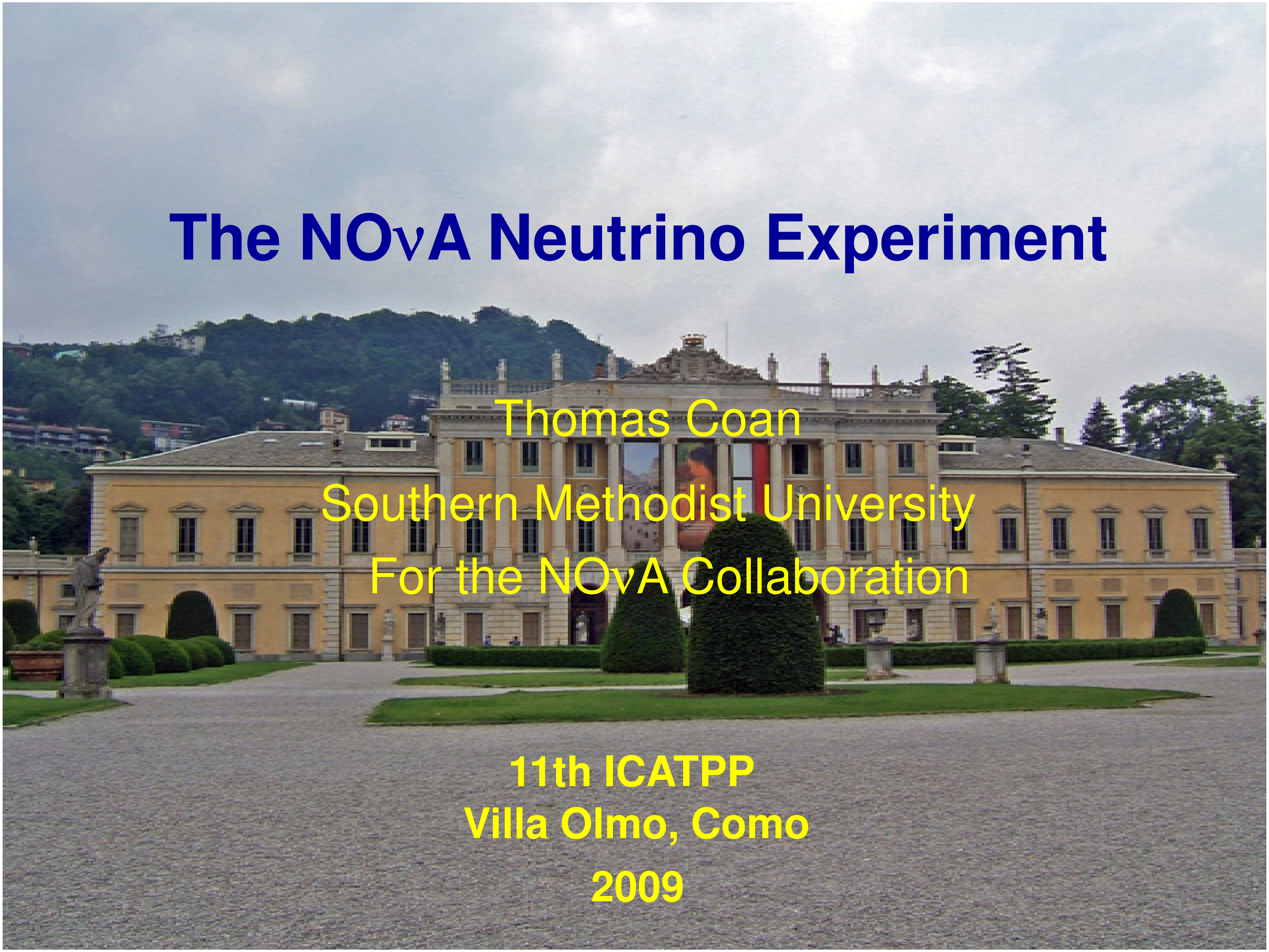


The NOνA Neutrino Experiment

Thomas Coan

Southern Methodist University

For the NOνA Collaboration

11th ICATPP

Villa Olmo, Como

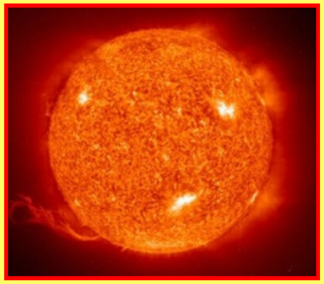
2009

Outline

NuMI Off-Axis νe Appearance Experiment

- Neutrino Physics Motivation
- Fermilab Neutrino Beam Upgrade
- NOνA Detector Design and Construction
- NOνA Sensitivities
- Timeline & Summary

Neutrinos Mix

Solar νs	Reactor νs	Atmospheric νs	Accelerator νs
			
Homestake, Gallex, SAGE, Super-K, SNO, Borexino	KamLAND, CHOOZ, …	Kamiokande, Super-K	K2K, MINOS, MiniBOONE

Neutrinos change flavor

⇒ Neutrinos have mass and mix

flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

PMNS Leptonic Mixing Matrix

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$U_{\alpha i}$ can be written w/ 3 mixing angles and 1 phase

and w/ $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

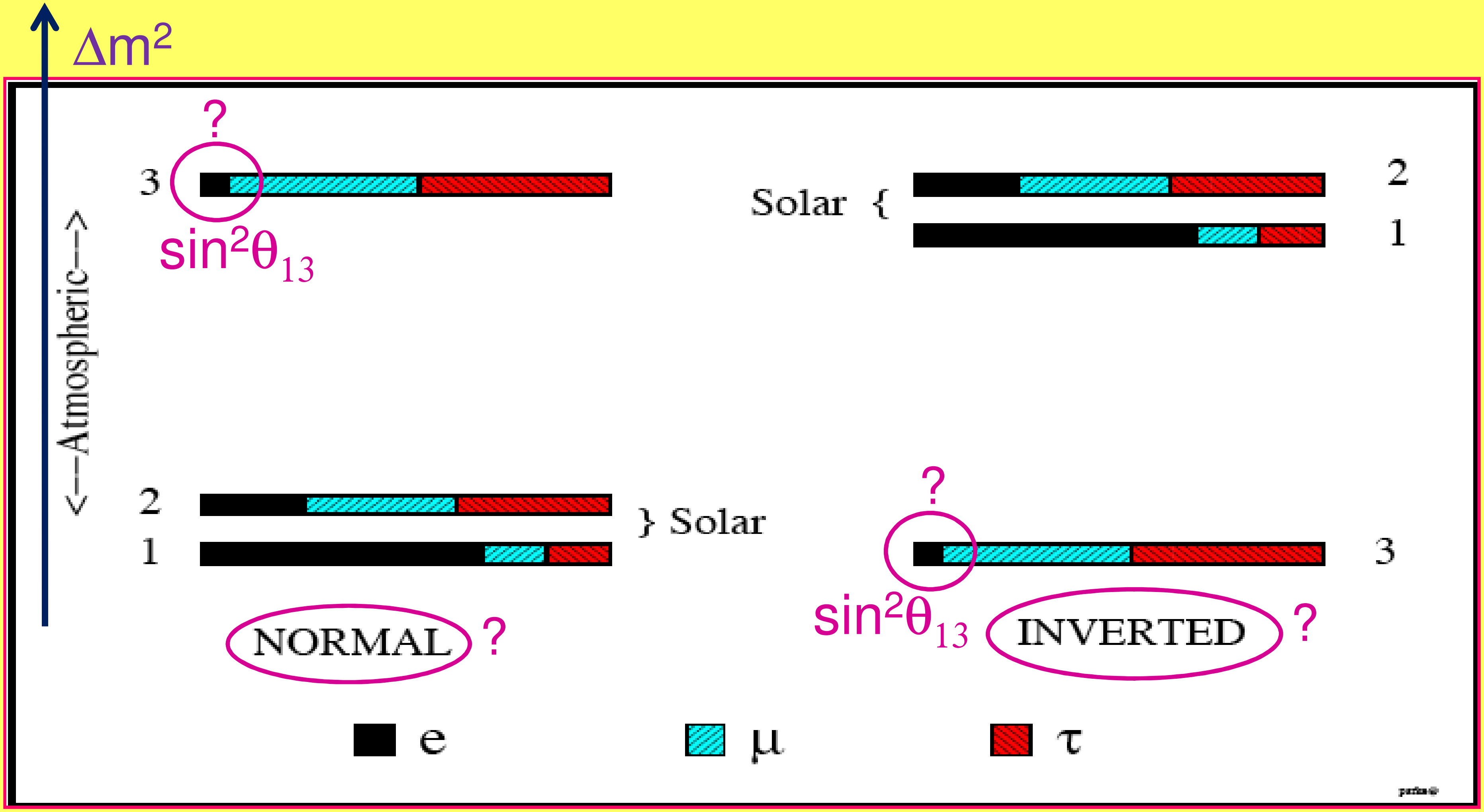
atmospheric cross-mixing solar

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

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

- Mixing angle θ_{13} unknown ($\sin^2 2\theta_{13} < 0.18$).
- CP violating phase δ unknown.

Neutrino Ignorance…



Vacuum Oscillations

Neutrinos propagate as mass eigenstates
Interact as different (i.e., weak) eigenstates

➤ Oscillations result

In absence of matter (key caveat) & to lowest order:

$$P_{vac}(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{atm}$$

$$\Delta_{atm} \simeq 1.27\left(\frac{\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Additional sub-dominant terms, sensitive to CPV phase δ:

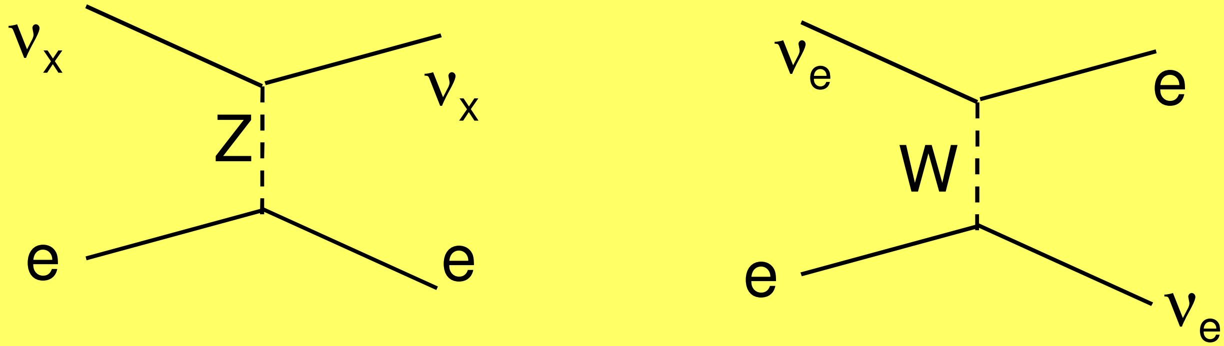
$$\Delta P_\delta(\nu_\mu \to \nu_e) = J\sin\Delta_{sol}\sin\Delta_{atm}(\cos\delta\cos\Delta_{atm} \mp \sin\delta\sin\Delta_{atm})$$

$$J = \sin 2\theta_{12}\sin 2\theta 23\sin 2\theta_{13}\cos\theta_{13}$$

ν (−) $\bar{\nu}$ (+)

… but NOνA's neutrinos travel though Earth ...

“Matter Effects”



ν_e – e scattering Hamiltonian modified

Effective mass eigenstates & mixing angles altered

$$P_{mat}(\nu_\mu \rightarrow \nu_e) \simeq (1 \pm 2\frac{E}{E_R}) P_{vac}(\nu_\mu \rightarrow \nu_e)$$

$E_R \cong 12$ GeV (earth’s mantle)

$E(\nu) \cong 2$ GeV $\Rightarrow$ 30% enhancement/suppression

NOνA’s long baseline key

NOνA Goals at a Glance

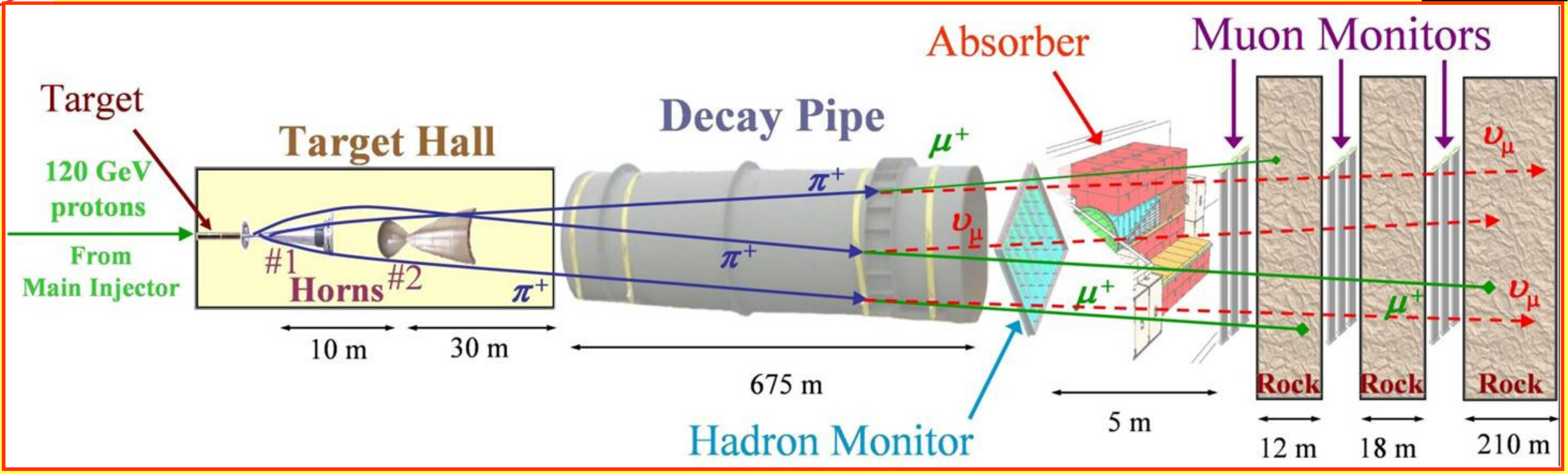
- Observe $\nu_\mu \rightarrow \nu_e$ transition
- Measure θ_{13}
- Determine mass hierarchy (sign of Δm^2_{23})
- Measure $\sin^2(2\theta_{23})$
- Constrain δ_{CP}

Large neutrino luminosity & detector mass req'd

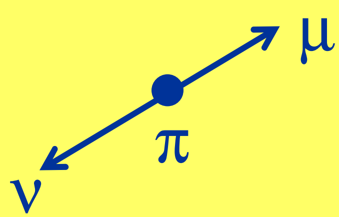
NOνA Collaboration

- 180+ scientists/engineers
- 27 institutions
- 4 countries

Off-Axis Beam Technique

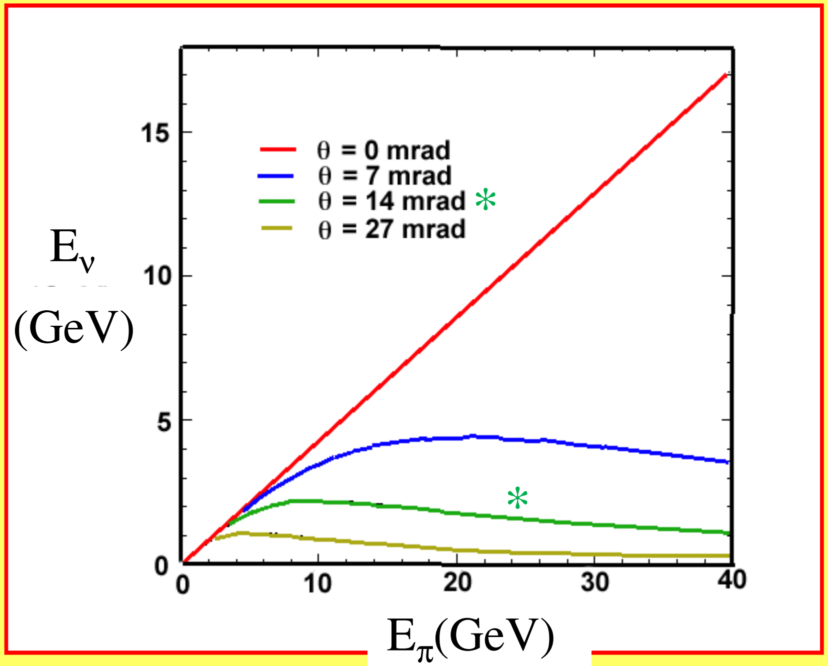


CoM:



Lab Frame: $$E_\nu \propto \frac{E_\pi}{1 + (E_\pi/m_\pi)^2\theta^2}$$

∴E(ν) ~independent of parent hadron E

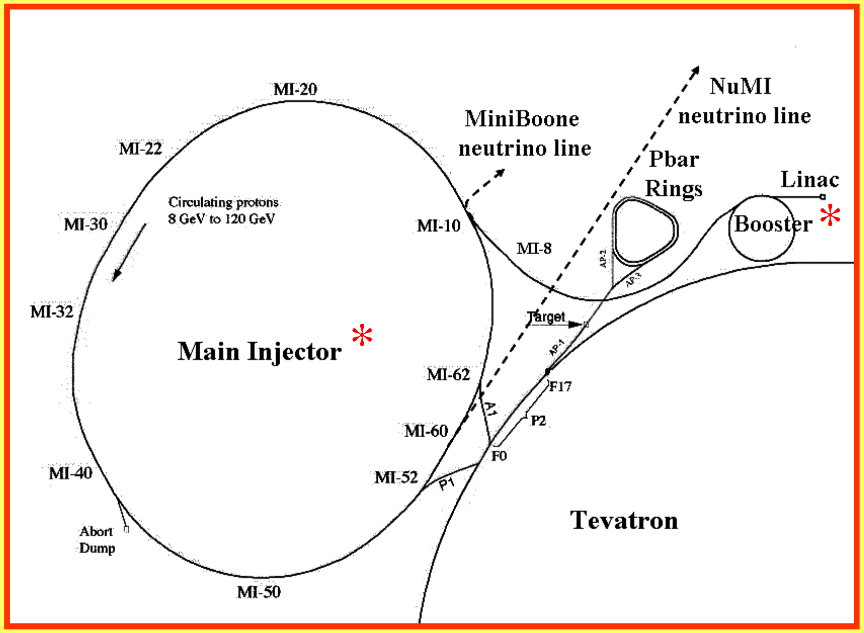


Accelerator Upgrade

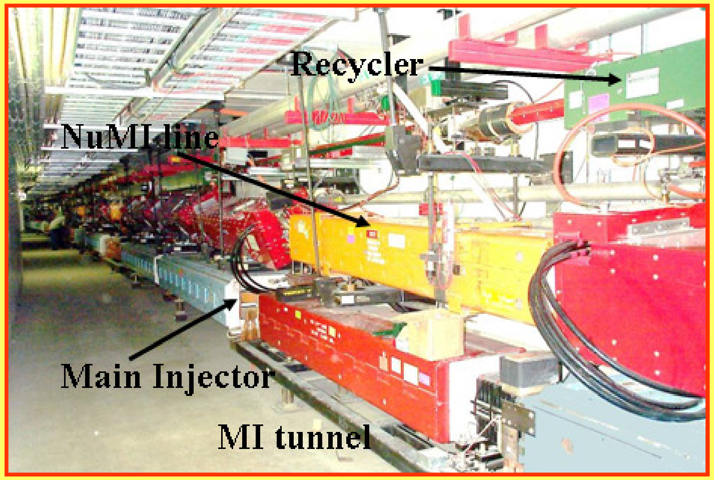
⇒ post-Tevatron era ⇐

Booster → Recycler → MI → target

p: 8 GeV → 120 GeV



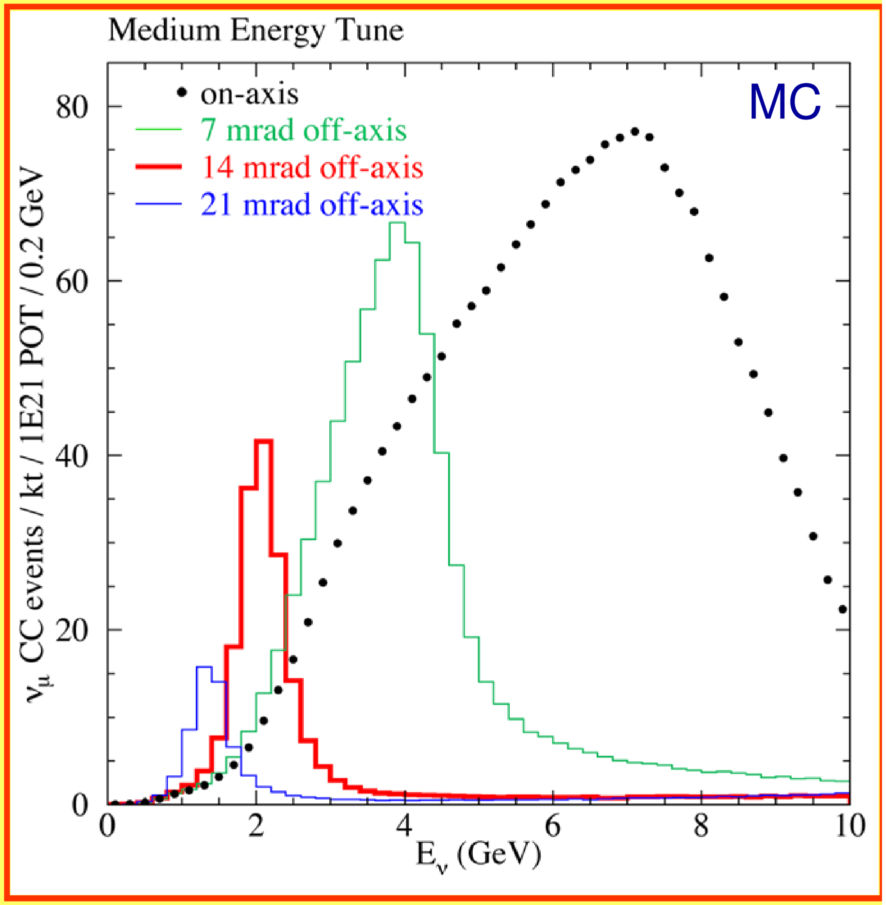
- Recycler: $\overline{p}$ → p storage ring
  - slip-stack batches in Recycler
  - single turn extraction into MI
  - 53 MHz RF added



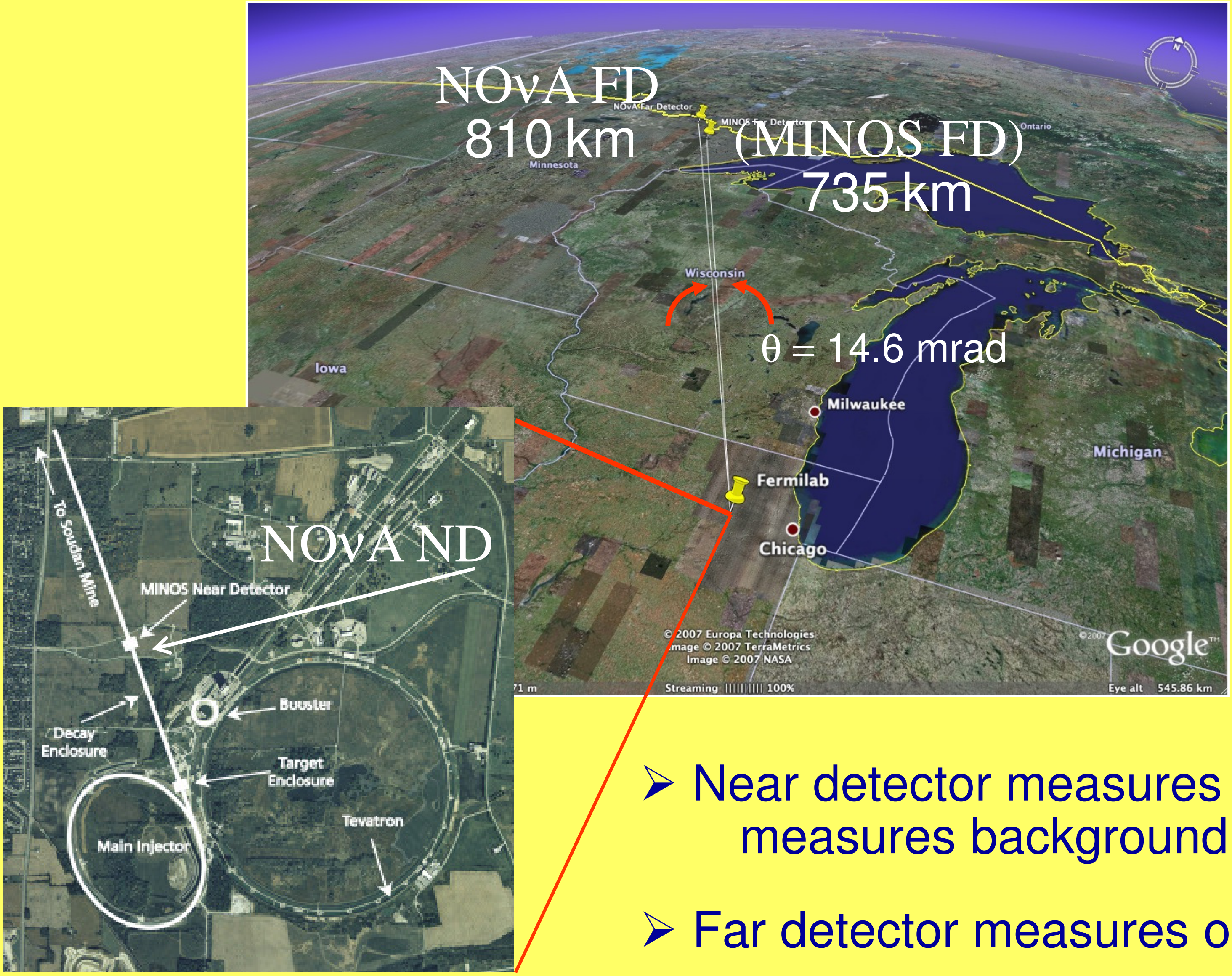
- MI cycle time: 2.2 s → 1.33 s
  - more 53 MHz RF

Upgraded NuMI Beam

- 14.6 mrad off-axis ν beam
- 10 μsec spill every 1.3 sec
- Horns @ "medium energy tune"
- 4.9×10^{13} p/pulse @120 GeV/p
- 700 kW beam power
- 6×10^{20} POT/yr
- Plan 3 yr ν_μ & 3 yr $\overline{\nu}_\mu$ running



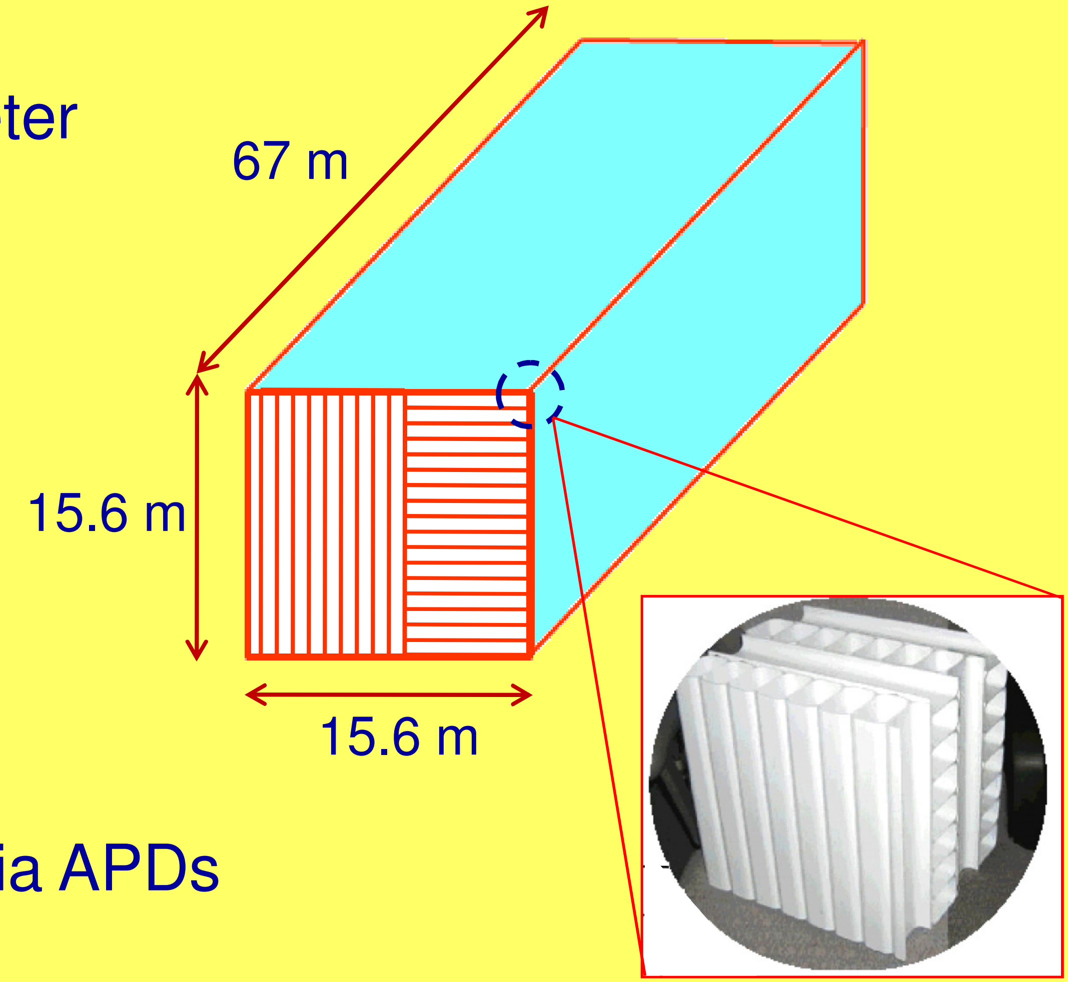
2-Detector Configuration



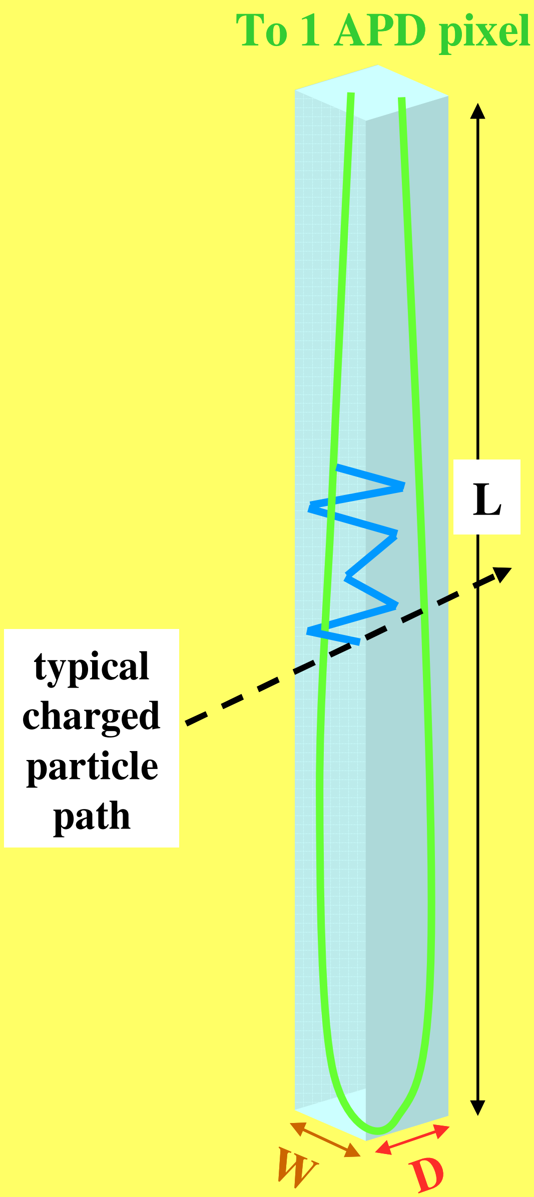
- Near detector measures ν flux, measures background rates
- Far detector measures osc ν flux

NOνA Far Detector Overview

- Low-Z tracking calorimeter
- Surface location
- 14 kT total mass
- 930 Detector planes
  - Alternate x-y layers
  - 73% active
- Liquid scintillator cells
  - 4 cm x 6 cm x 1540 cm
- 1-sided readout/plane via APDs



NOνA Detector "Atom"



Liquid Scintillator

- Mineral oil solvent
- Primary scintillator: 4.1% (BW) pseudocumene
- Waveshifters: PPO + bis-MSB

Hollow PVC cells provide granularity

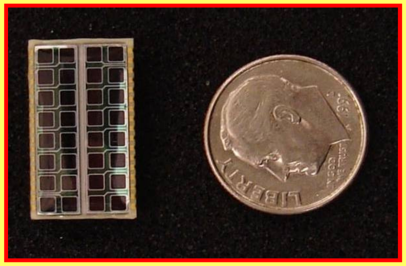
- 15% (BW) TiO: high reflectivity walls
- Horizontal cell: 3.87 cm x 6.0 cm x 15.4 m long
- Vertical cell: 3.76 cm x 5.7 cm x 15.4 m long

Looped Wavelength Shifting Fiber

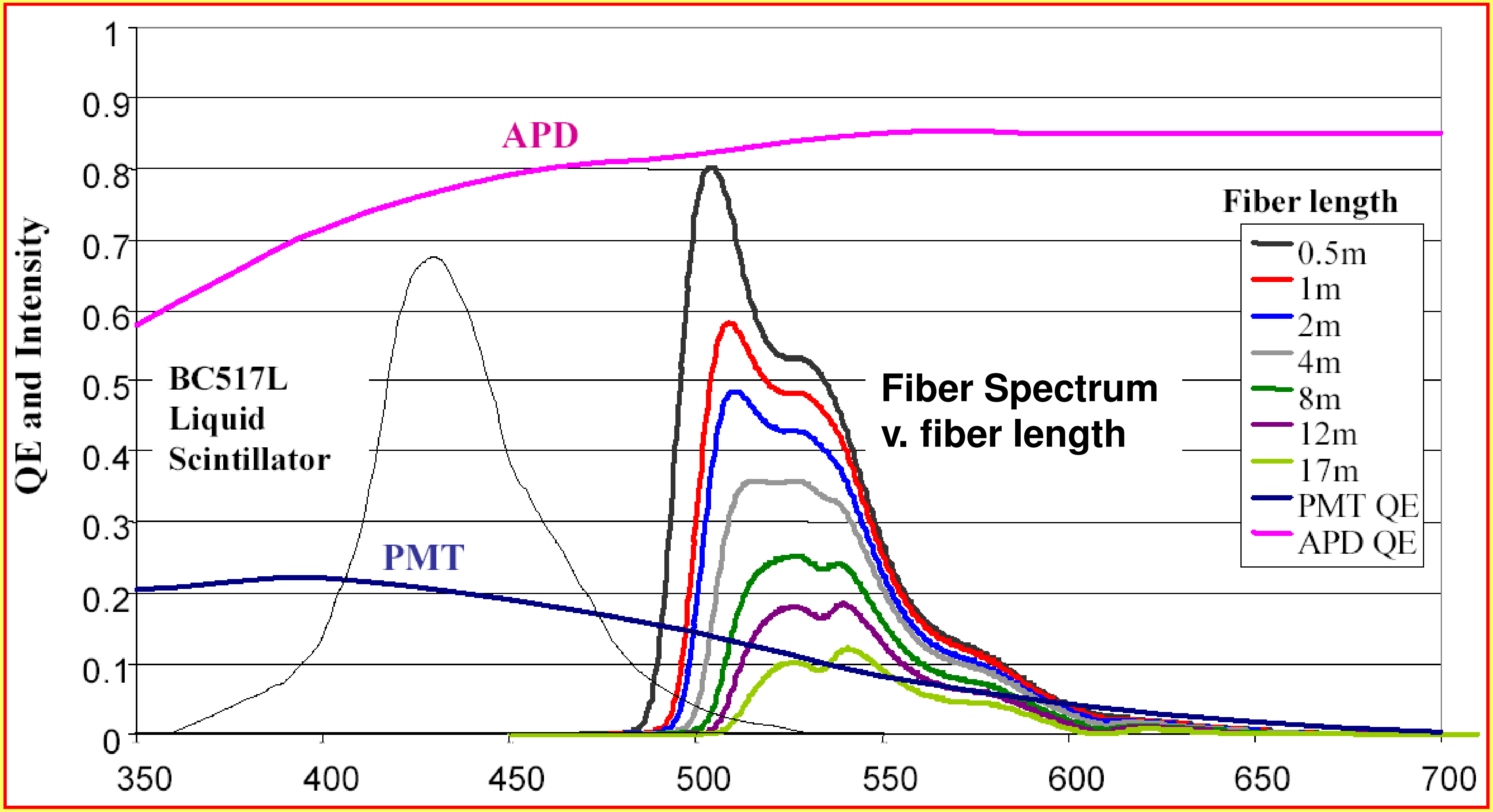
- Maximizes light collection: no mirrors
- Diameter = 0.7mm, K-27 dye @ 300ppm

Avalanche Photodiode

- QE = 85%
- Gain = 100
- T_run = -15 C



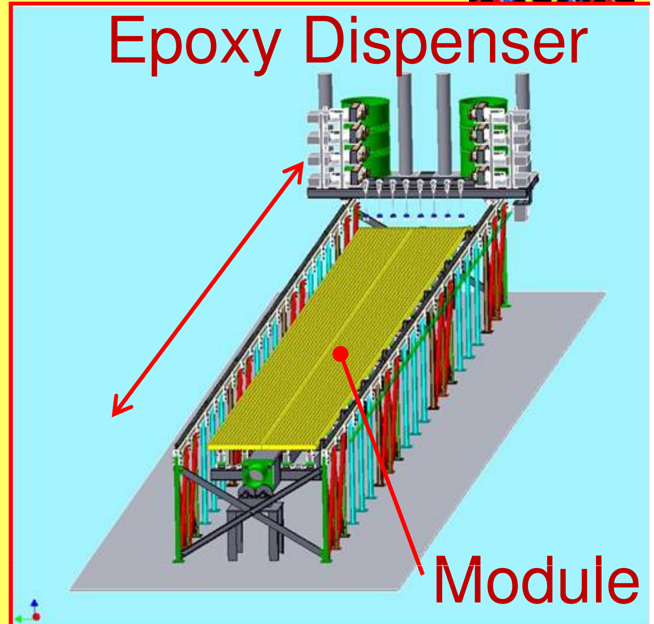
Why APDs

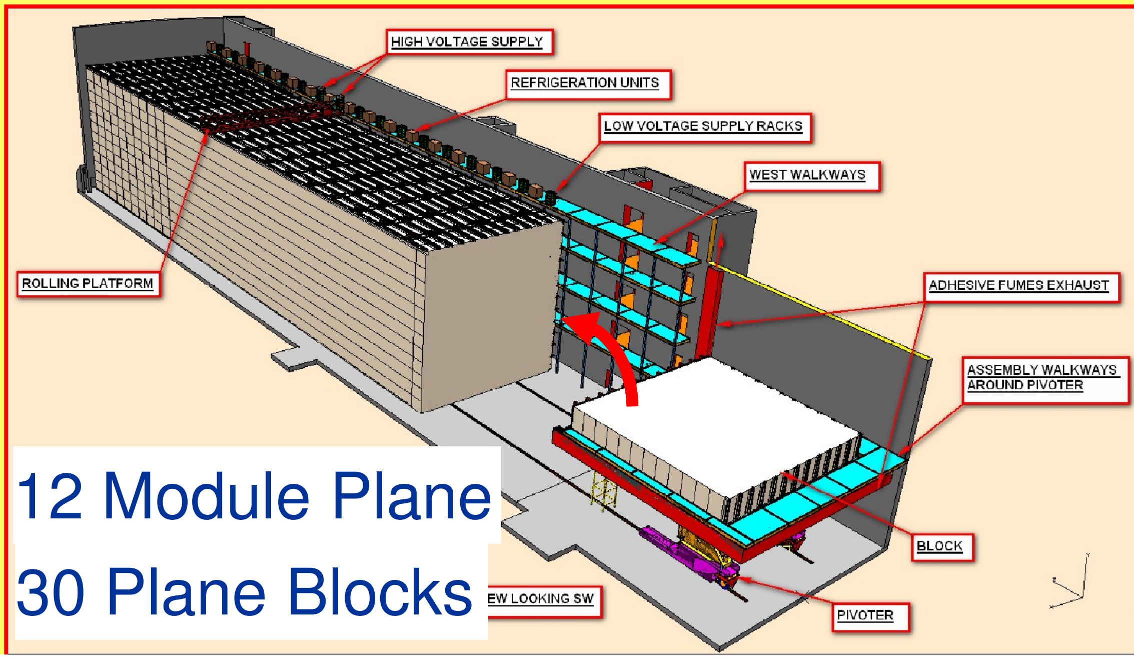


QE and Intensity
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
350
400
450
500
550
600
650
700
APD
PMT
BC517L
Liquid
Scintillator
Fiber Spectrum
v. fiber length
Fiber length
0.5m
1m
2m
4m
8m
12m
17m
PMT QE
APD QE

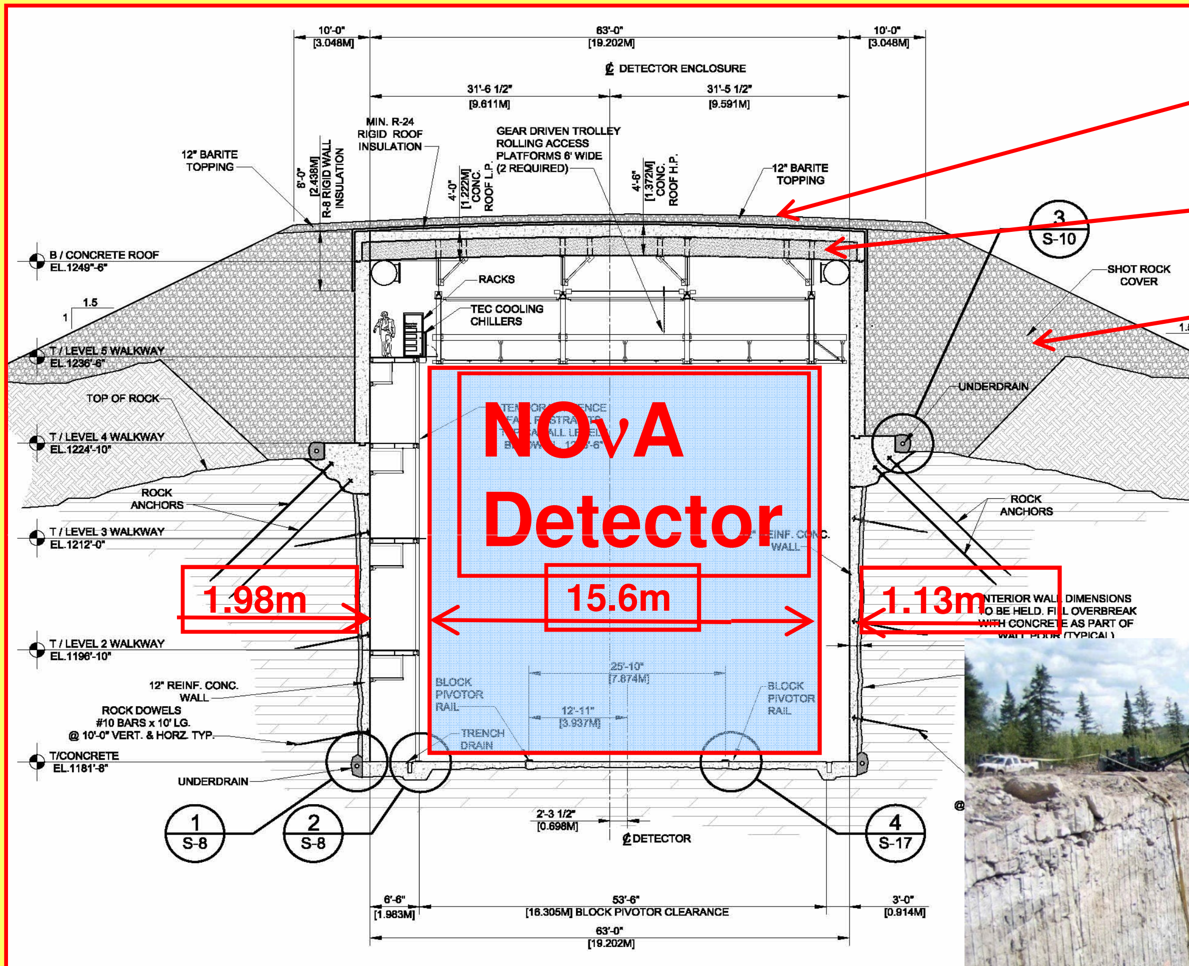
λ (nm)

Far Detector Module Construction





Far Site & Building



Barite ($BaSO_4$)

Concrete planks

Excavated granite

Near Detector

ND: 6 blocks + “μ-catcher”

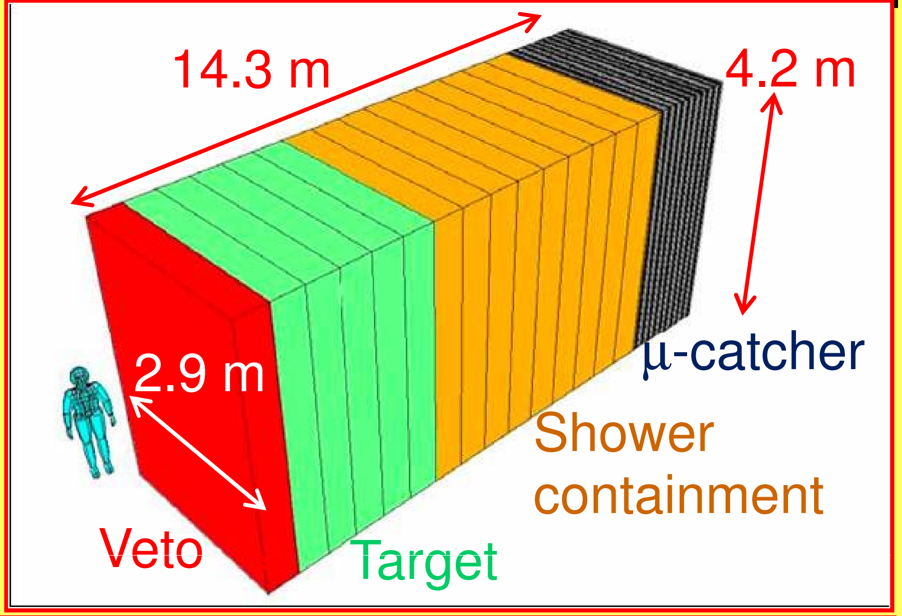
- Position @ surface (2010)
- θ_beam = 100 mrad

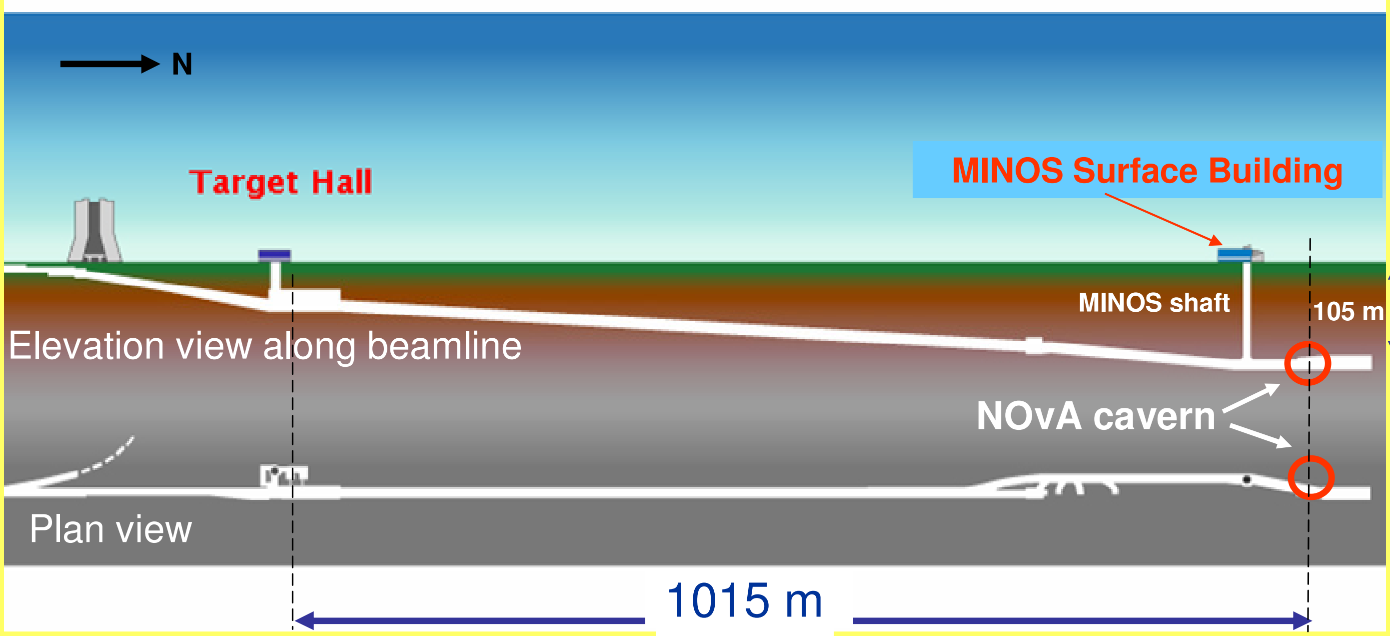
Surface → MINOS tunnel

- θ_beam = 14.6 mrad

ND mass(es)

- 222 T
- 125 T active
- 23 T fiducial



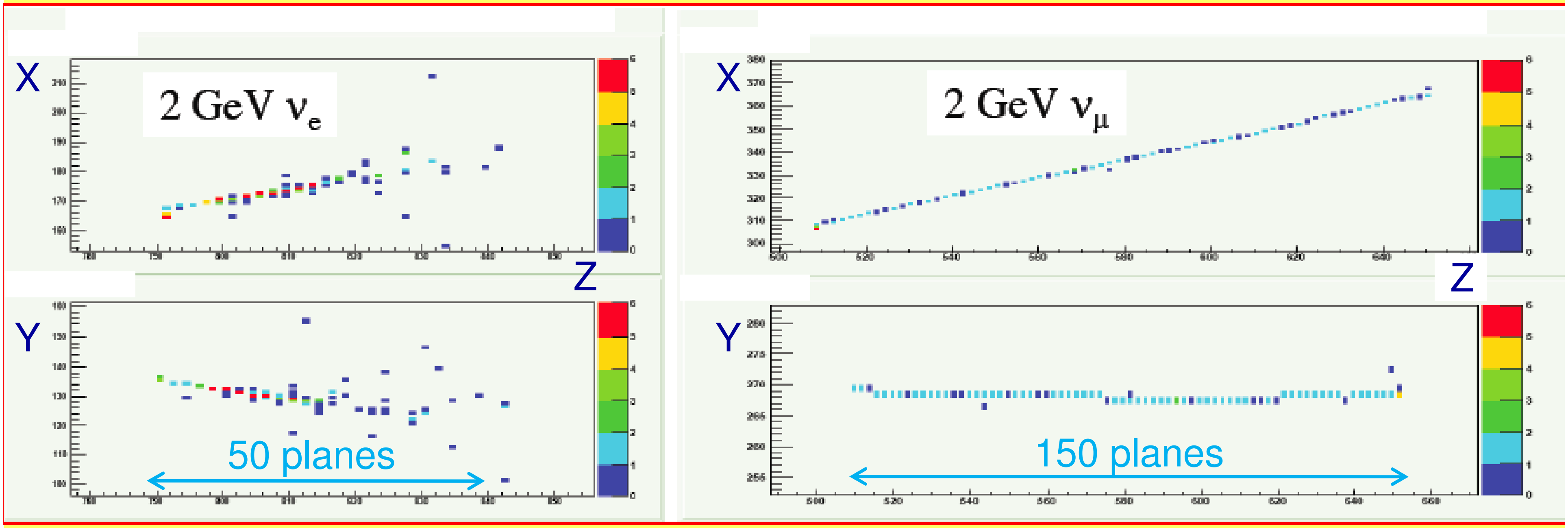


TE Coan/SMU

Expected *e* v. μ Signature

Fine sampling (~ 0.2 X_0/plane): excellent e/μ separation

Monte Carlo



ν_e CC event

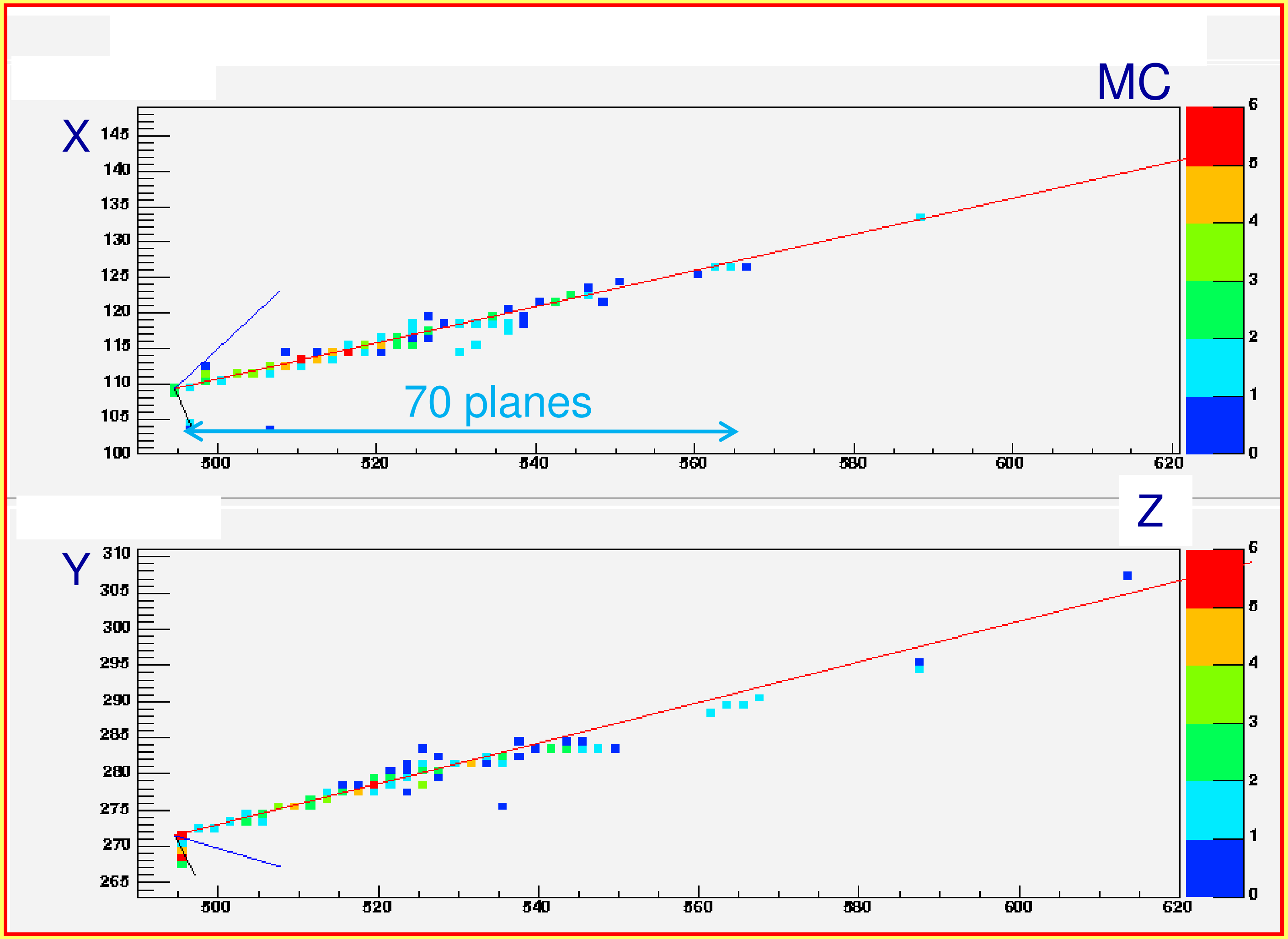
$\nu_e\, p \rightarrow e^-\, p\, \pi^+$

E_ν=2.5 GeV

E_e=1.9 GeV

E_p=1.1 GeV

E_π=0.2 GeV



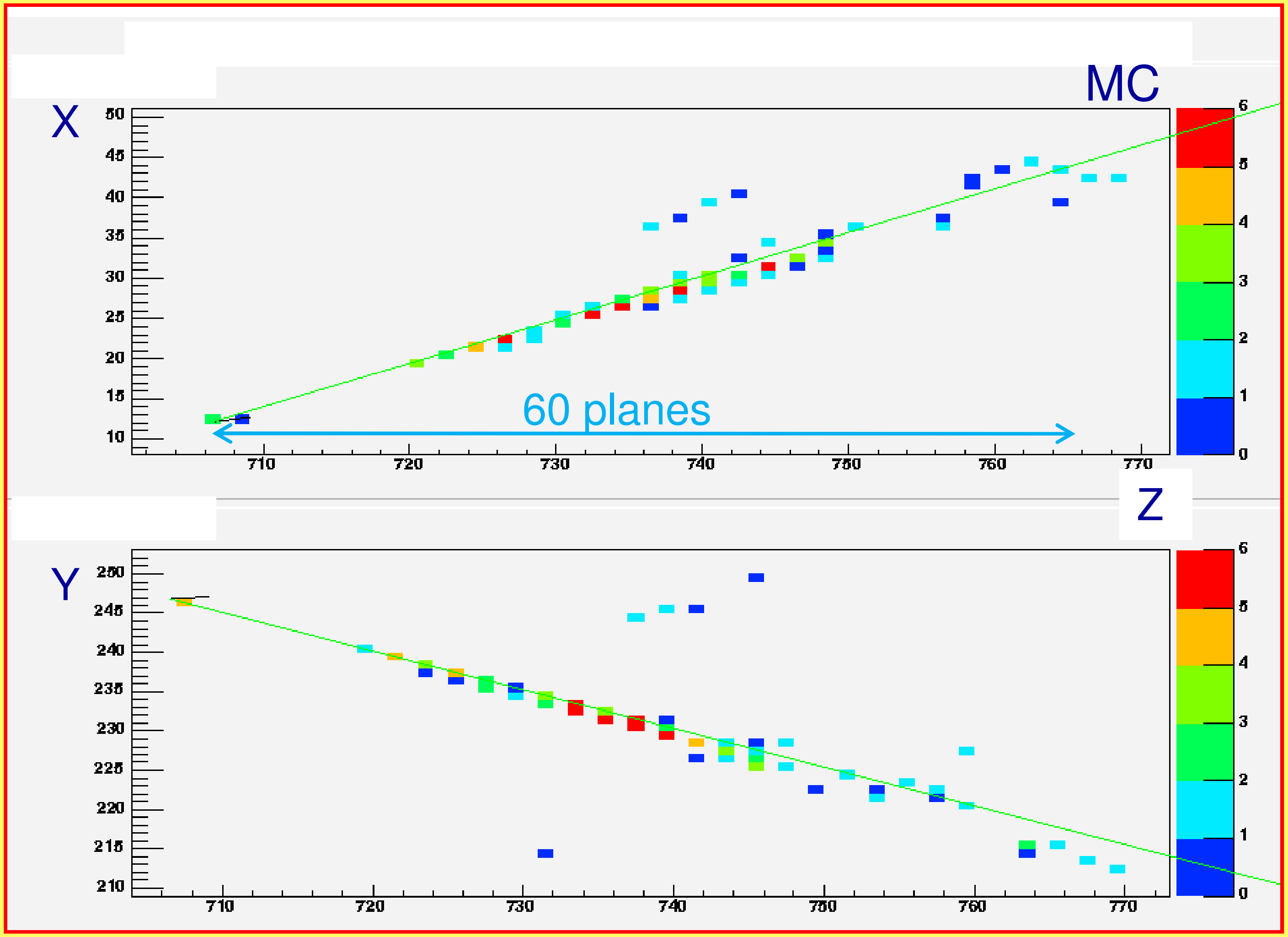
Background ν_μ NC Event

$\nu_\mu N \rightarrow \nu_\mu p \pi^o$

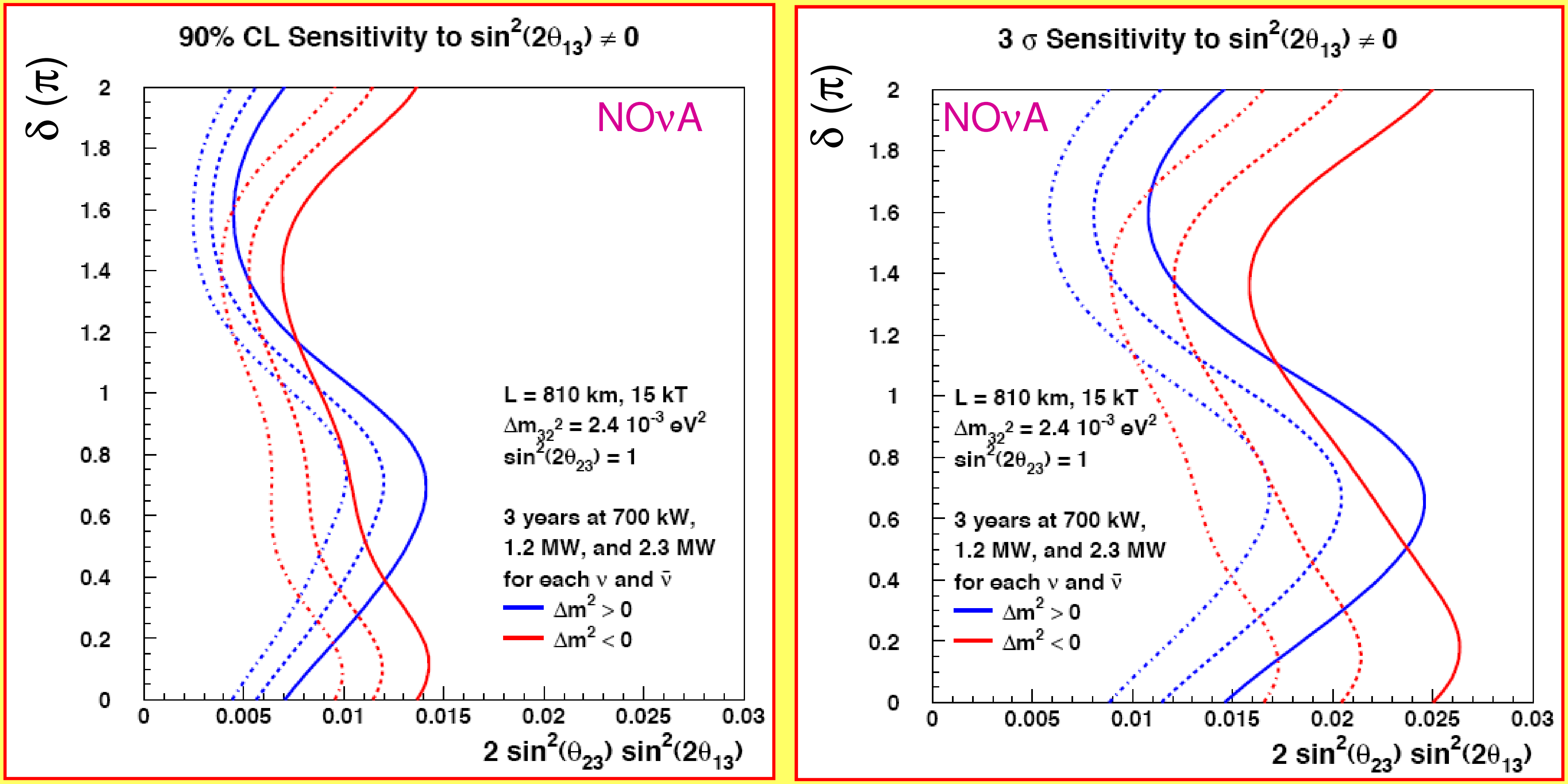
$E_\nu = 10.6$ GeV

$E_p = 1.04$ GeV

$E_{\pi o} = 1.97$ GeV



Sensitivity to $\sin^2(2\theta_{13}) \neq 0$



Mass Ordering Discrimination

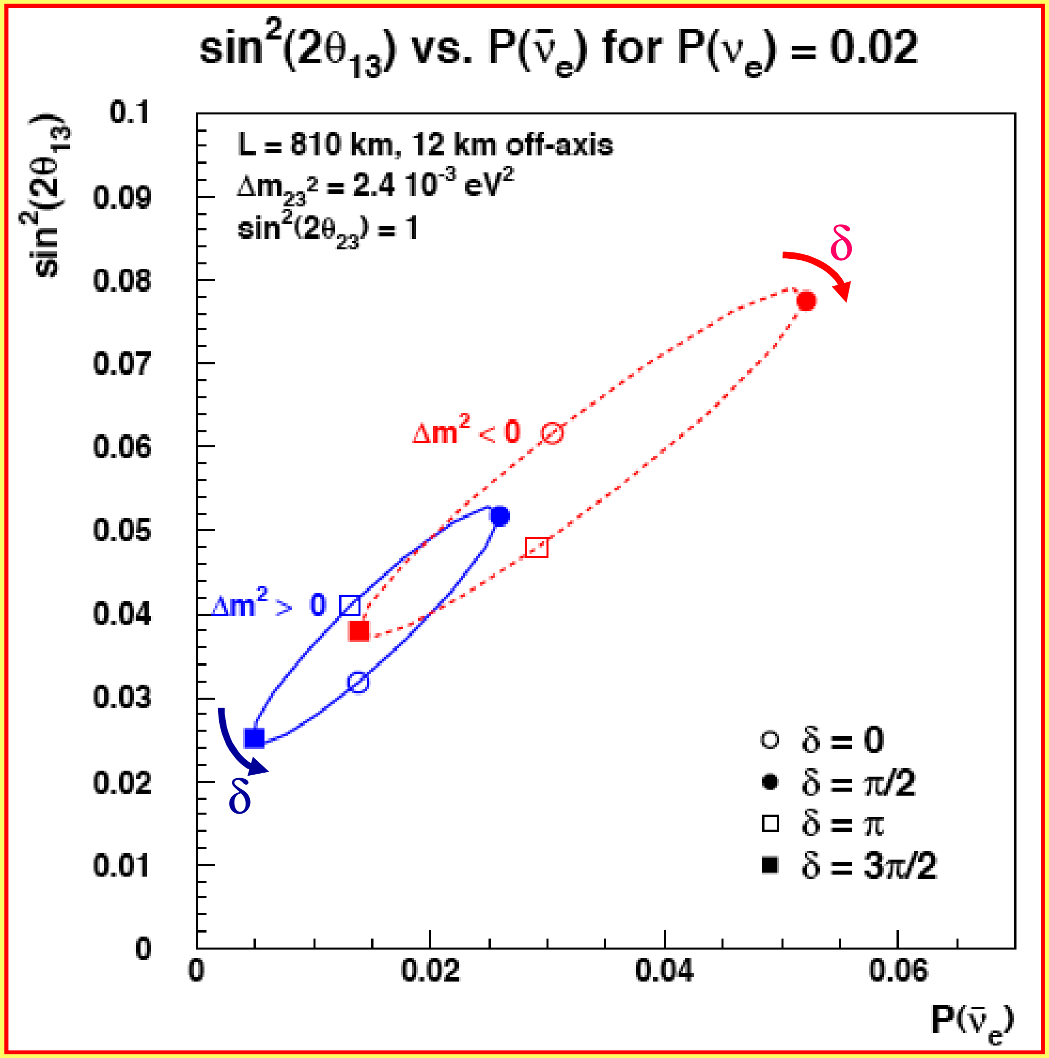
Matter effects v. CPV from δ

In general, sign (Δm^2) req'd for δ m'ment.

But, Nature may be kind…
e.g., assume $P(\nu_e) = 0.02$

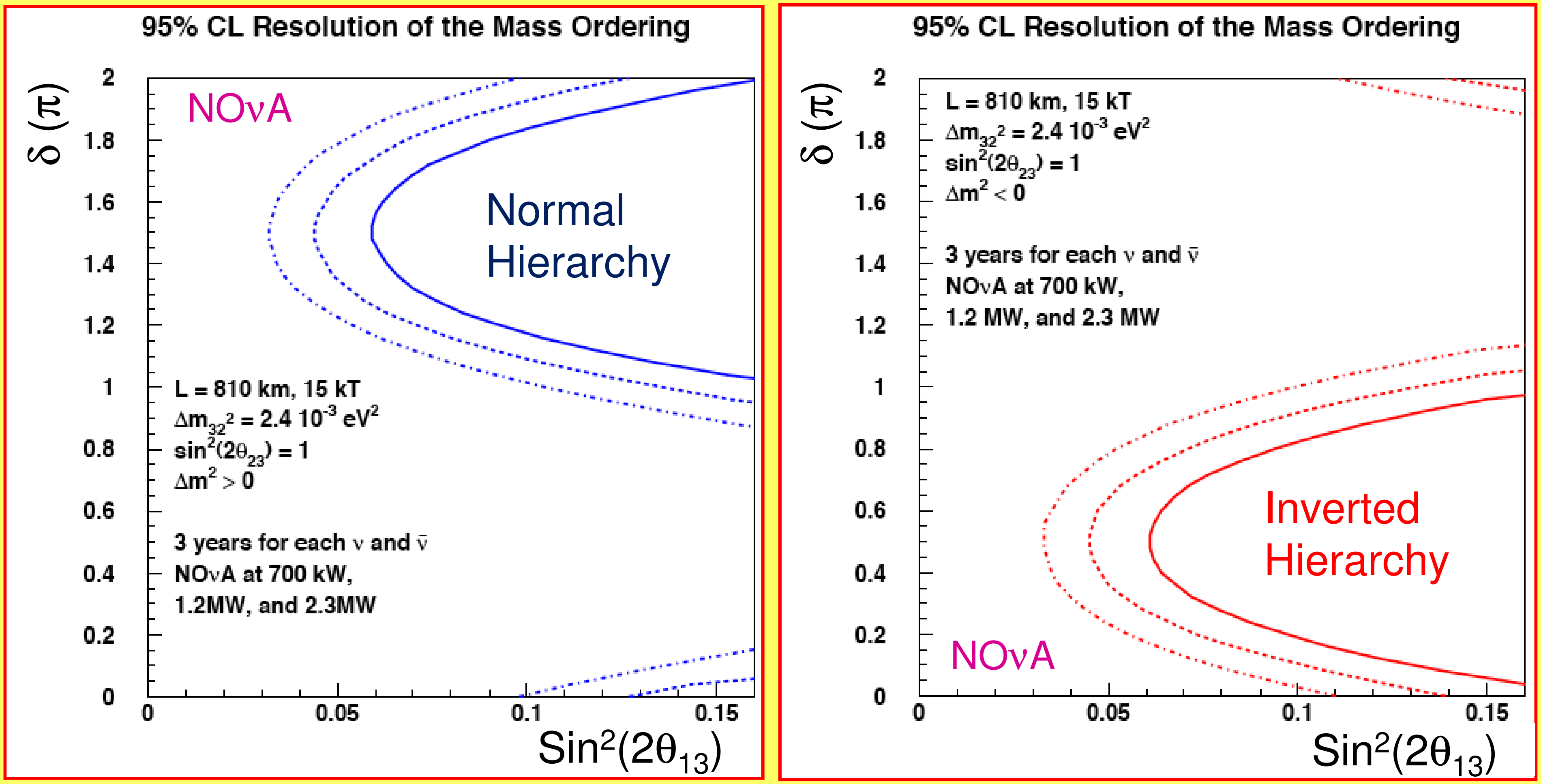
Measure $P(\overline{\nu}_e)$.
Favorable δ may exist.

Otherwise, 3rd m'ment req'd, e.g., T2K



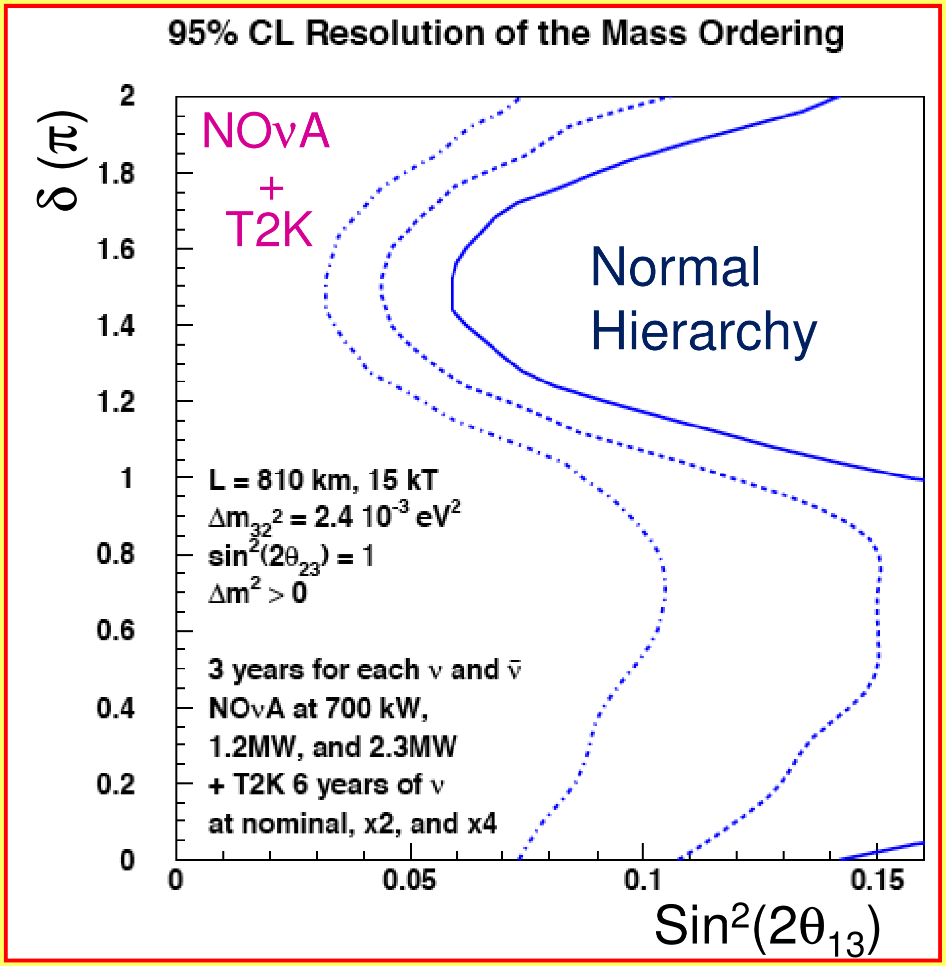
Sensitivity to Mass Ordering

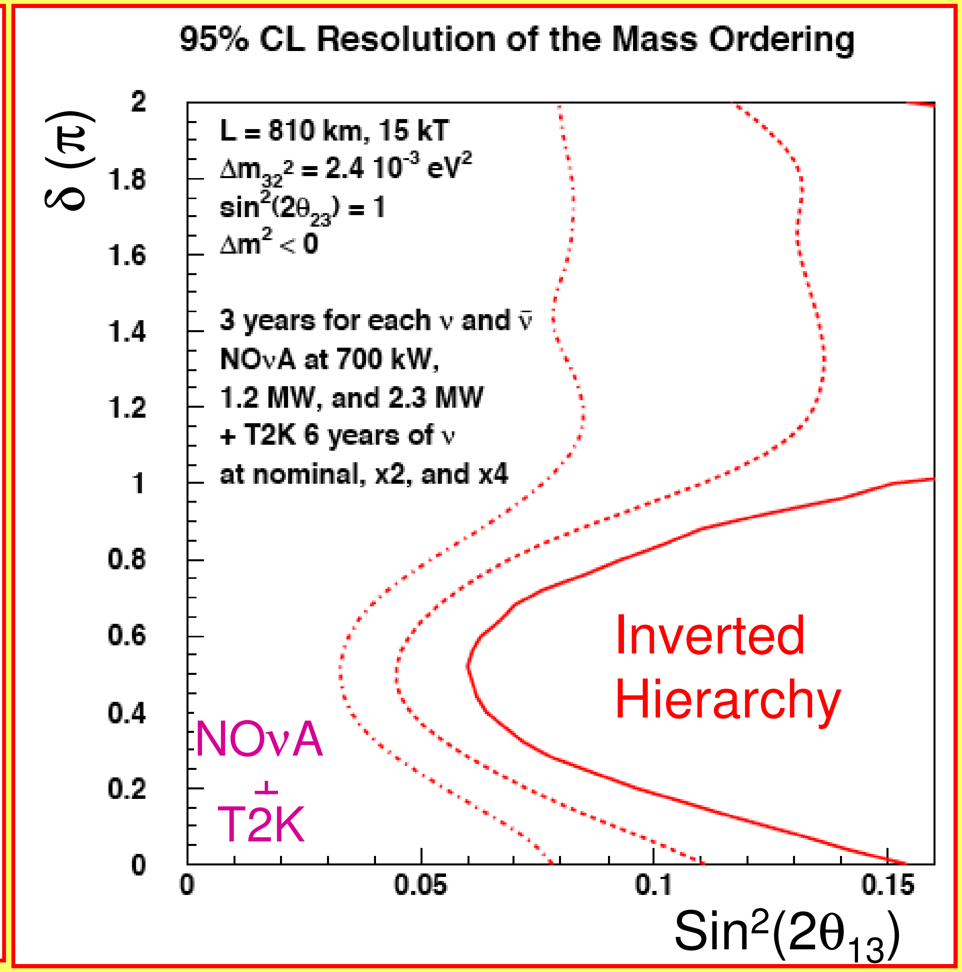
95% C.L. : NOνA alone



Sensitivity to Mass Ordering (2)

95% C.L. : NOνA + T2K





Measurement of $\sin^2(2\theta_{23})$

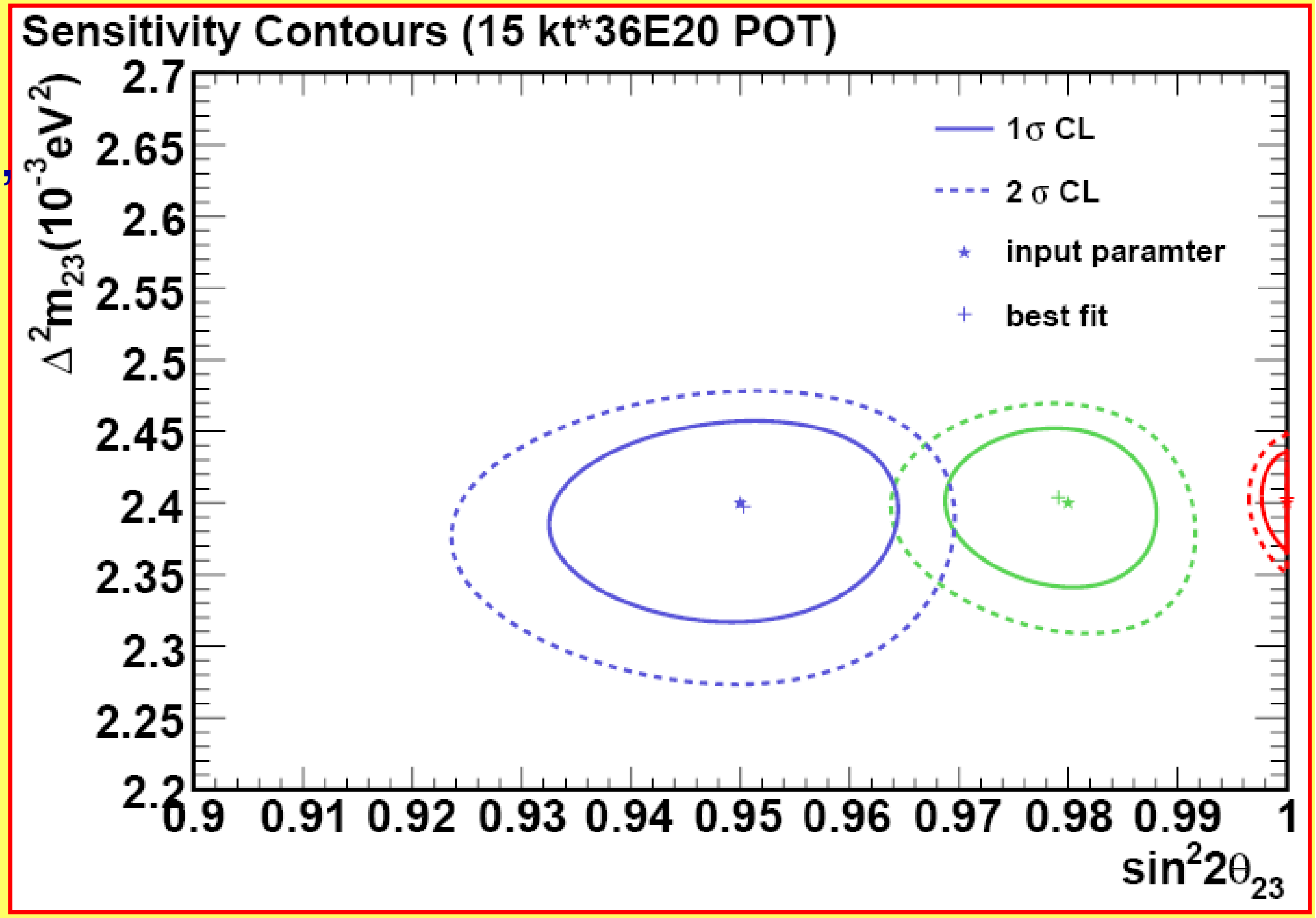
Excellent $\delta(E)$ in ν_μ CC events key, NOνA's $\delta(E)$ ~ 2%

If $\sin^2(2\theta_{23}) = 1$,

$\delta(\sin^2(2\theta_{23}))$ ~ 0.003,

Otherwise,

$\delta(\sin^2(2\theta_{23}))$ ~ 0.02,



Sensitivity to CP Phase δ

Favorable scenario:

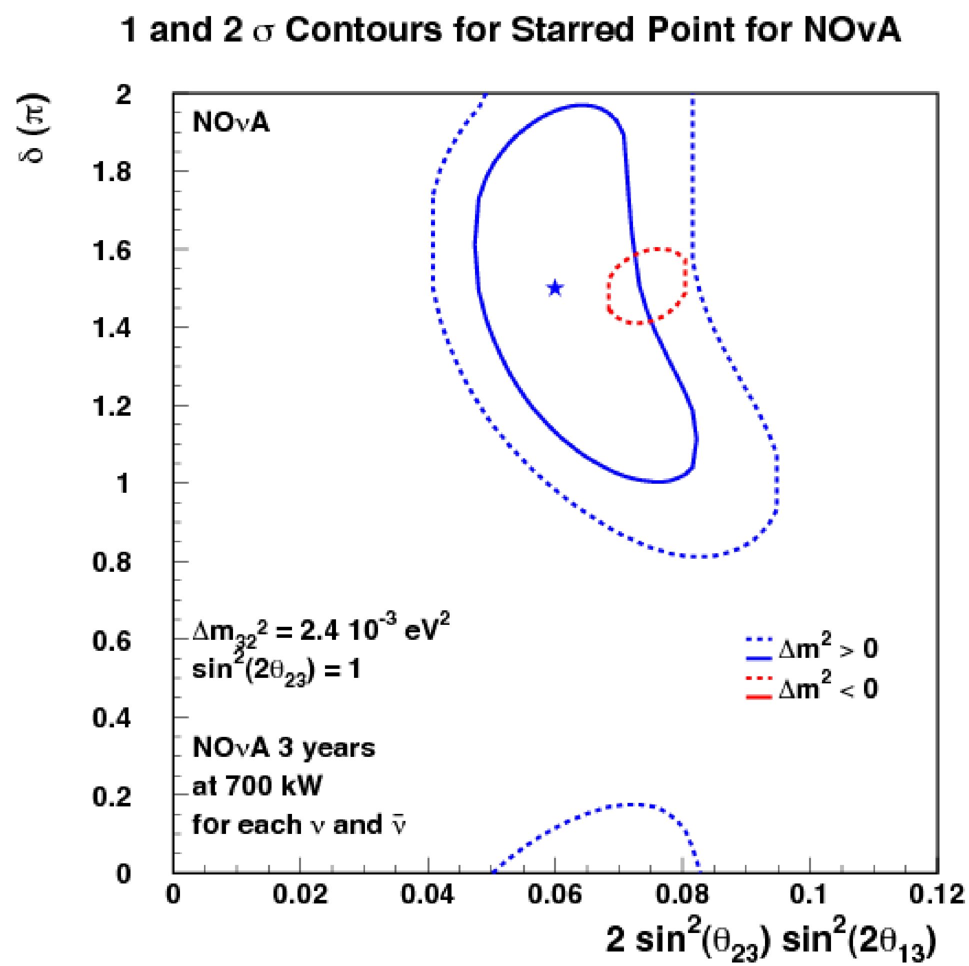
$\delta = 3\pi/2$

normal hierarchy

Oscillation at starred pt *

CP δ constrained:

$\pi \leq \delta \leq 2\pi$



Current Timeline

- Near Detector data taking mid-2010 (surface running)
- Near Detector → underground Fall 2012
- Far Detector construction 2011 - 2013
- Data taking starts Jan-2012 (partial FD)
- Full far detector operational May-2013

Summary

- NOνA is a next generation long-baseline ν experiment
- Order-of-magnitude gain in sensitivity to $\sin^2 2\theta_{13}$
- Sensitive to mass hierarchy and CP violation
- Yield highly precise Δm^2_{23} & $\sin^2 2\theta_{23}$
- Far detector site construction started
- Far detector complete & operational in 2013
- Near detector data taking mid-2010