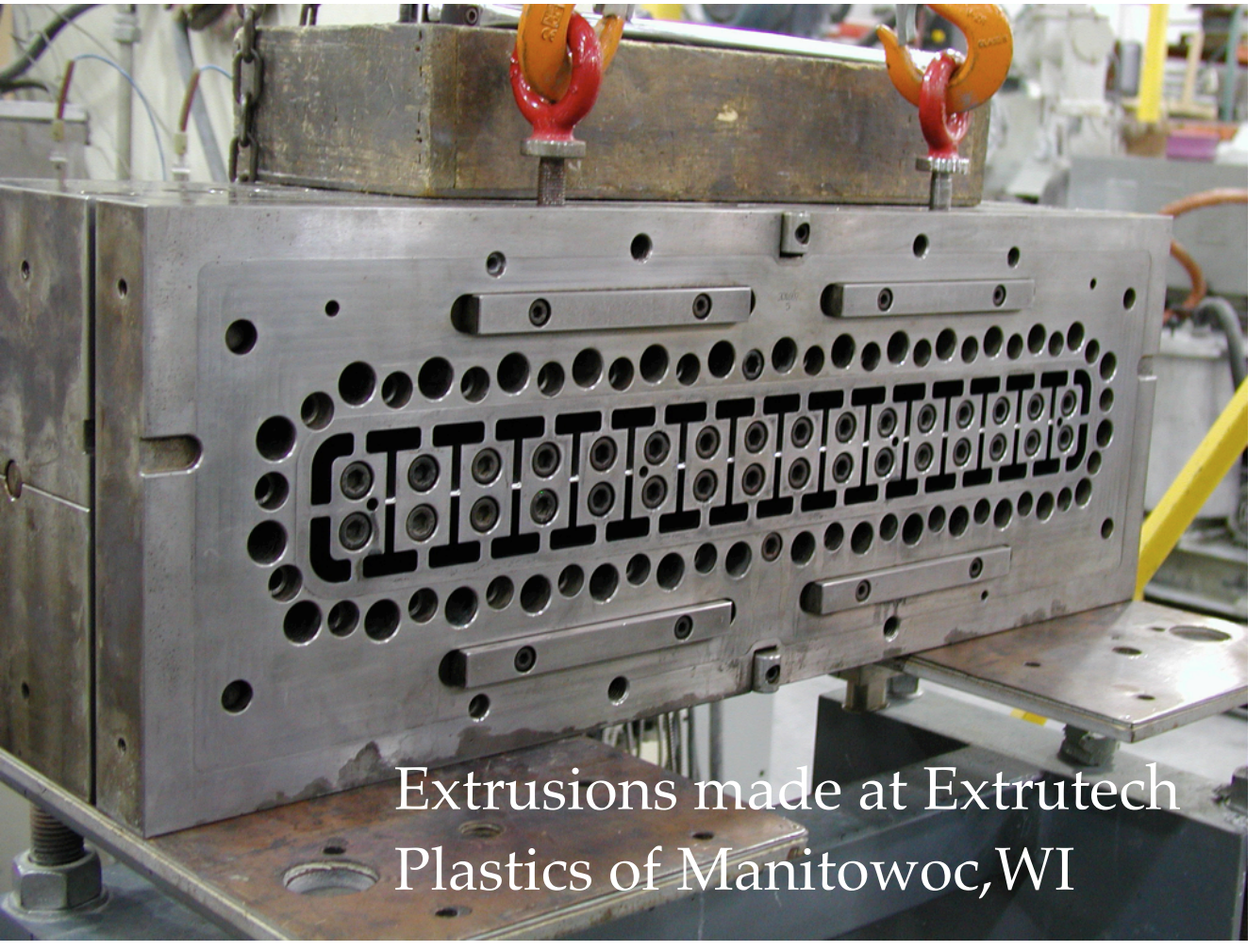


http://www-visualmedia.fnal.gov/VMS_Site/gallery/stillphotos/2010/0100/10-0127-02D.jpg

- Cells with liquid scintillator grouped into alternating planes



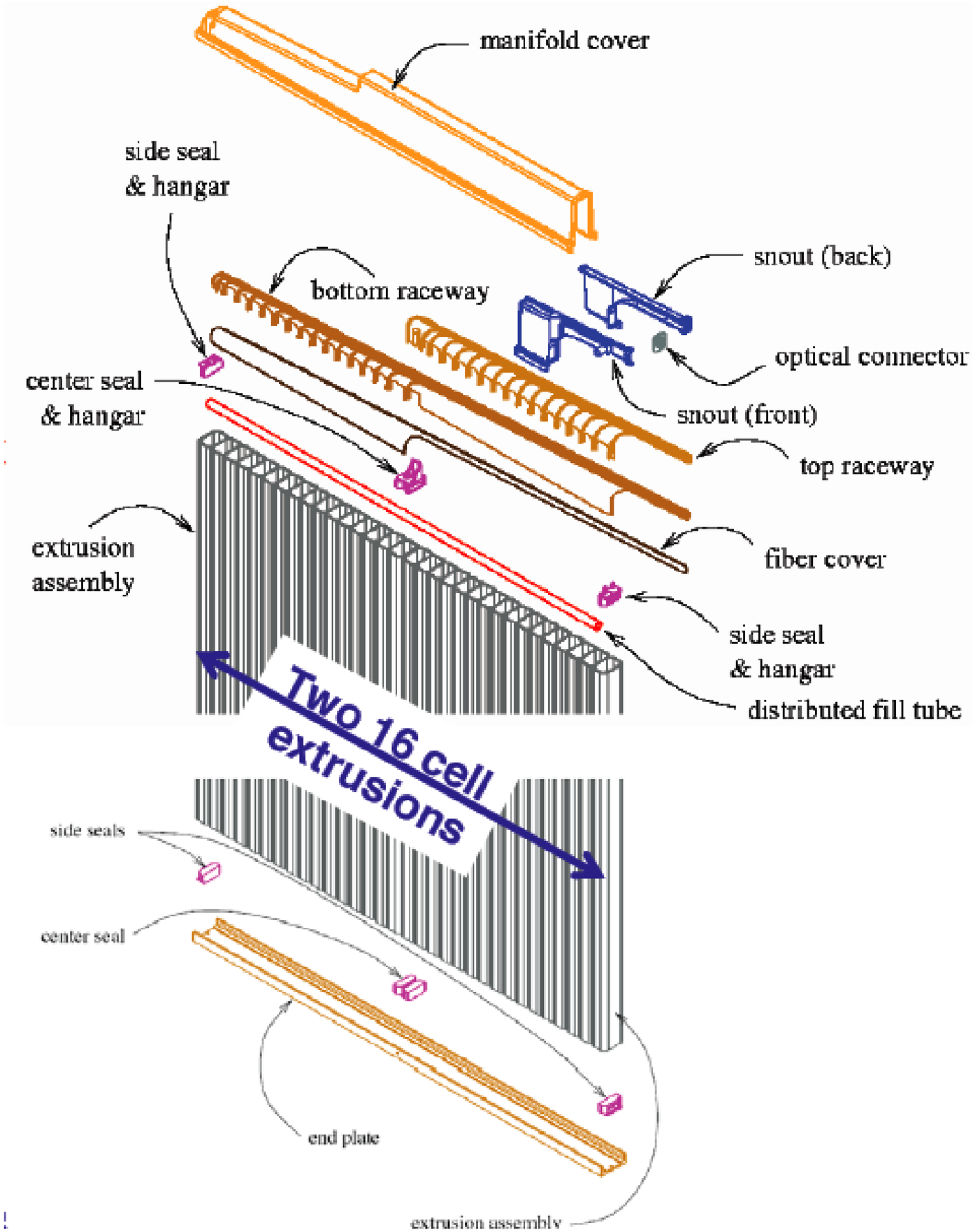
Extrusions

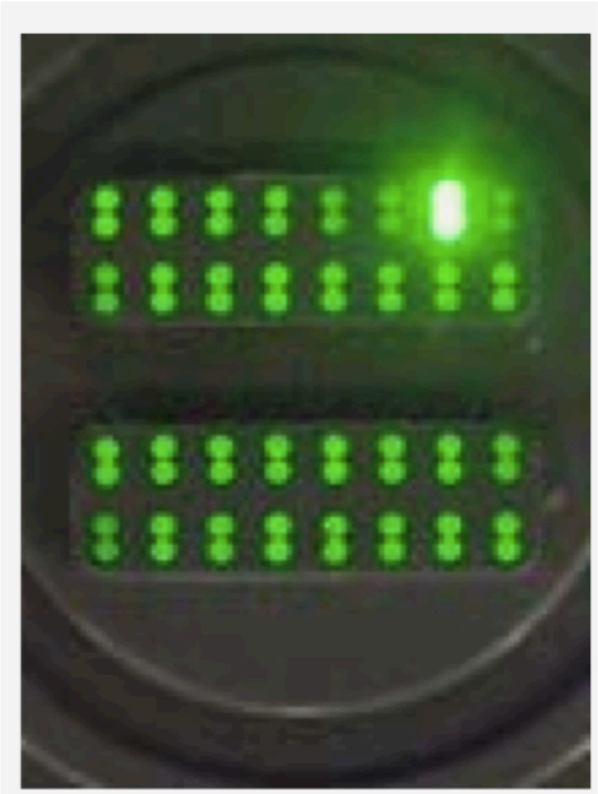

Extrusions made at Extrutech Plastics of Manitowoc,WI

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

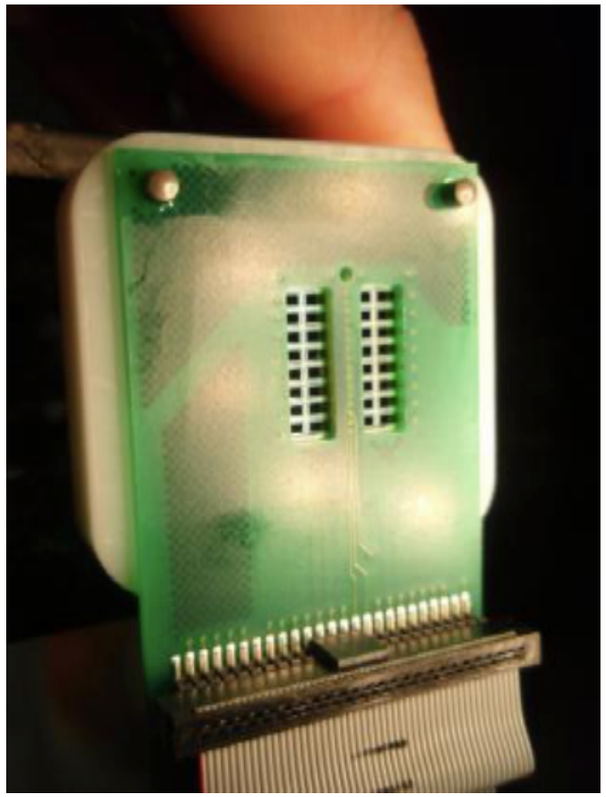
Modules

- 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.





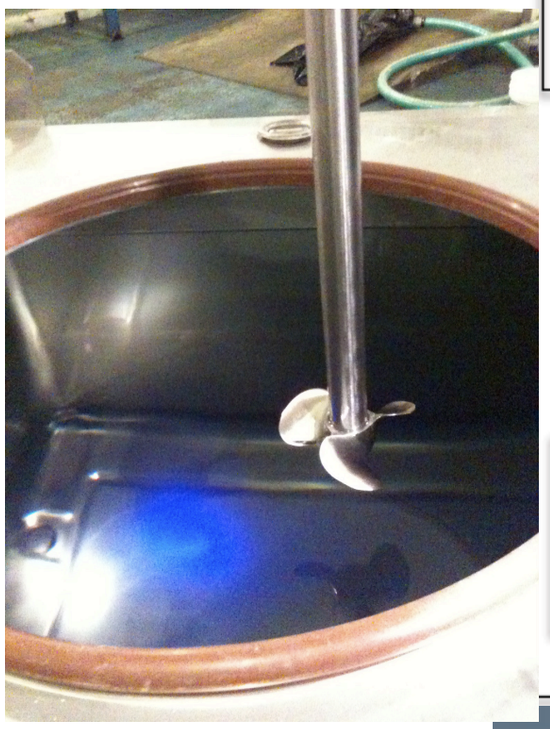
Scintillation light travels along wavelength shifting fibers to end of manifold

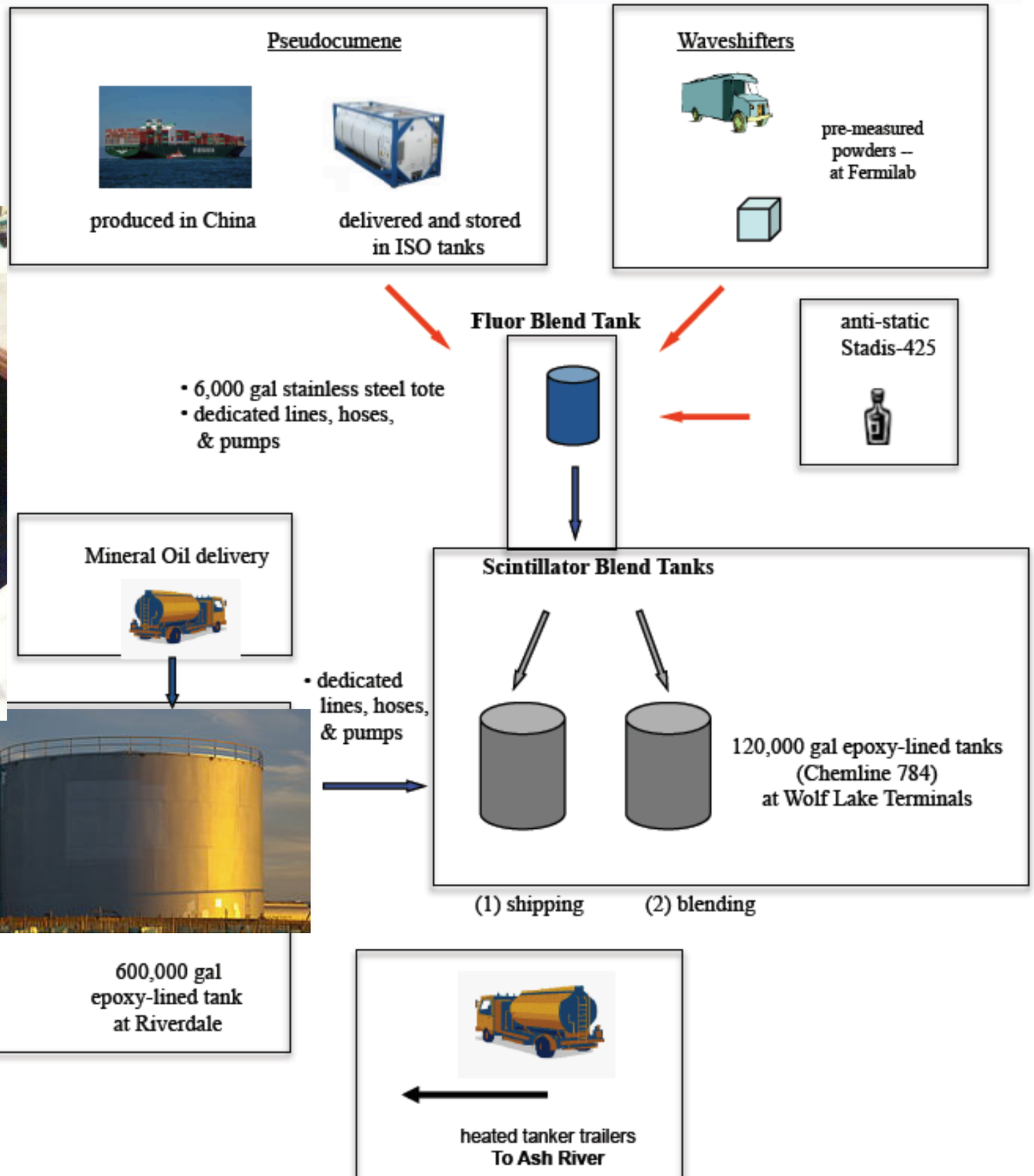


Light detected in by avalanche photodiodes (APDs) that are sealed, cooled (to -15 °C) and mated to the detector data acquisition system.

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

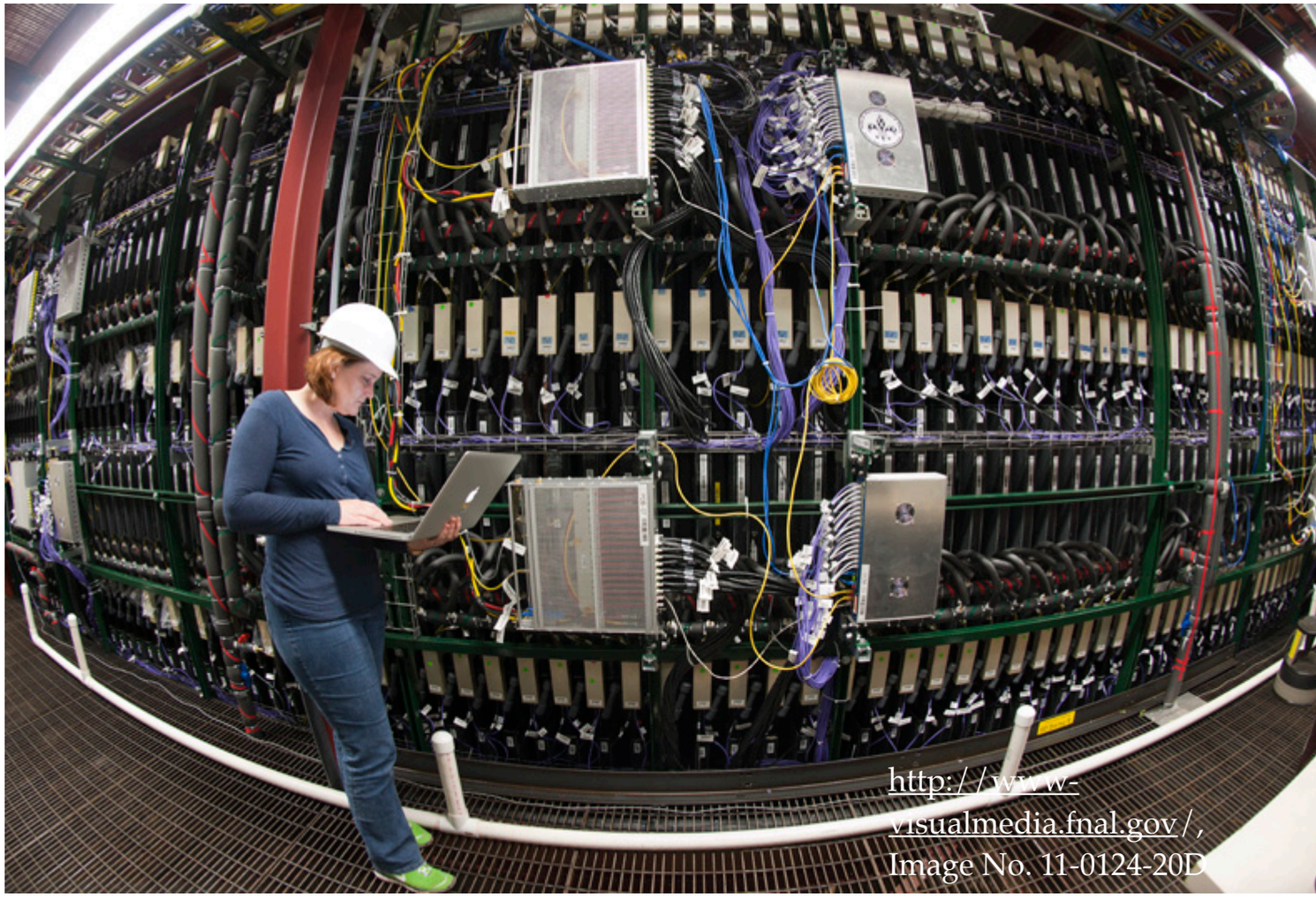
Filling

- 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

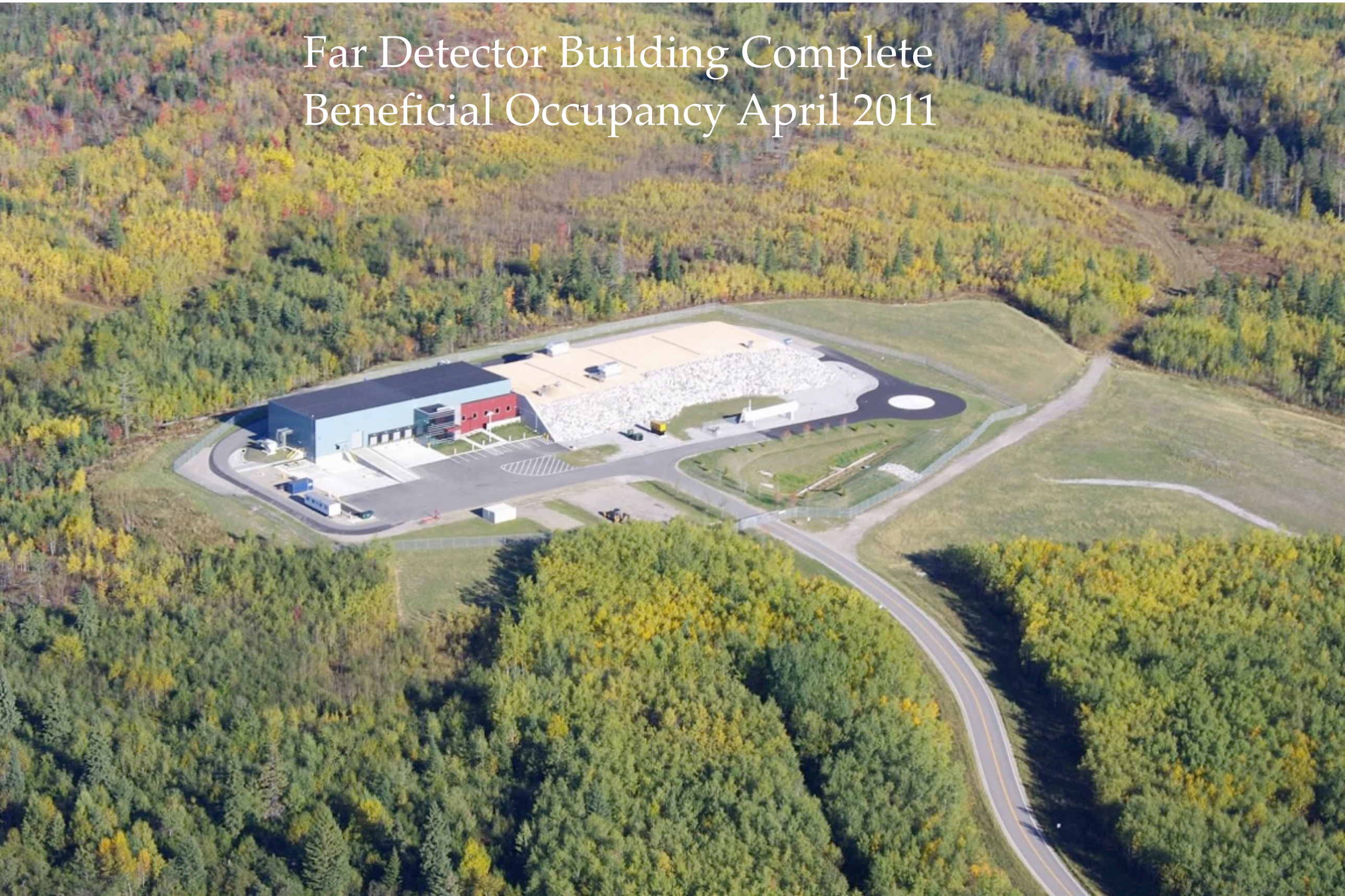
NDOS is Built and Functioning

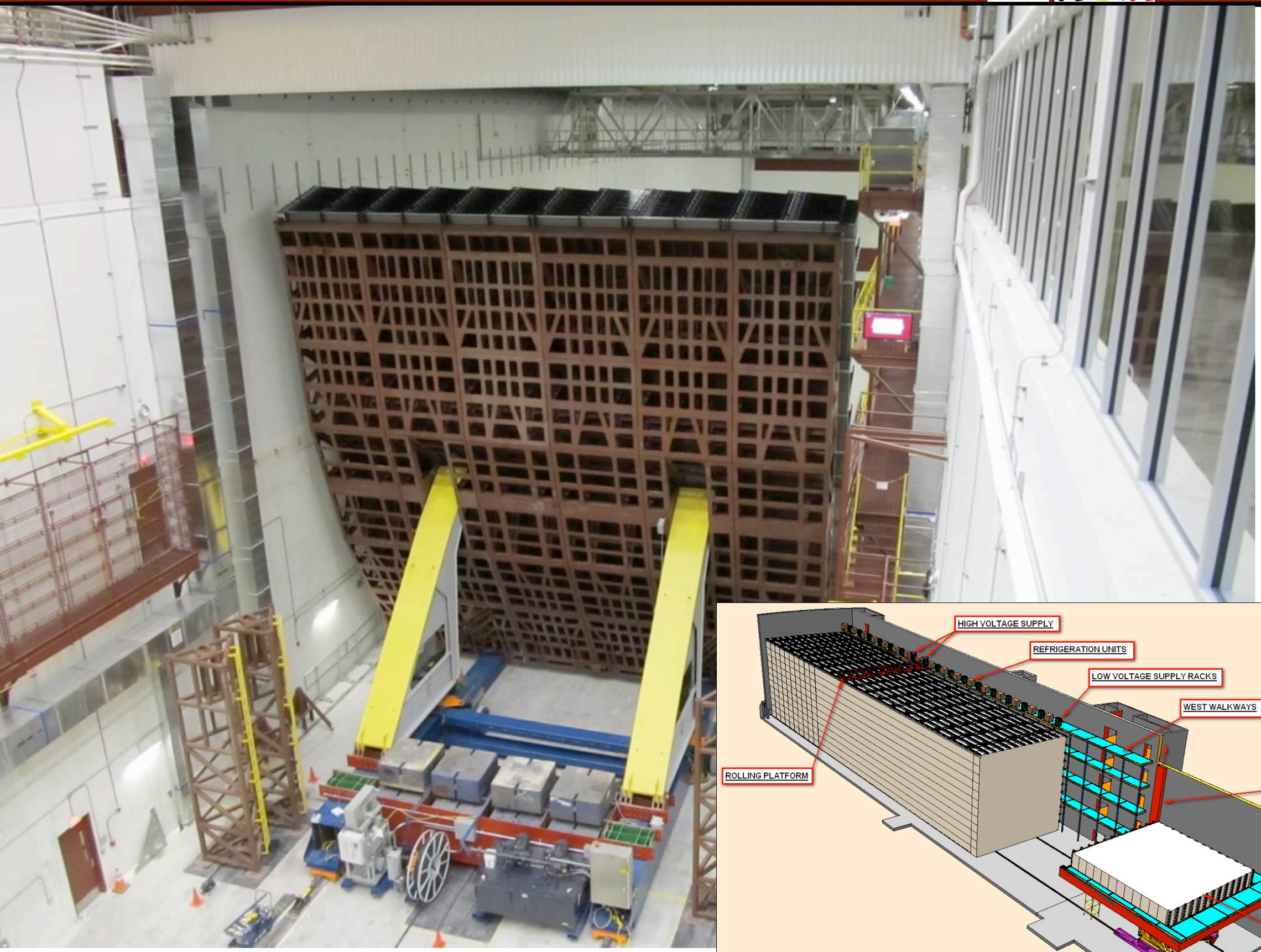
http://www-visualmedia.fnal.gov/, Image No. 11-0124-13D

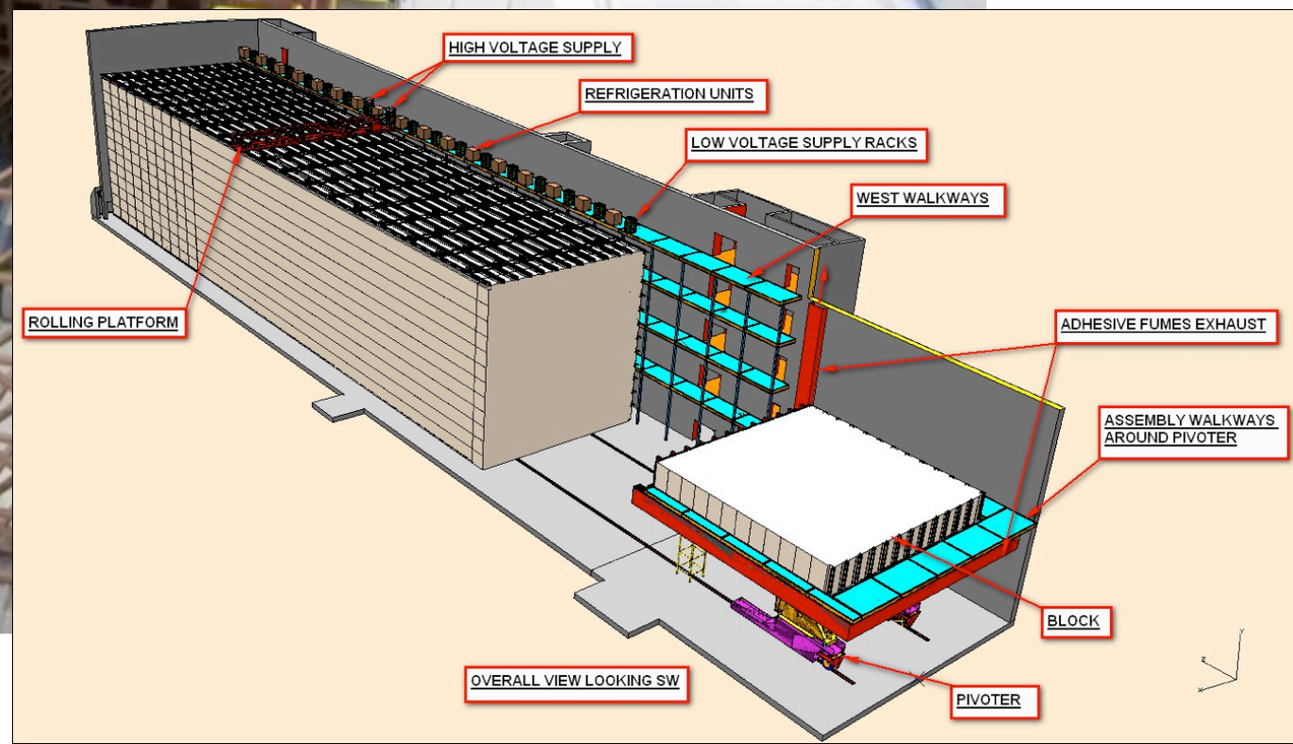
- Our prototype near detector
- It has taught us many valuable lessons for building NOvA near and far detectors.


http://www-visualmedia.fnal.gov/, Image No. 11-0124-20D

Near Detector Excavation


Far Detector Building Complete
Beneficial Occupancy April 2011



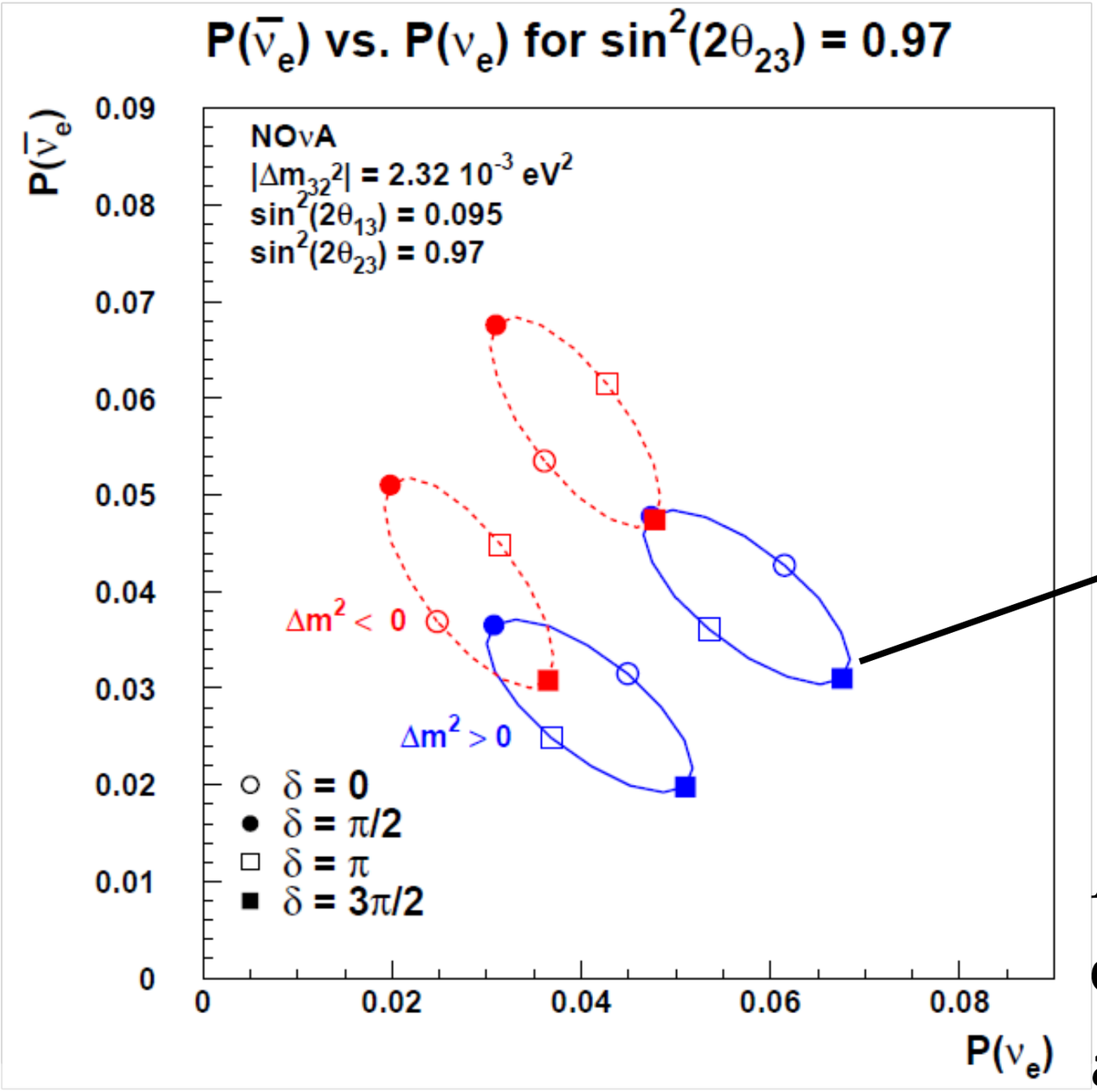

HIGH VOLTAGE SUPPLY
REFRIGERATION UNITS
LOW VOLTAGE SUPPLY RACKS
WEST WALKWAYS
ROLLING PLATFORM
ADHESIVE FUMES EXHAUST
ASSEMBLY WALKWAYS AROUND PIVOTER
BLOCK
OVERALL VIEW LOOKING SW
PIVOTER

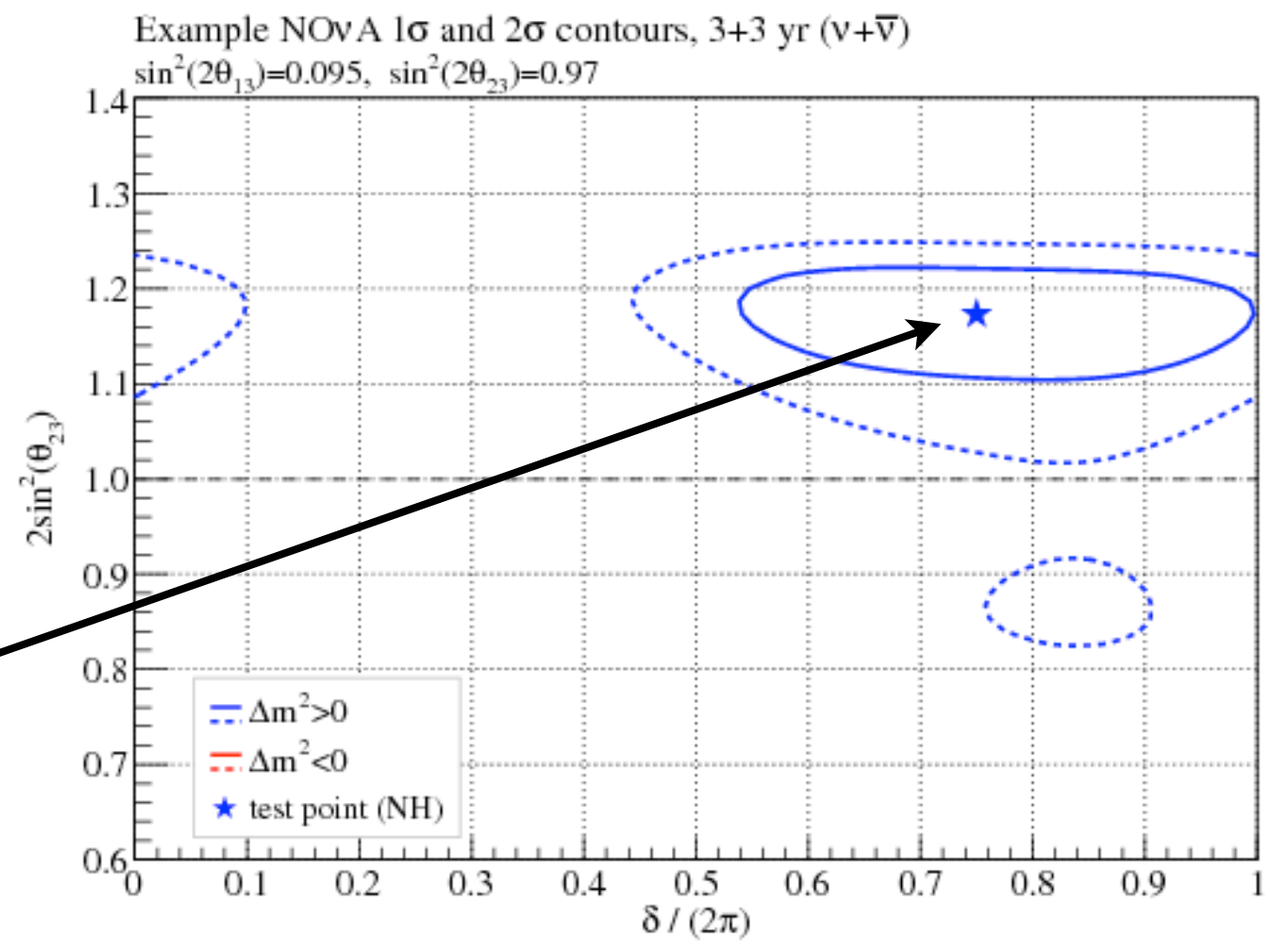
First block in place and
freestanding on Sep. 10, 2012

Second Block on Oct. 4, 2012

Only 26 more to go!

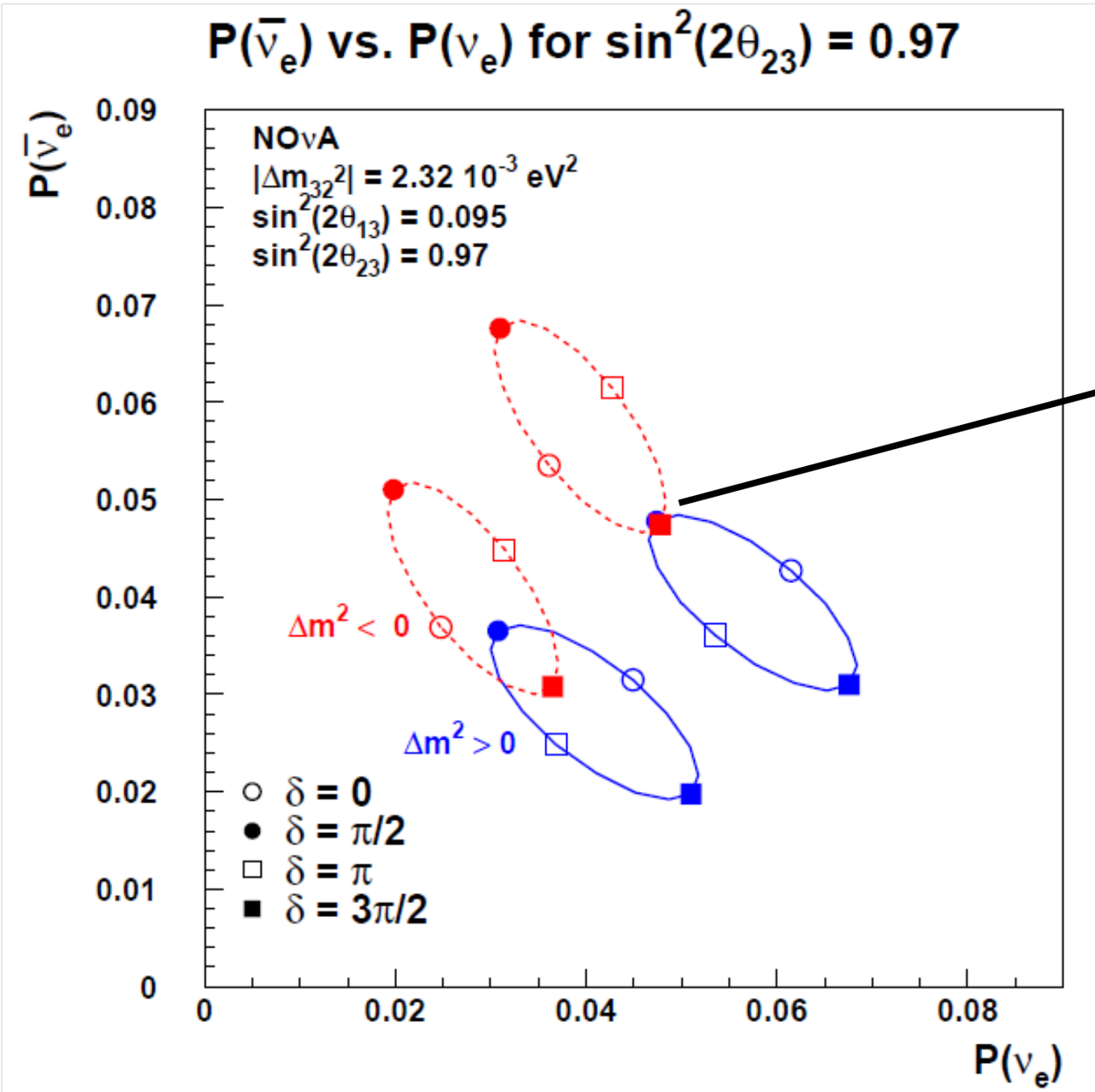
Physics Sensitivities (if we're lucky)

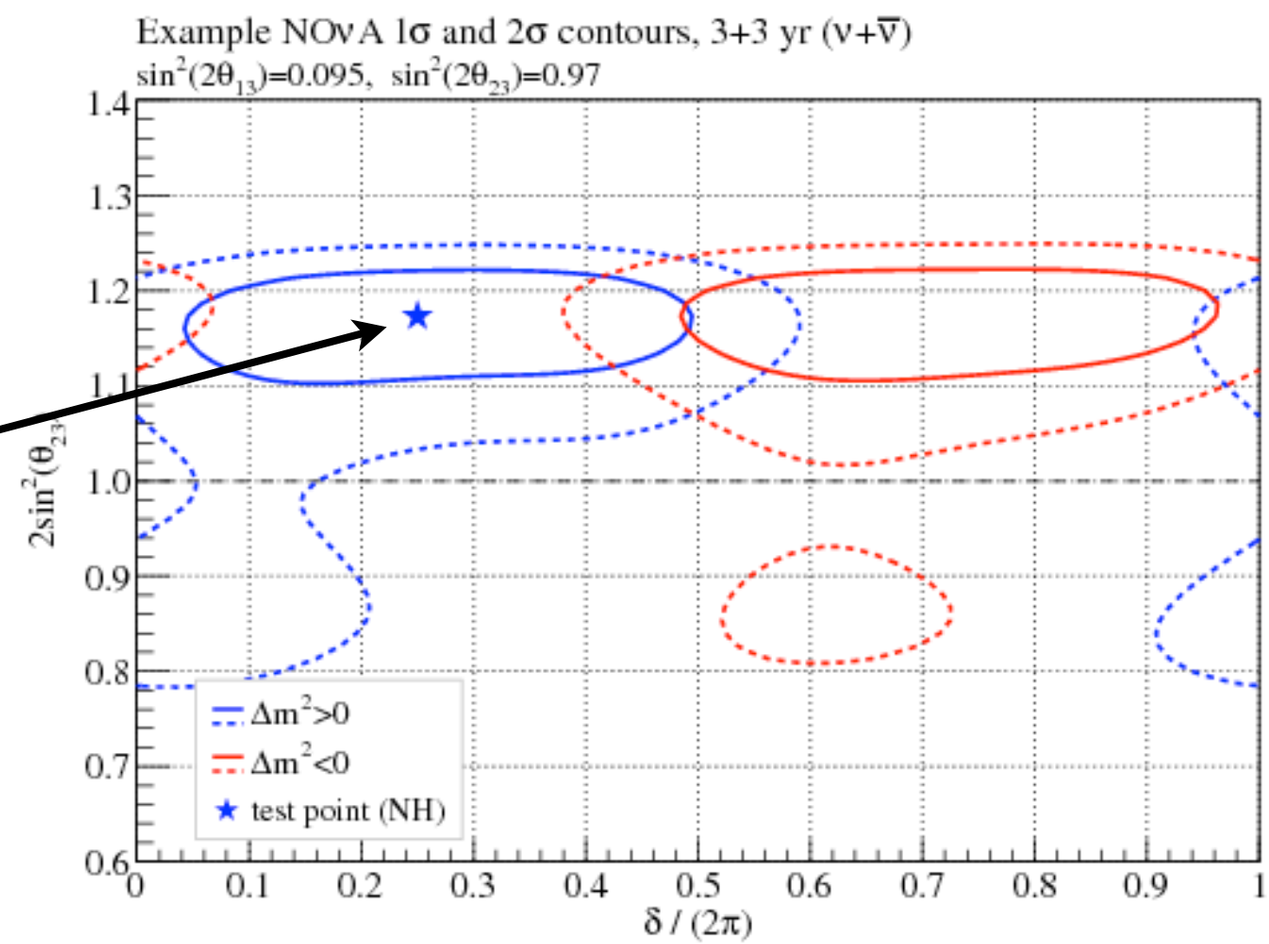




At this best-case point, we exclude the wrong hierarchy and a good fraction of δ_{CP} at 2σ.

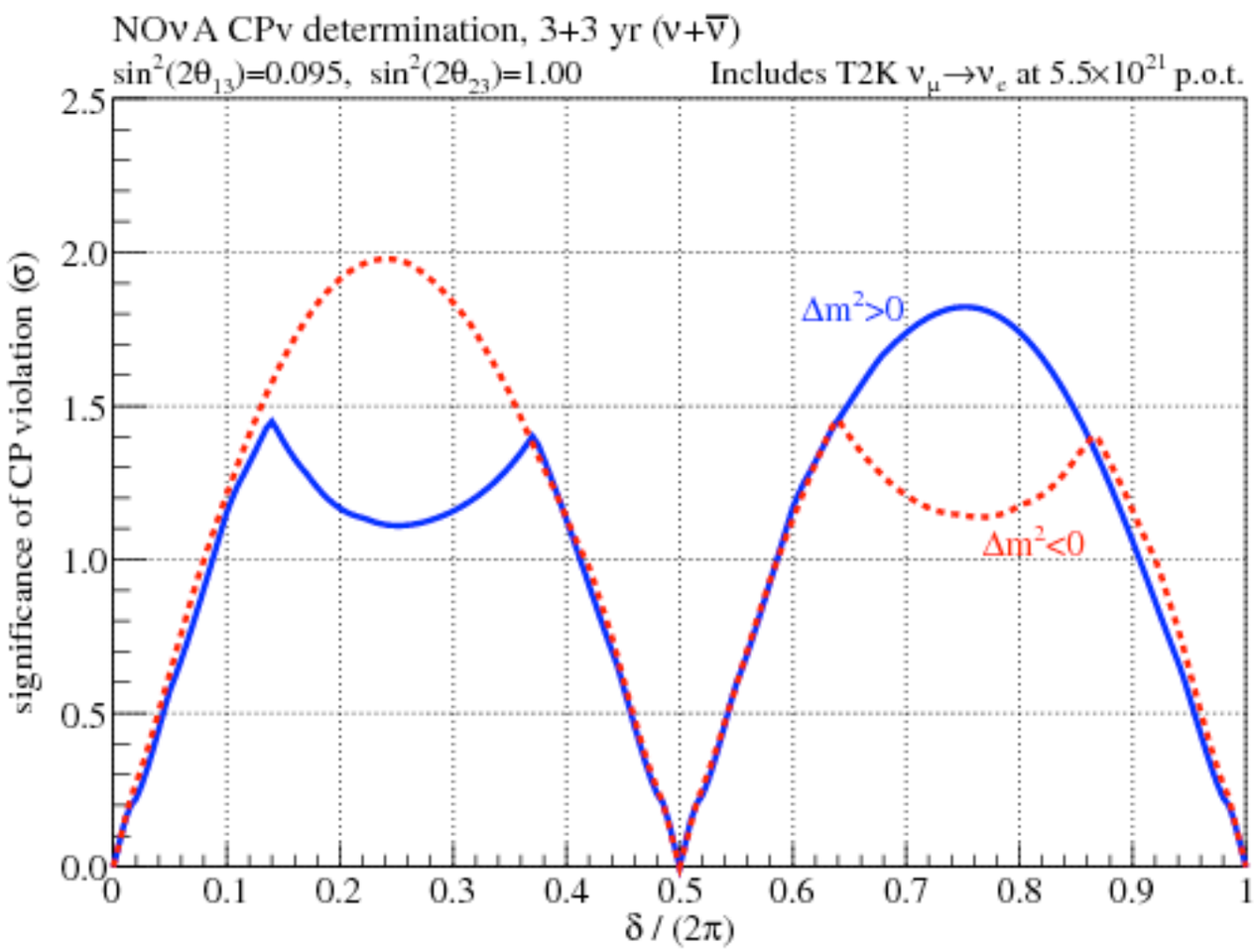
Physics Sensitivities (if we're unlucky)





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

δ_{CP} Sensitivity



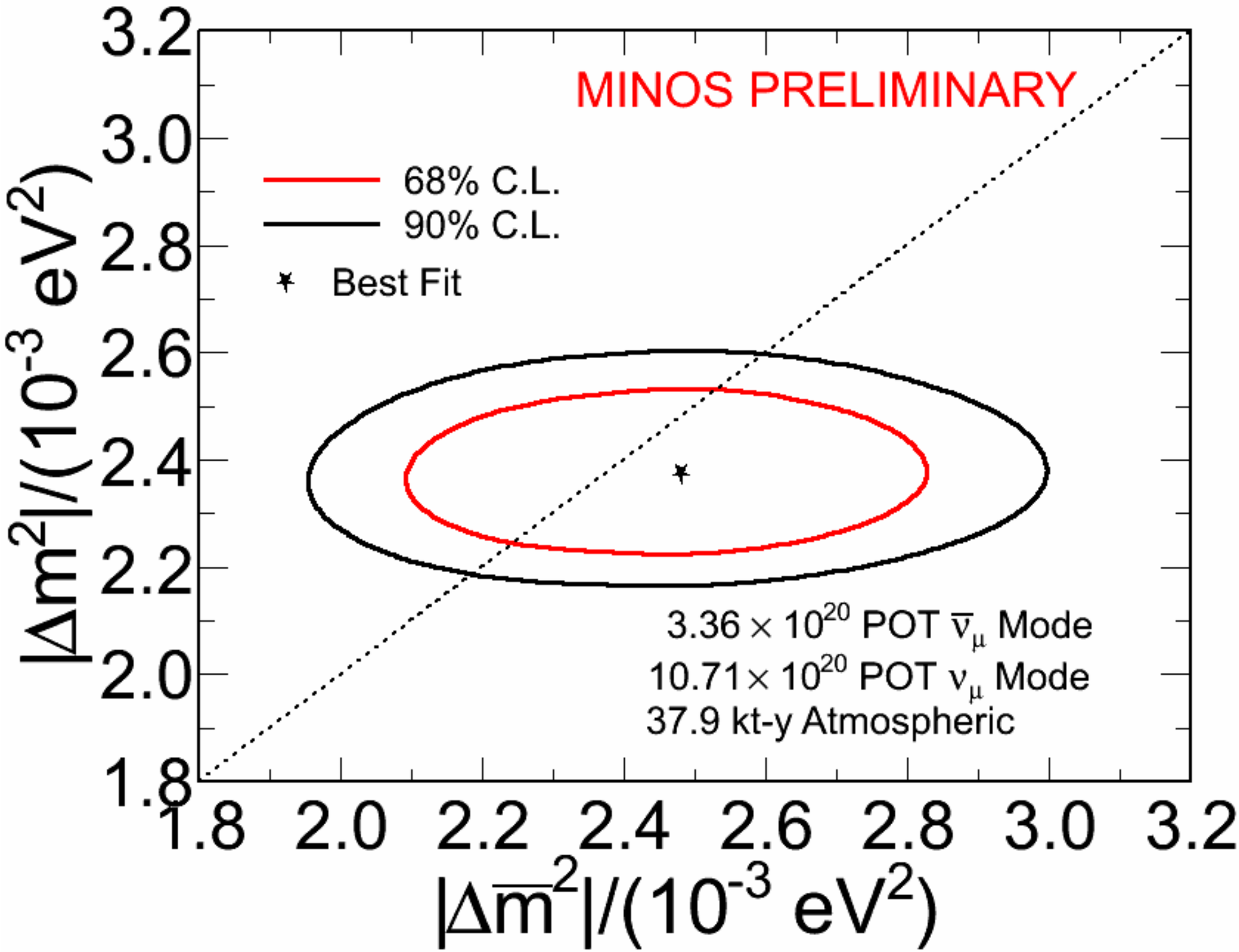
- With complimentary data from T2K, we can determine δ_{CP} at 1σ over a good fraction of possible values.

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 $\bar{\nu}_\mu$ Mode
10.71 × 10^20 POT ν_μ Mode
37.9 kt-y Atmospheric
$|\Delta m^2|/(10^{-3}\ eV^2)$
$|\Delta \bar{m}^2|/(10^{-3}\ eV^2)$
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.

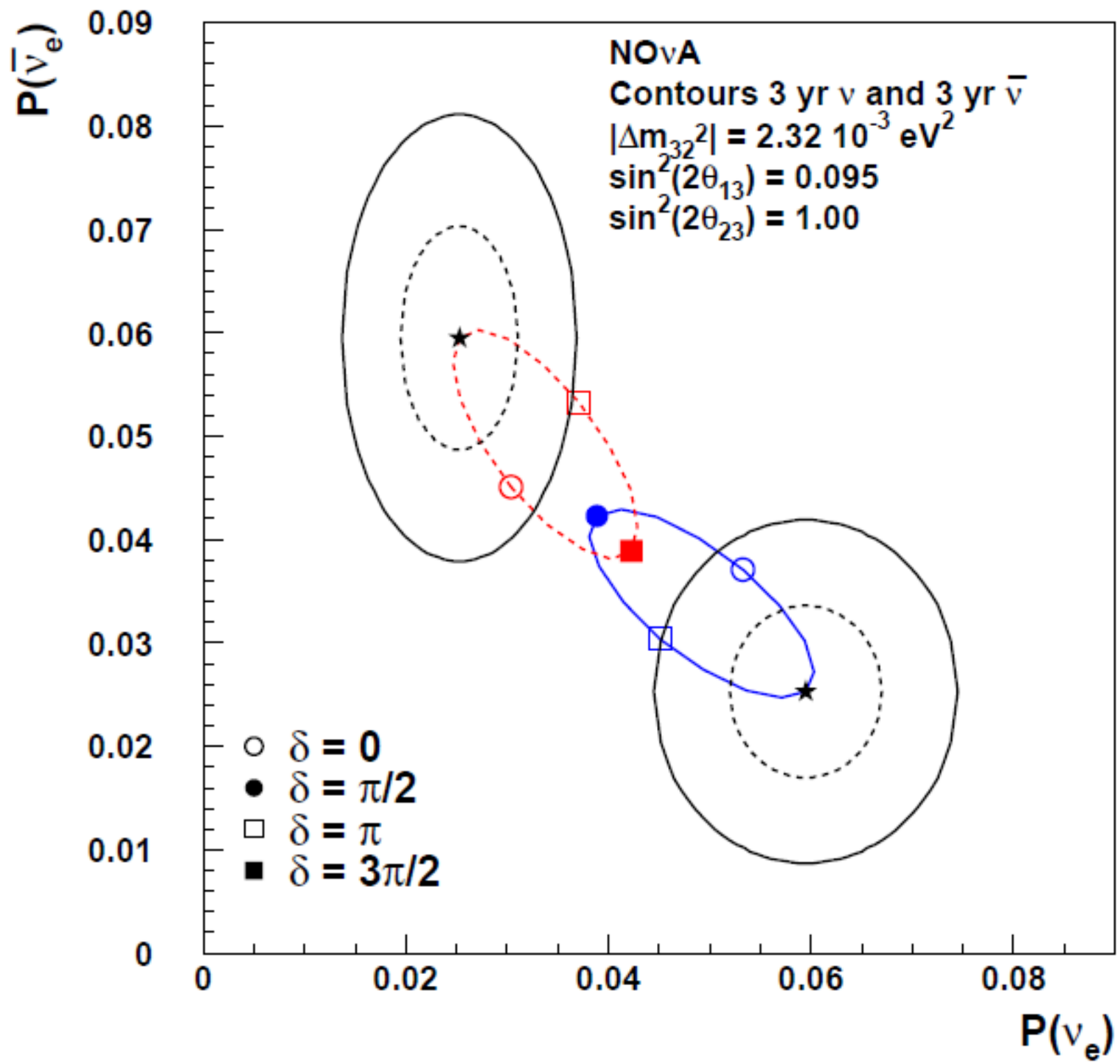
2. Mix fluor blend into mineral oil to produce NOvA liquid scintillator

Quality Control

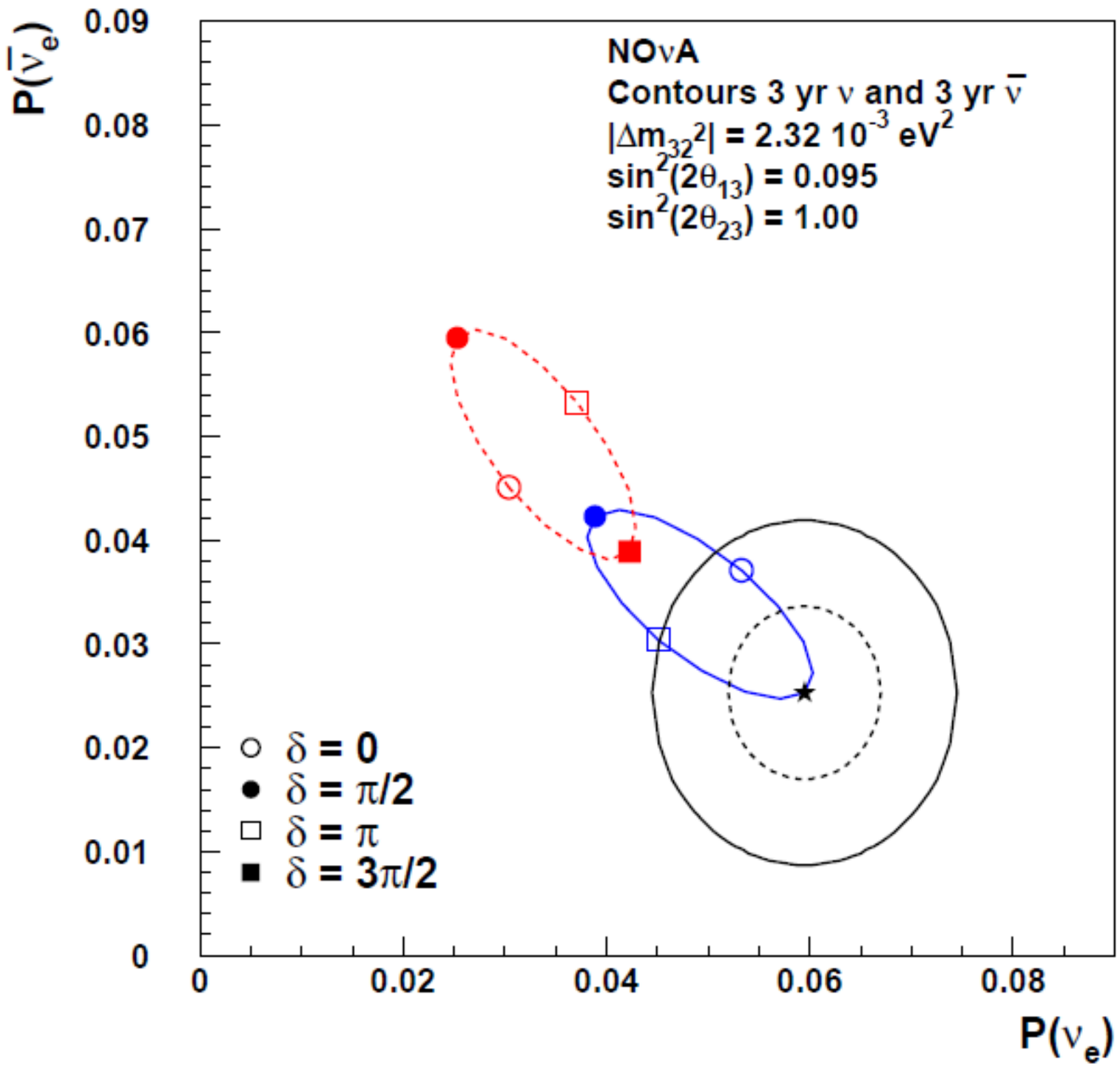
- Light Yield
  - Use radioactive sources to verify sufficient scintillator light
- Chemistry
  - Verify correct chemical composition.
- Clarity (15 m long far detector cells)
  - Use a "tintometer"
  - Maintaining cleanliness critical at every stage!

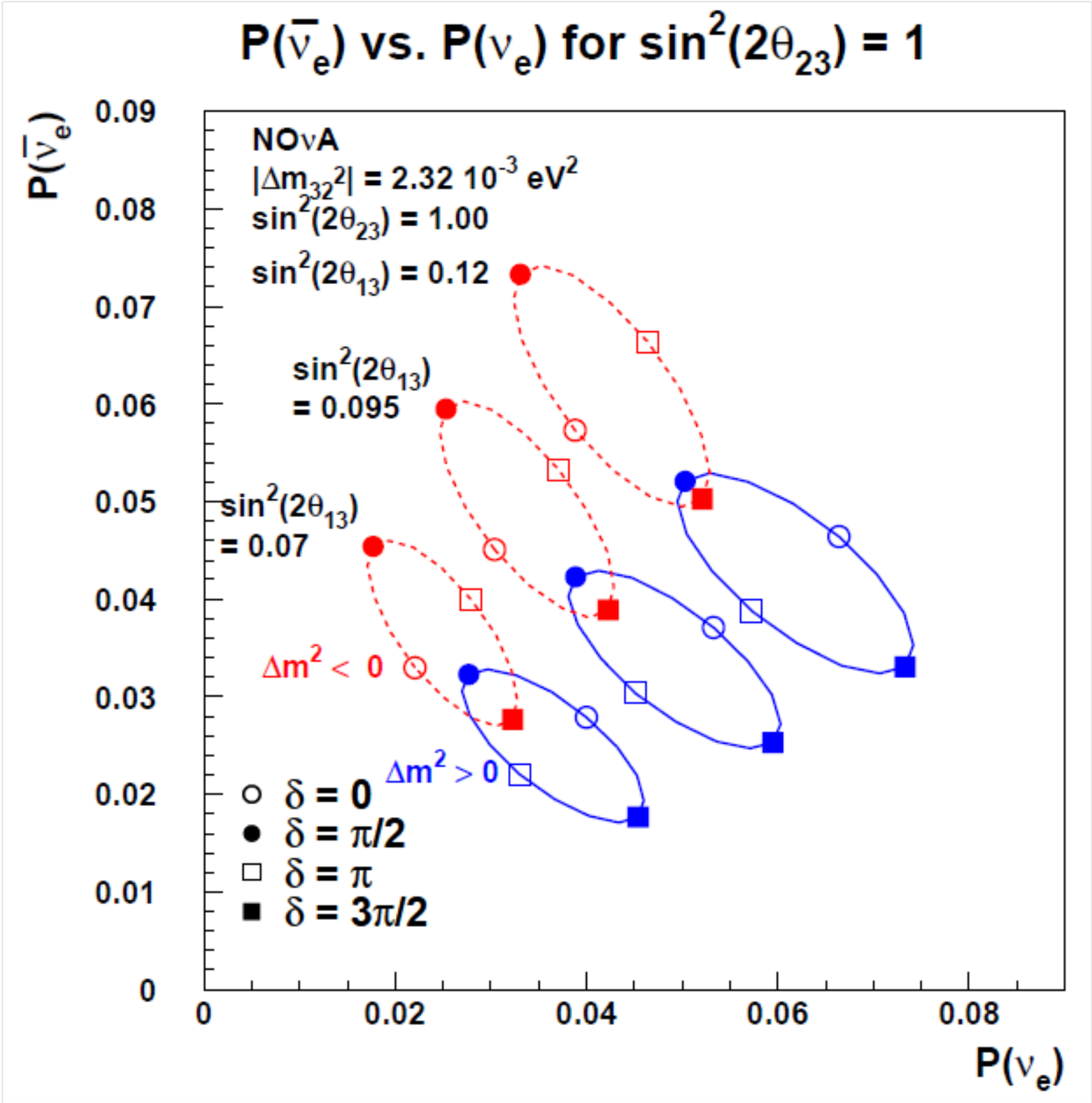
This is what we found when we looked inside of one of the fluor blending totes for the NDOS. The green substance was not identified (my guess was Mountain Dew). It was thoroughly cleaned by the blending company before any scintillator components were added.

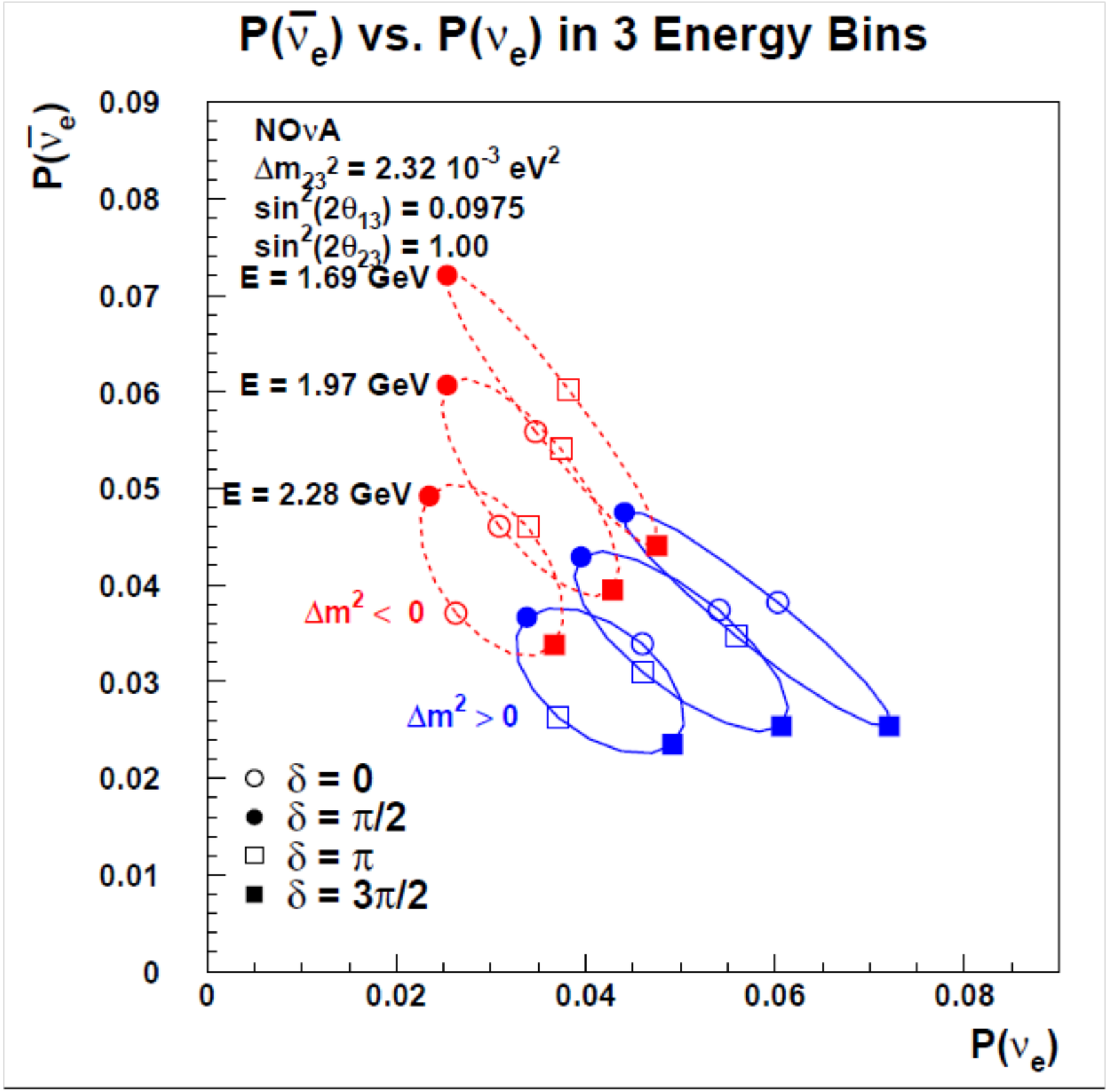
1 and 2 σ Contours for Starred Points

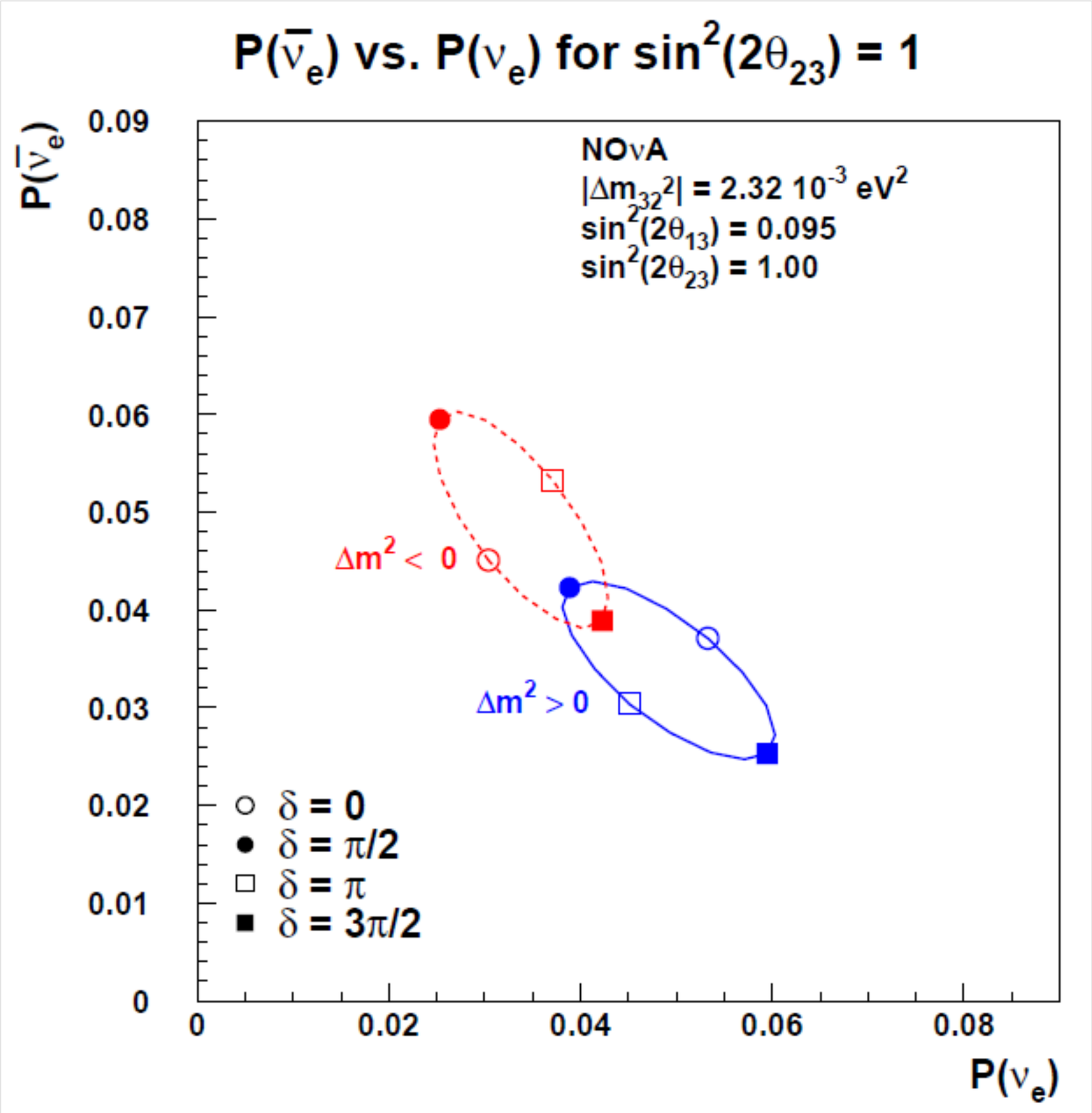


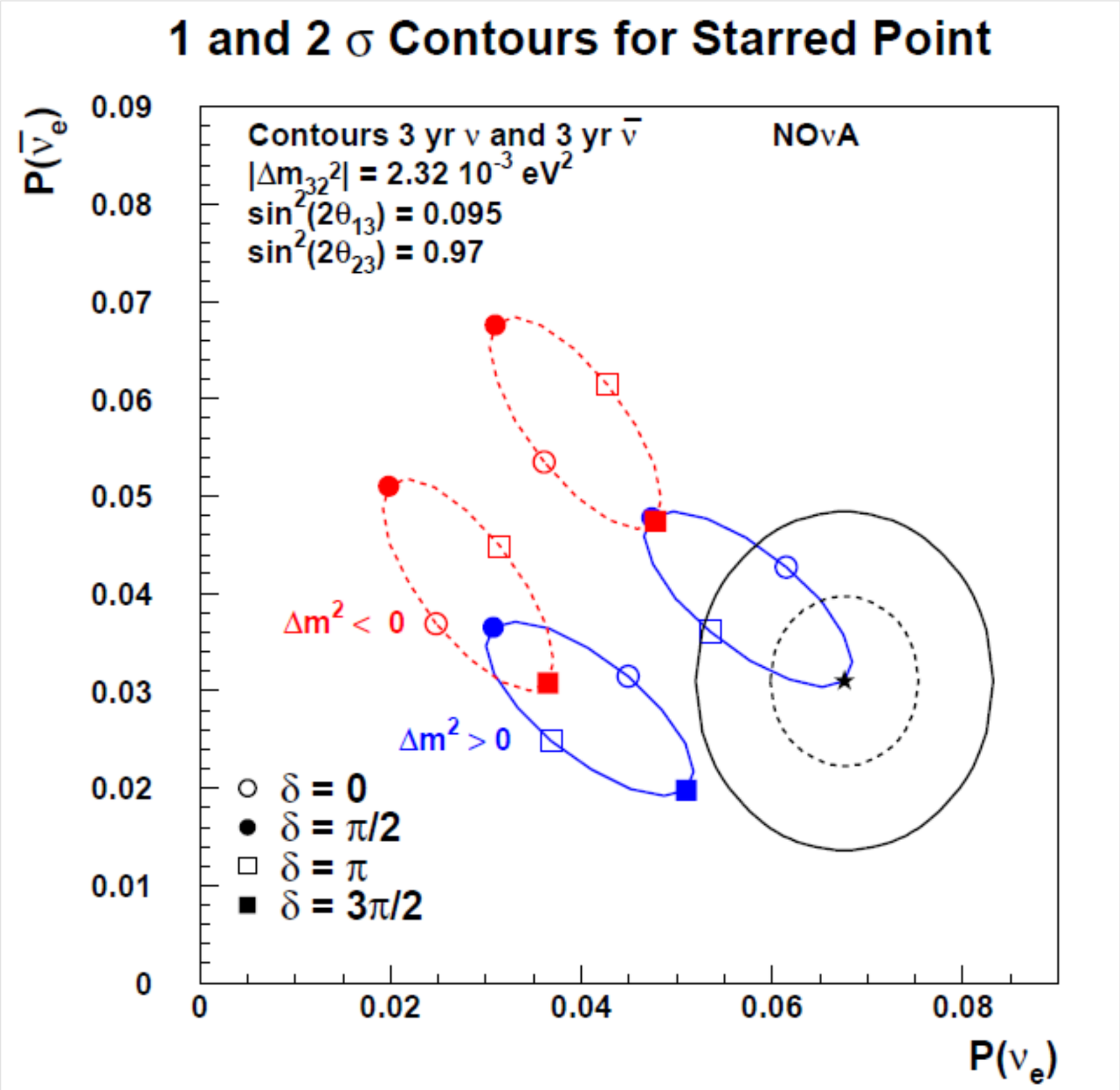
1 and 2 σ Contours for Starred Point




P($\bar{\nu}_e$) vs. P(ν_e) for $\sin^2(2\theta_{23})$ = 1
NOνA
$|\Delta m_{32}^2|$ = 2.32 10^{-3} eV^2
$\sin^2(2\theta_{23})$ = 1.00
$\sin^2(2\theta_{13})$ = 0.12
$\sin^2(2\theta_{13})$ = 0.095
$\sin^2(2\theta_{13})$ = 0.07
$\Delta m^2 < 0$
$\Delta m^2 > 0$
$\delta = 0$
$\delta = \pi/2$
$\delta = \pi$
$\delta = 3\pi/2$
P($\bar{\nu}_e$)
P(ν_e)
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


P($\bar{\nu}_e$) vs. P(ν_e) in 3 Energy Bins
NOνA
Δm_{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
$\Delta m^2 < 0$
$\Delta m^2 > 0$
$\delta = 0$
$\delta = \pi/2$
$\delta = \pi$
$\delta = 3\pi/2$
P($\bar{\nu}_e$)
P(ν_e)
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


P($\bar{\nu}_e$) vs. P(ν_e) for $\sin^2(2\theta_{23})$ = 1
NOνA
$|\Delta m_{32}^2|$ = 2.32 10^{-3} eV^2
$\sin^2(2\theta_{13})$ = 0.095
$\sin^2(2\theta_{23})$ = 1.00
$\Delta m^2 < 0$
$\Delta m^2 > 0$
δ = 0
δ = π/2
δ = π
δ = 3π/2
P($\bar{\nu}_e$)
P(ν_e)
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
Contours 3 yr ν and 3 yr ν̄
|Δm32²| = 2.32 10⁻³ eV²
sin²(2θ13) = 0.095
sin²(2θ23) = 0.97
NOνA
Δm² < 0
Δm² > 0
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

Far Detector

- 14,000 tons
- Will detected oscillated beam