Status of the NOνA Experiment

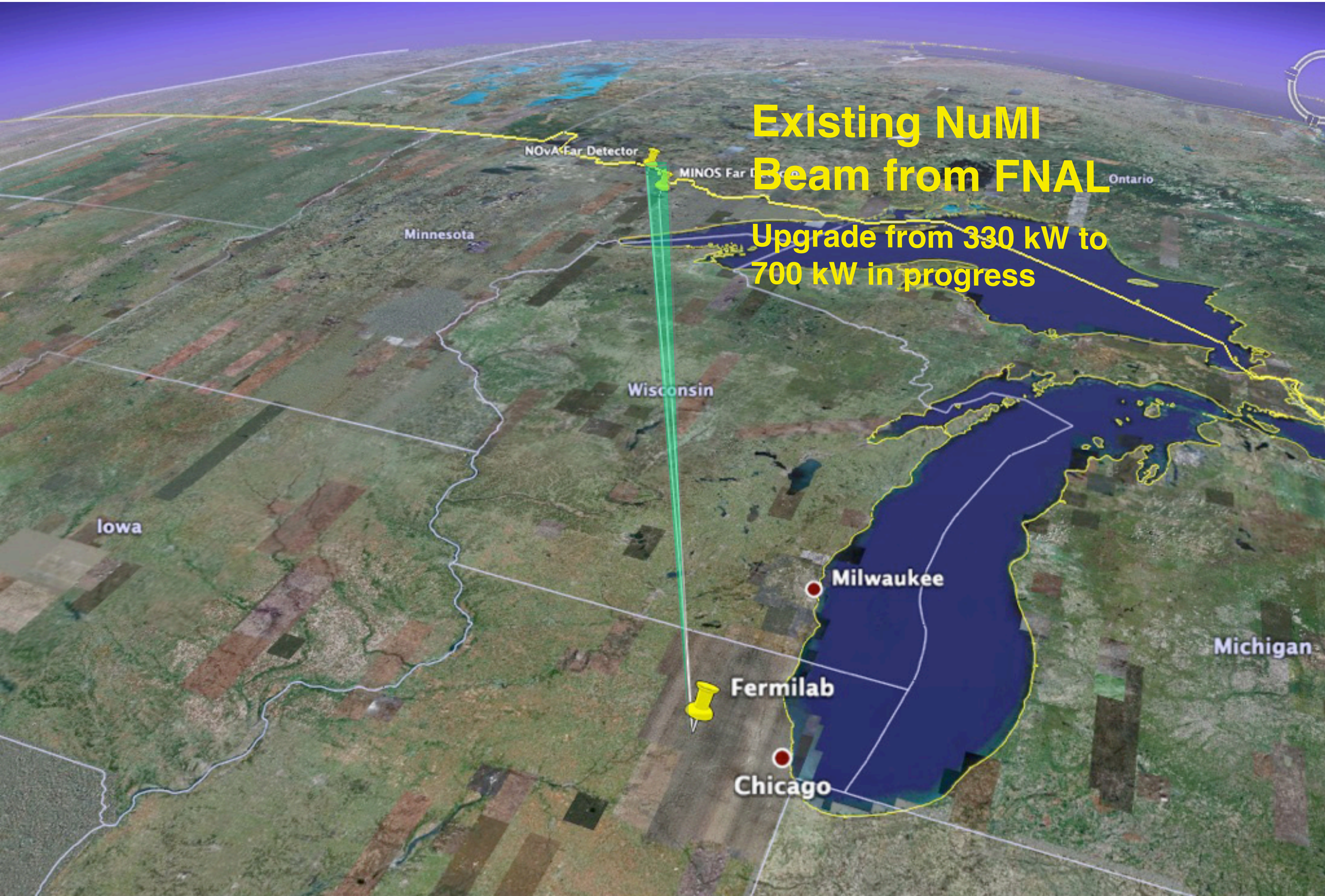
Jonathan M Paley
Argonne National Laboratory

NuFact 2013
Beijing, China
August 20, 2013

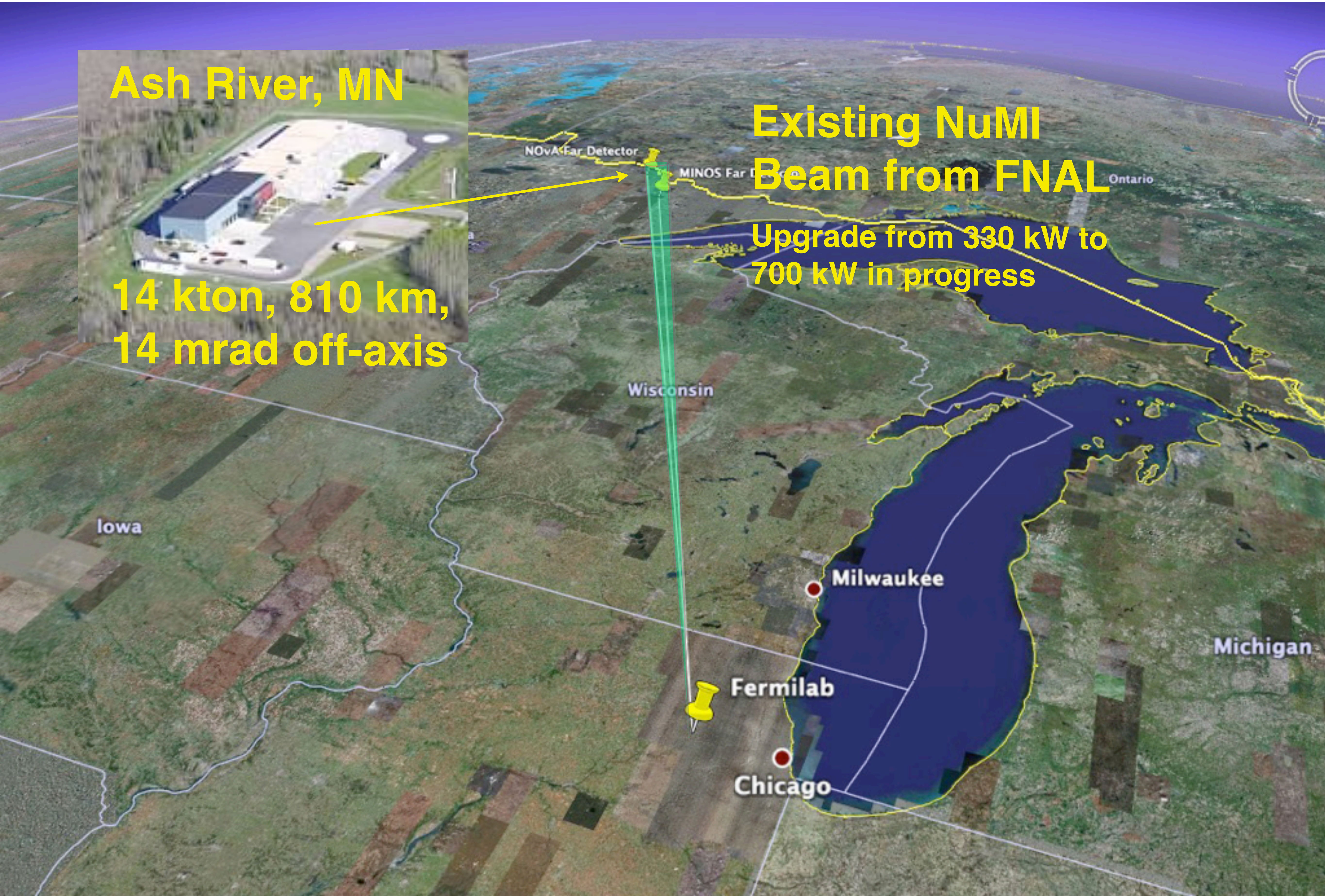
The NuMI Off-Axis ν_e Appearance (NOνA) Experiment

A growing collaboration of over 180 scientists and engineers from 36 institutions and 7 countries.

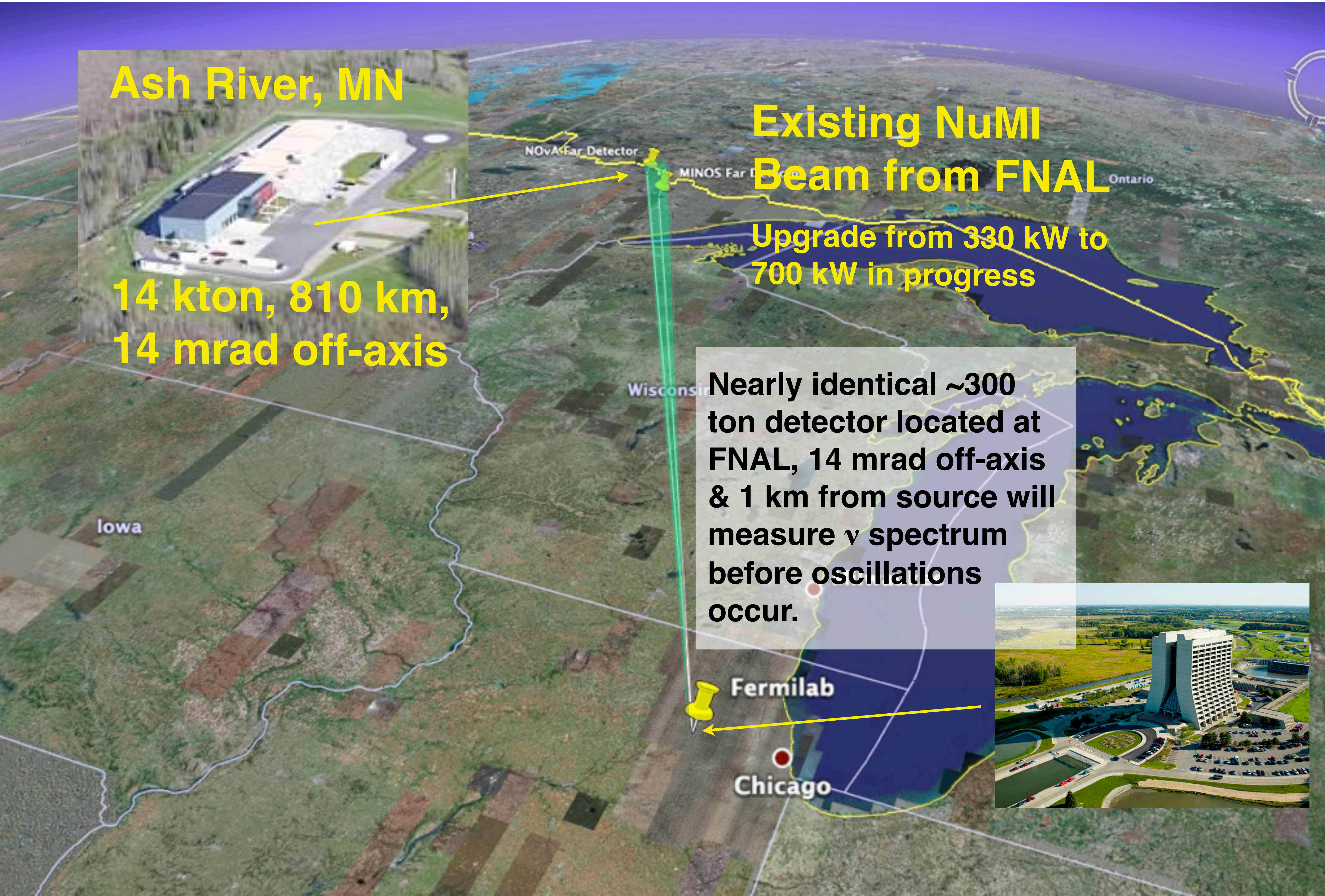
The NuMI Off-Axis ν_e Appearance (NOνA) Experiment



The NuMI Off-Axis ν_e Appearance (NOνA) Experiment



The NuMI Off-Axis ν_e Appearance (NOνA) Experiment



Ash River, MN

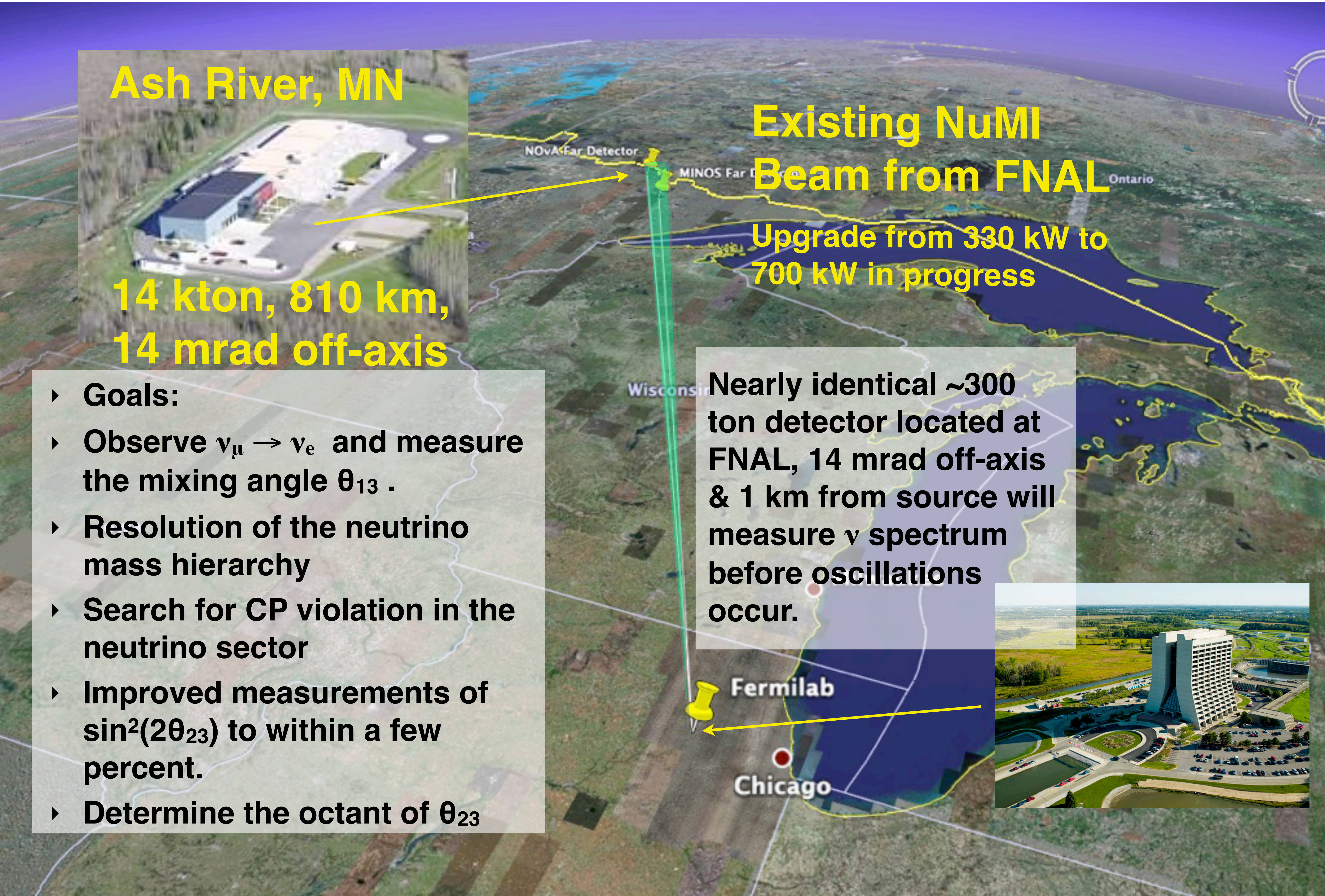
14 kton, 810 km, 14 mrad off-axis

Existing NuMI Beam from FNAL

Upgrade from 330 kW to 700 kW in progress

Nearly identical ~300 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

The NuMI Off-Axis ν_e Appearance (NOνA) Experiment



Ash River, MN

14 kton, 810 km, 14 mrad off-axis

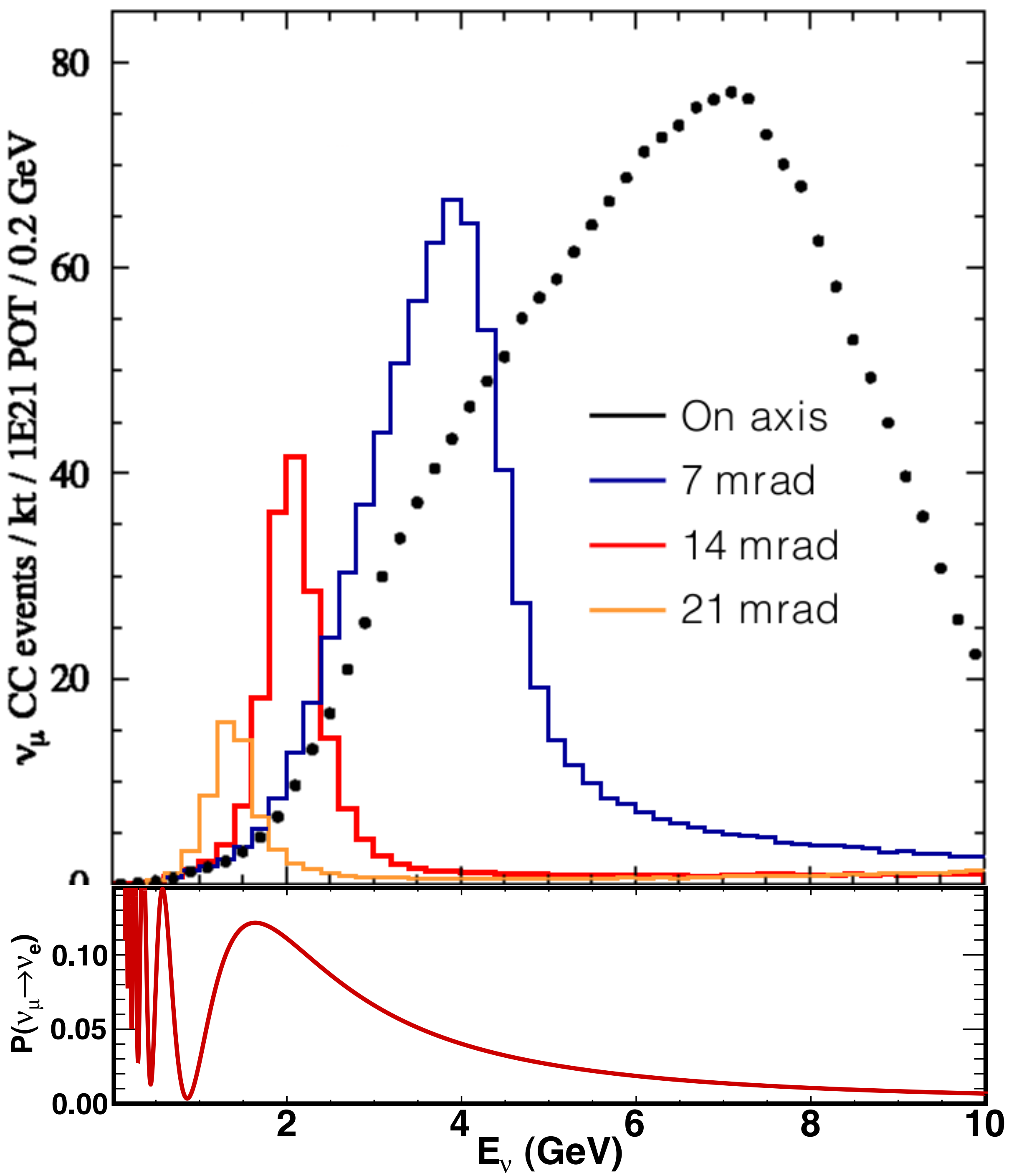
Existing NuMI Beam from FNAL

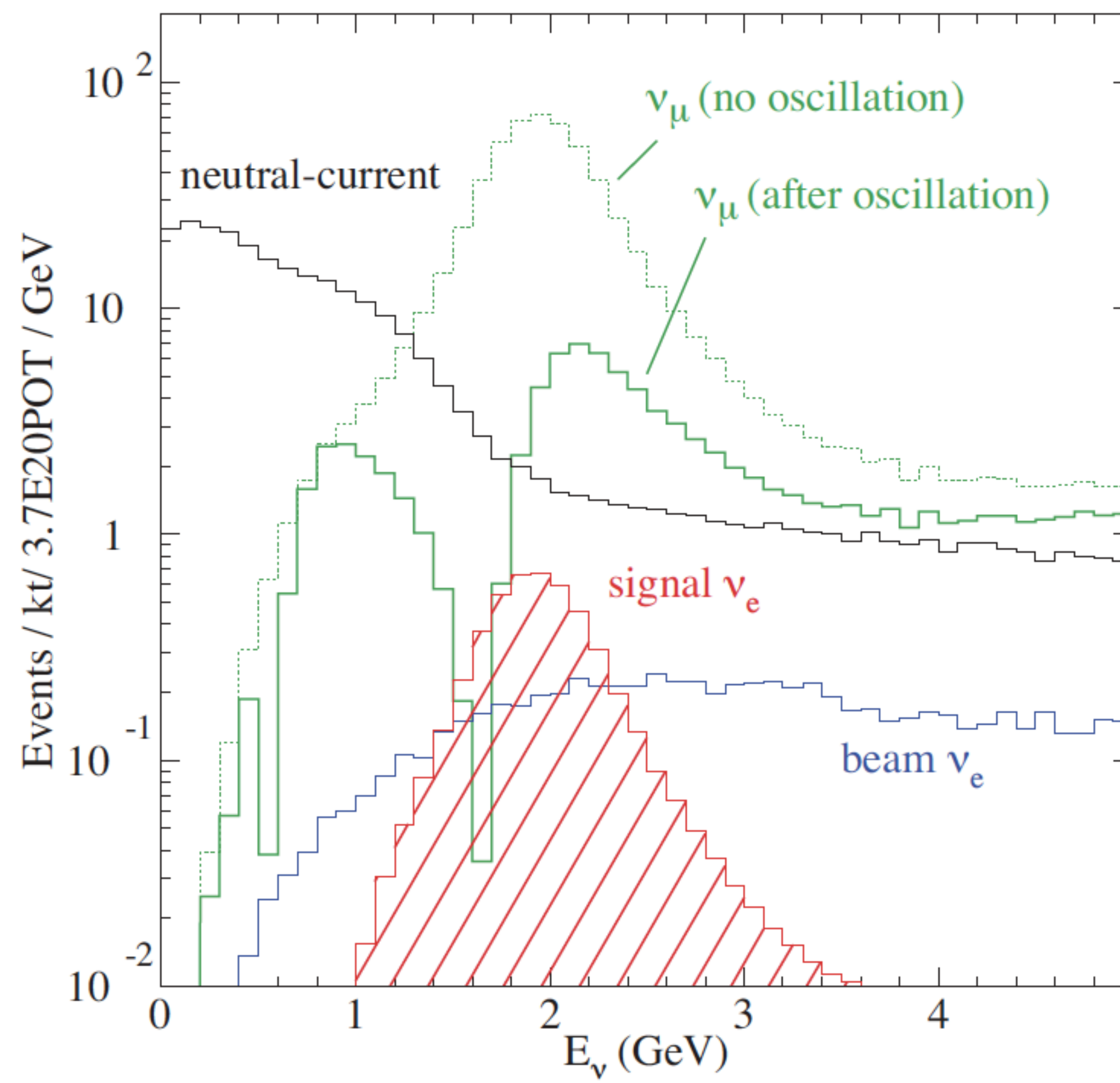
Upgrade from 330 kW to 700 kW in progress

- **Goals:**
- **Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13} .**
- **Resolution of the neutrino mass hierarchy**
- **Search for CP violation in the neutrino sector**
- **Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.**
- **Determine the octant of θ_{23}**

Nearly identical ~300 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

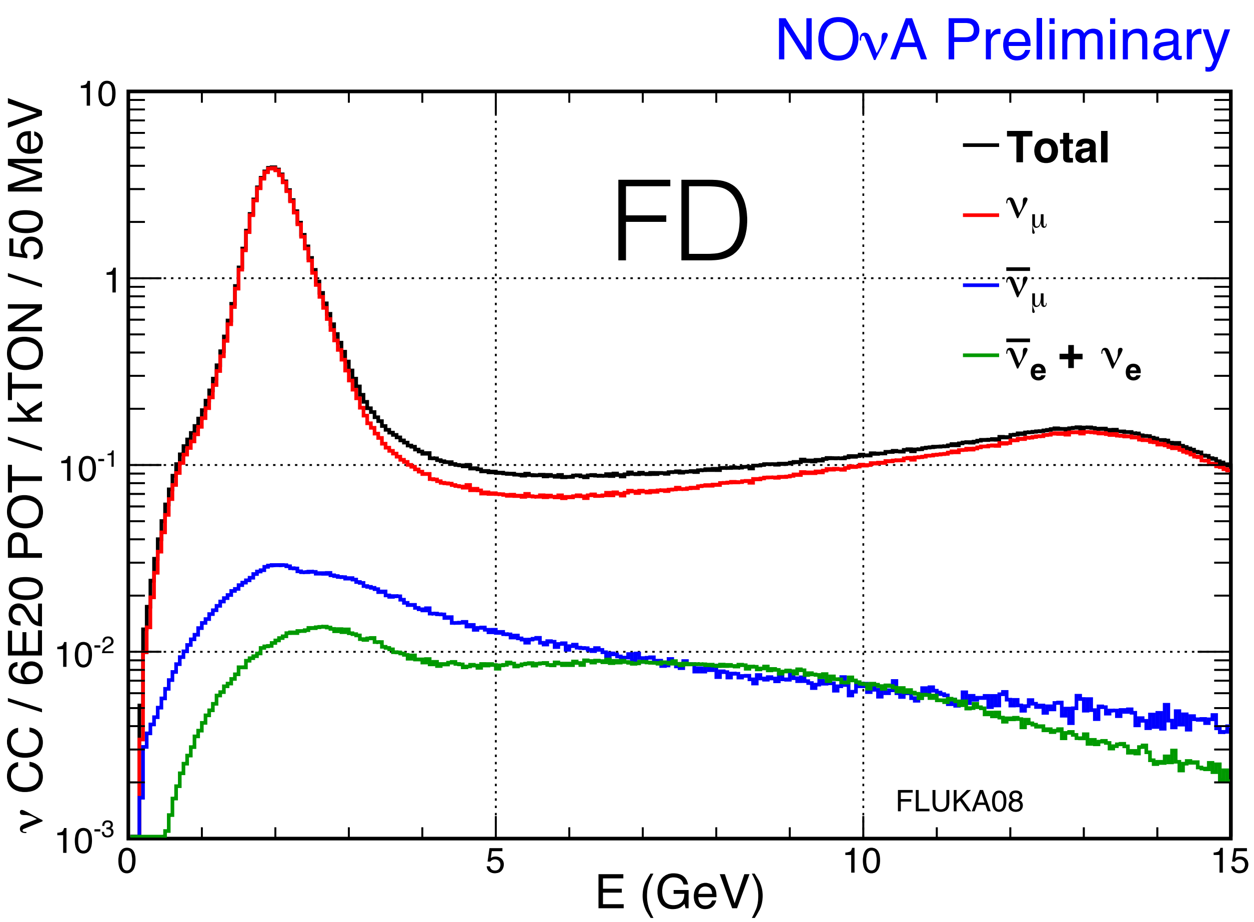
Why Go Off-Axis?

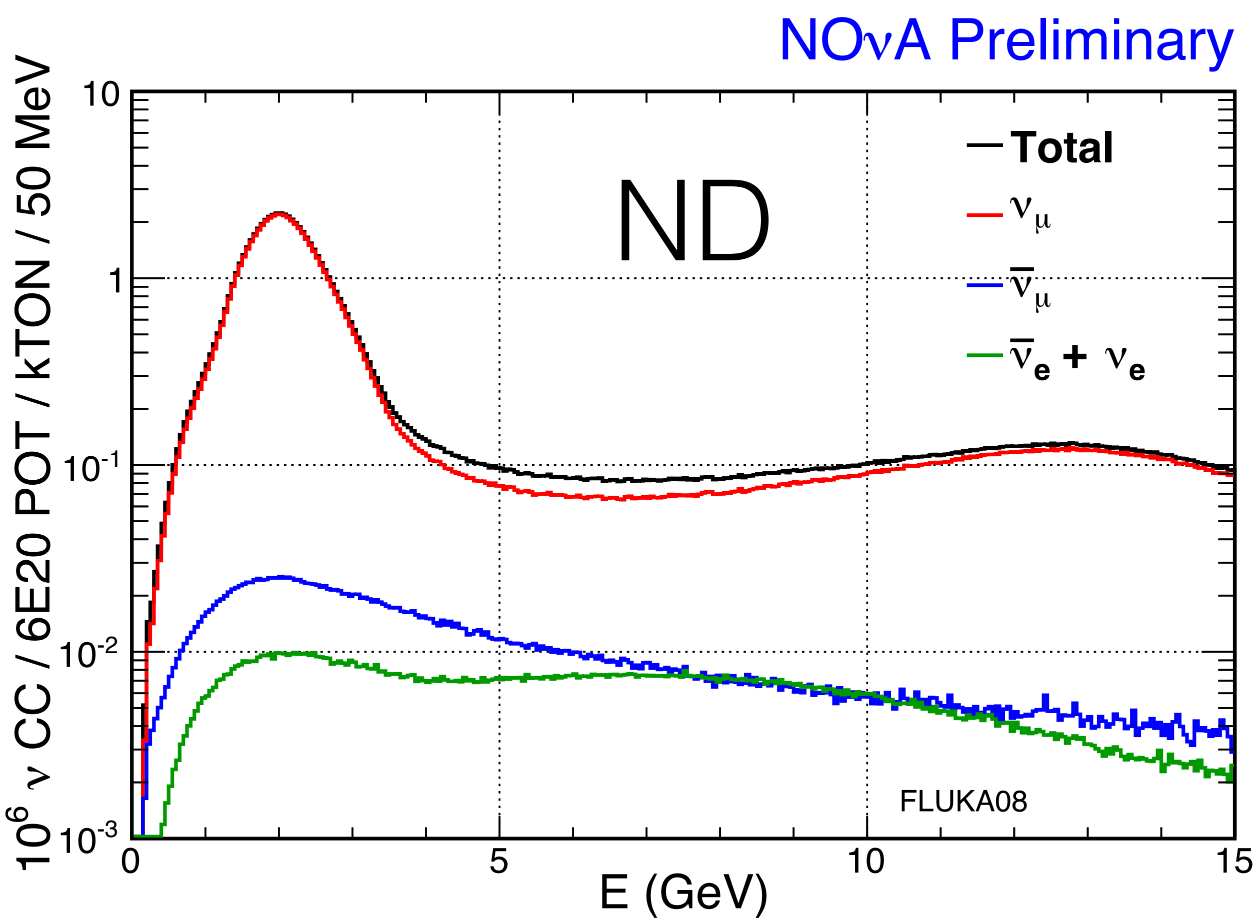




- Narrow-band beam, in conjunction with topology of final state particles, allows one to more easily reject potential backgrounds.

Forward Horn Current Mode





	[1,3]GeV	[0,120]Gev
Total	63.5	103.8
Numu	62.1	97.6
Anti-Numu	1.0	3.9
Nue+Anti-Nue	0.4	2.3

$[1,3]$GeV: $\bar{\nu}_\mu / \nu_\mu = 1.6\%$

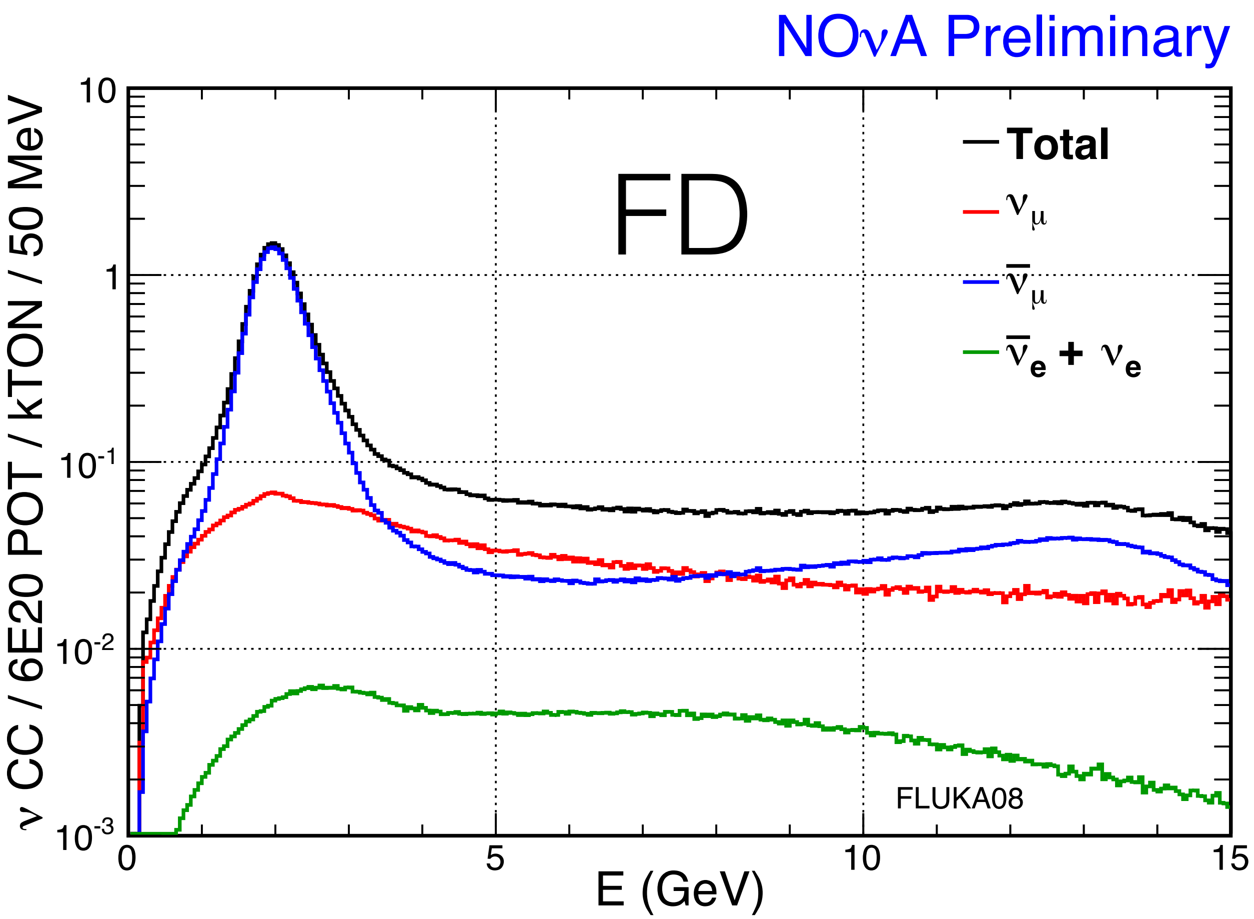
$[1,3]$GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.6\%$

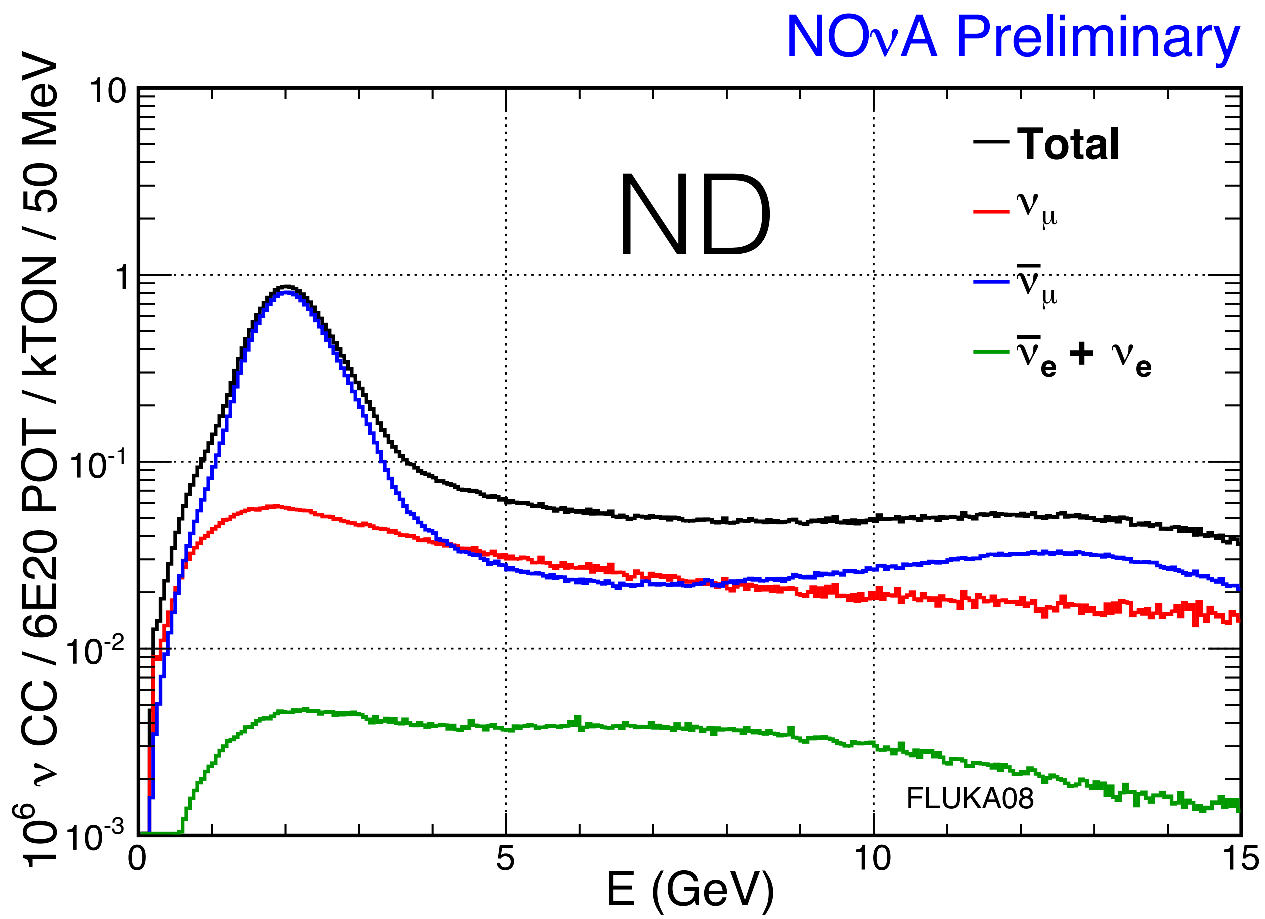
x10⁶	[1,3]GeV	[0,120]Gev
Total	53.9	95.0
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2.0

$[1,3]$GeV: $\bar{\nu}_\mu / \nu_\mu = 1.7\%$

$[1,3]$GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu = 0.7\%$

Reverse Horn Current Mode





	[1,3]GeV	[0,120]Gev
Total	25.1	46.7
Numu	2.4	13.2
Anti-Numu	22.5	32.2
Nue+Anti-Nue	0.2	1.3

[1,3]GeV: $\nu_\mu / \bar{\nu}_\mu$ = 10.7%

[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 0.8%

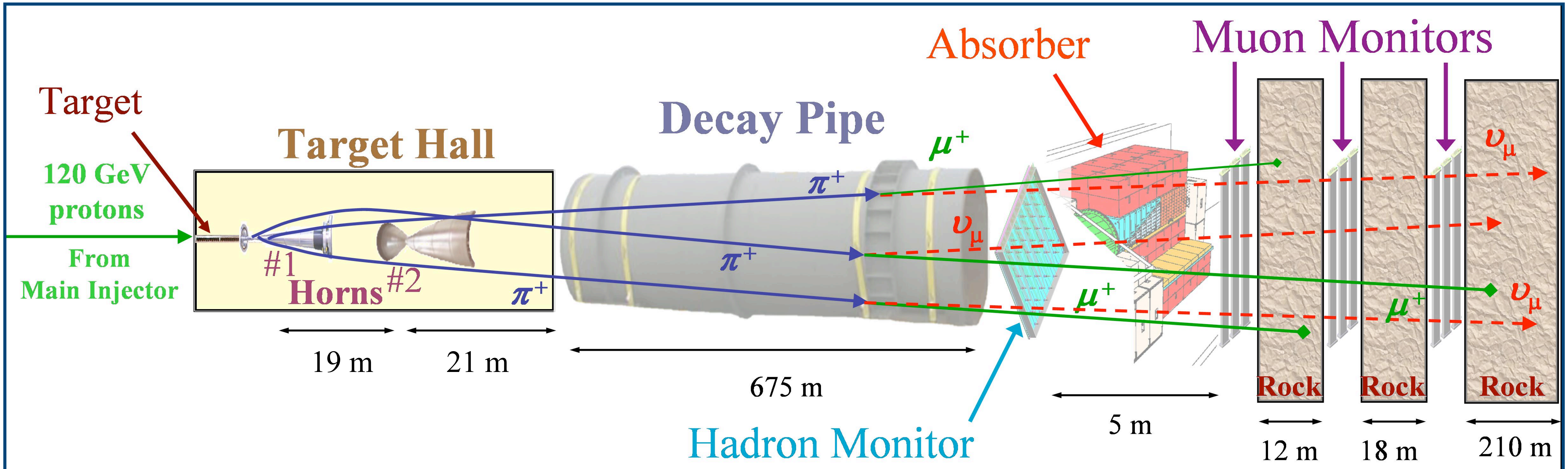
x10^6	[1,3]GeV	[0,120]Gev
Total	21.4	42.3
Numu	2.1	11.9
Anti-Numu	19.1	29.3
Nue+Anti-Nue	0.2	1.1

[1,3]GeV: $\nu_\mu / \bar{\nu}_\mu$ = 11.0%

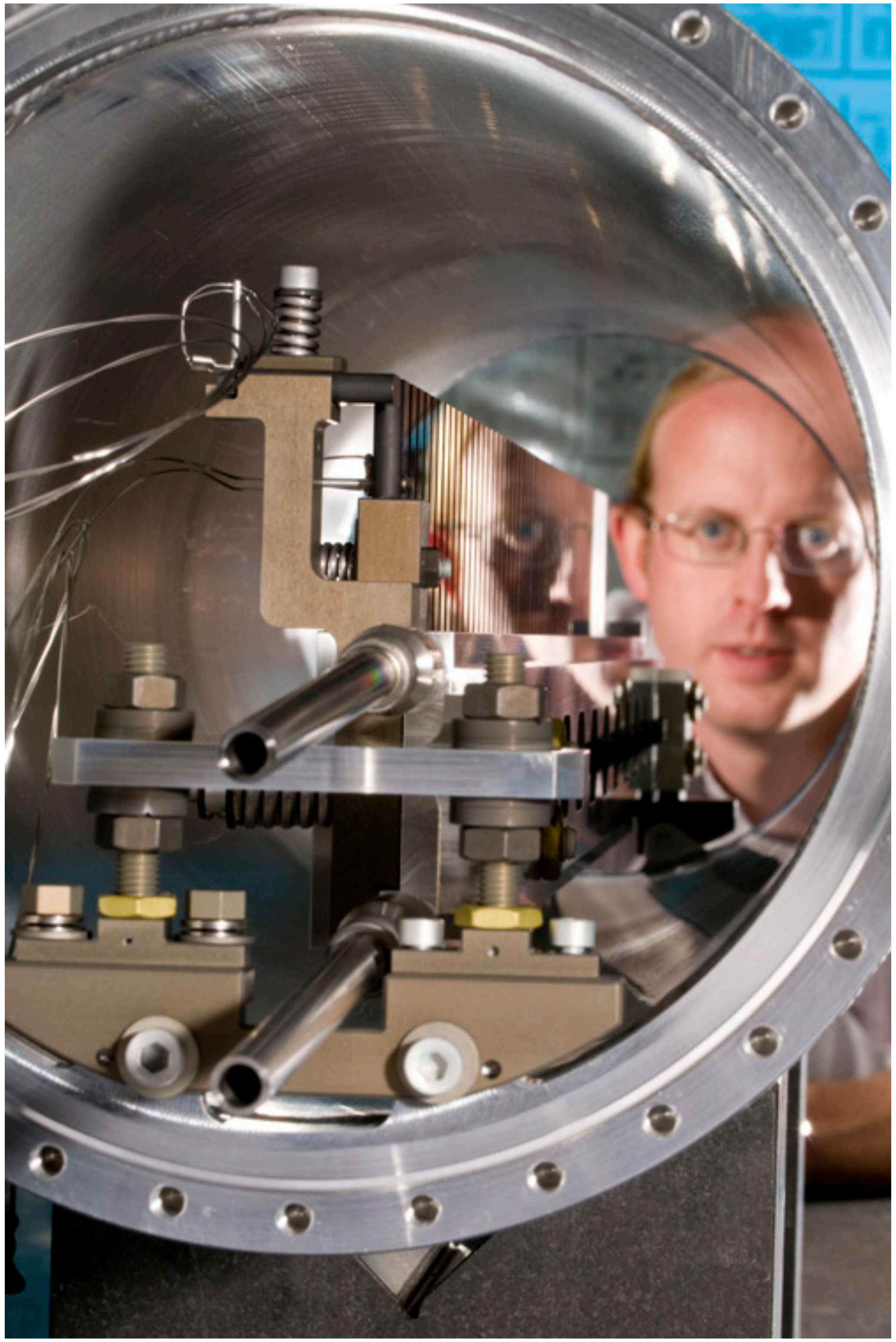
[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 1.0%

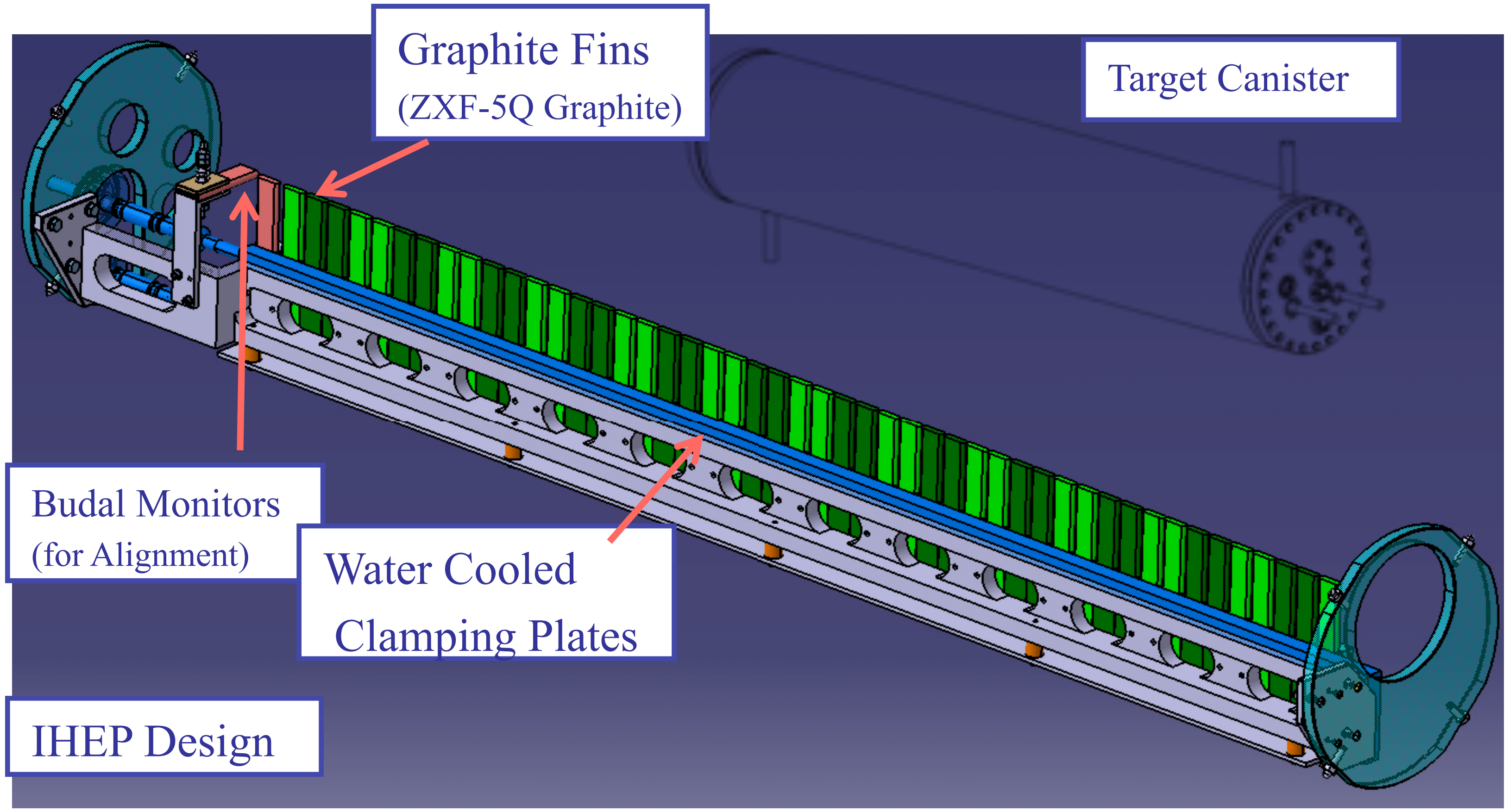
Accelerator Upgrades for NOνA

- Require upgrades to Fermilab's accelerator complex to go from 330 kW to 700 kW
- Mostly achieved by:
  - Use Recycler for "slip stacking" protons (instead of storing p-bars)
  - Reduce cycle time in the Main Injector from 2.2 s to 1.33 s
  - Upgrades to target station to handle the increased power and provide the desired neutrino energy beam



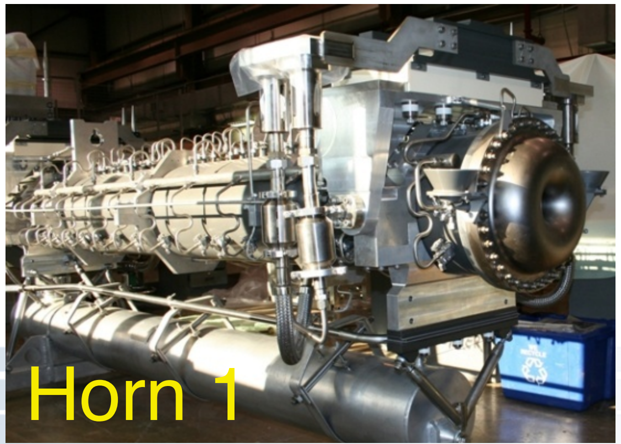
NuMI Target and Horns for the NOνA Era



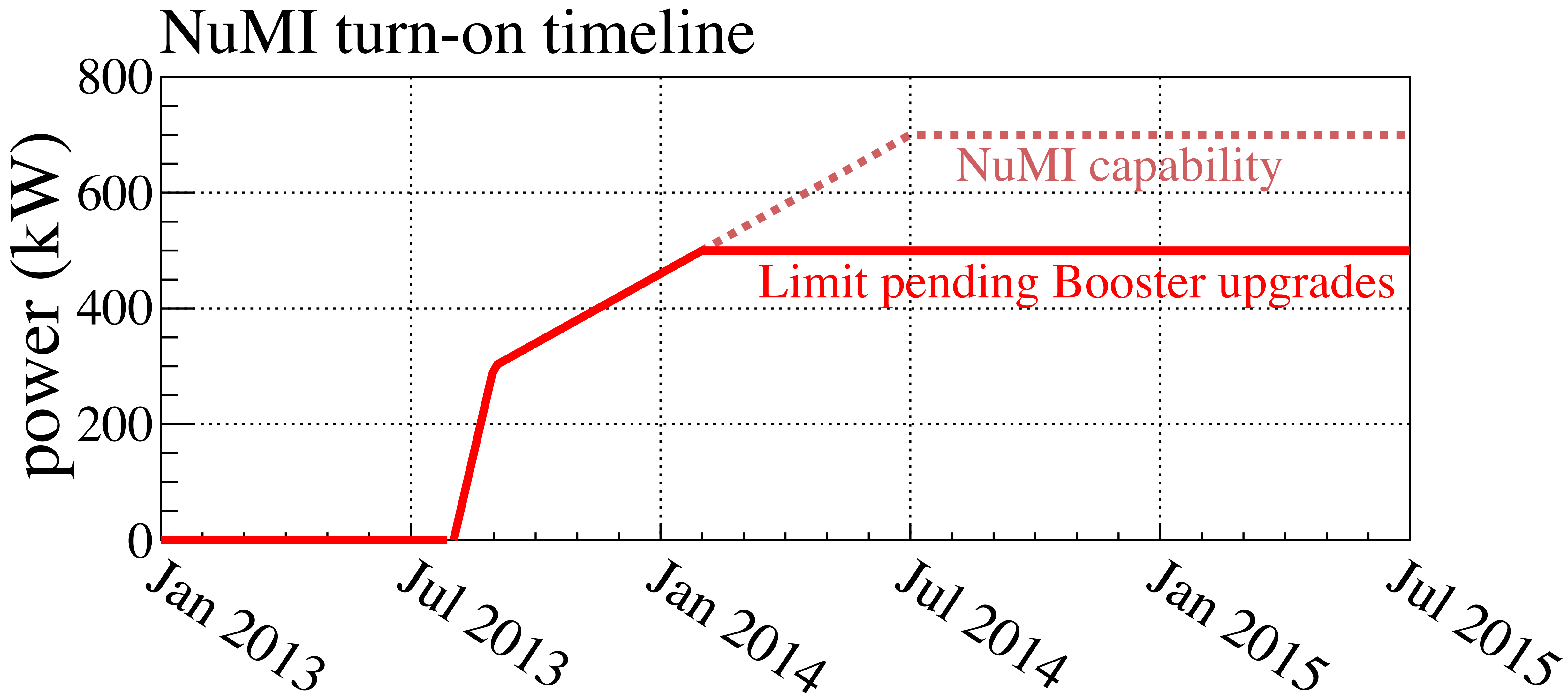


NuMI Medium Energy Target

- Simplified target for medium energy running since target does not need to fit inside of horn.
- Horn 2 moved ~9m downstream.

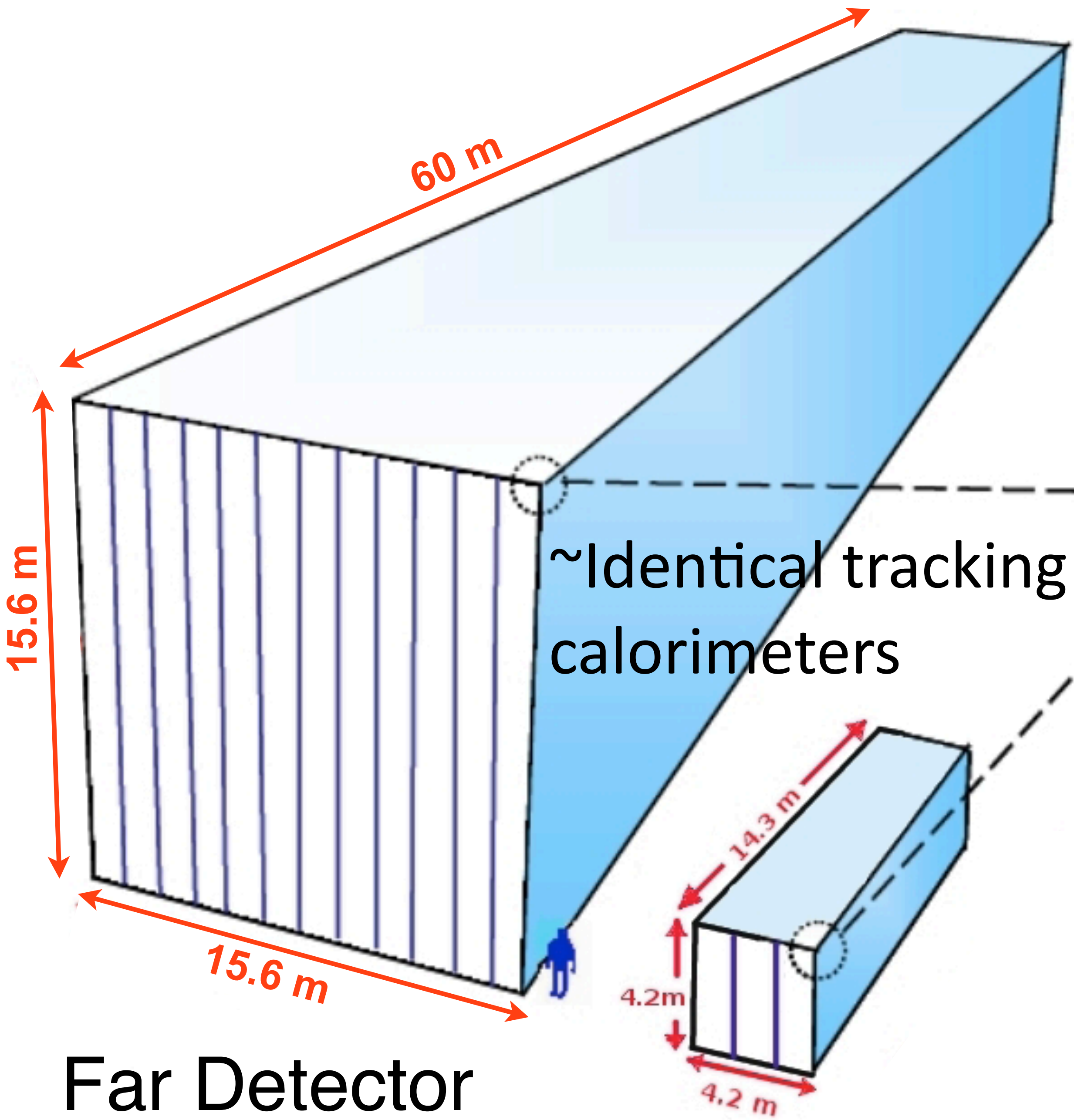


Return of NuMI Beam



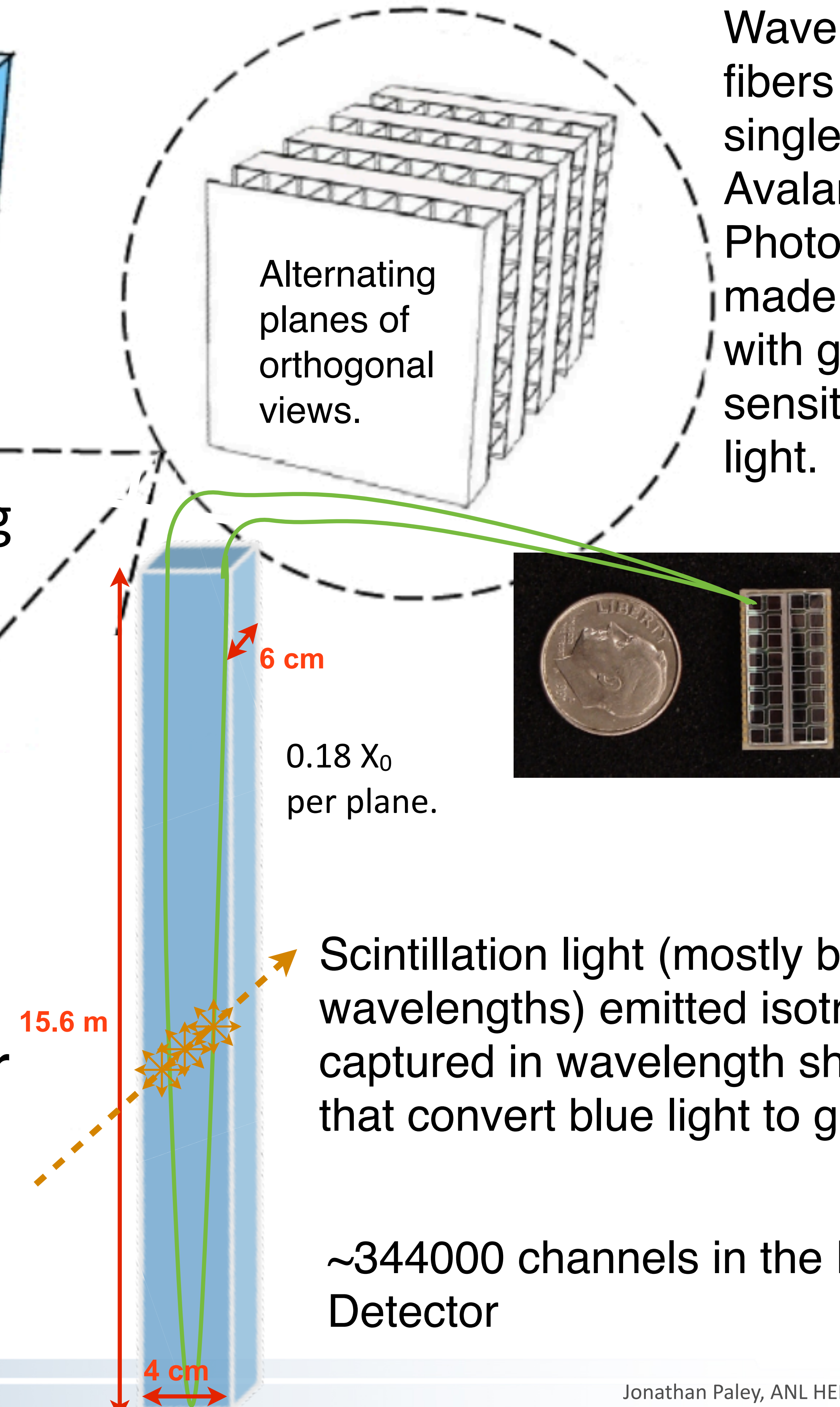
- Commissioning of the NuMI beam has begun and will continue through end of the year
  - beam to target hall achieved Aug. 5
  - horn and target scans with beam should happen any day now
- 330 kW (pre-shutdown capability) → 500 kW achieved by use of recycler and reduction of cycle time in MI.
- Limited in short-term to ~500 kW until Booster RF system upgrades are complete.

The NOνA Detectors



Far Detector

Near Detector



Wavelength-shifting fibers routed to a single cell on an Avalanche Photodiode (APD) made of materials with greatest sensitivity to green light.

Scintillation light (mostly blue wavelengths) emitted isotropically and captured in wavelength shifting fibers that convert blue light to green.

~344000 channels in the NOvA Far Detector

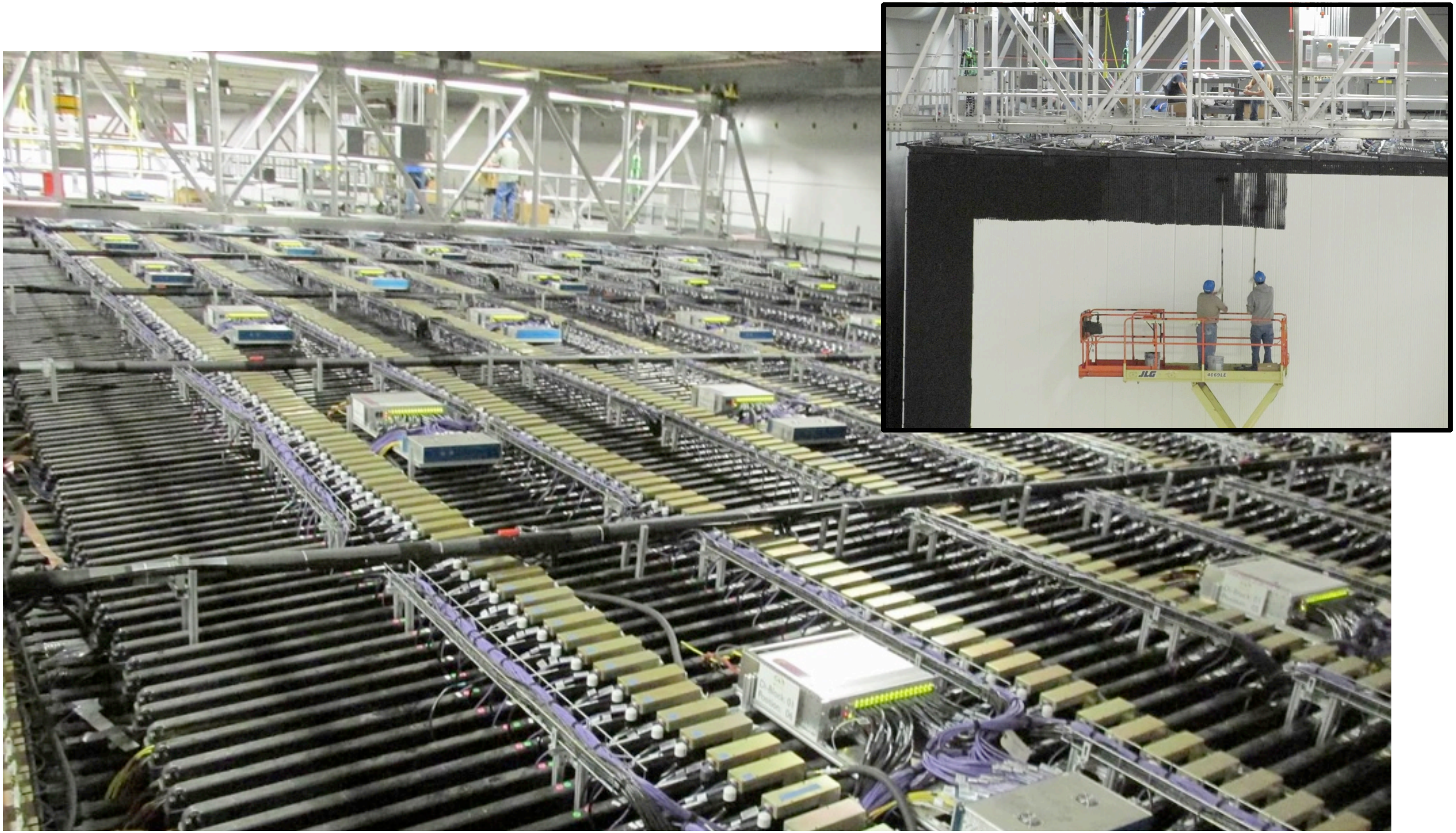
Tracking calorimeter:

- ~63% active
- muon energy resolution (range): few %
- Moliere radius is ~2.5 cell widths
- EM shower max at ~5 X_0

NOνA Far Detector Construction Progress

Far Detector, August 2012

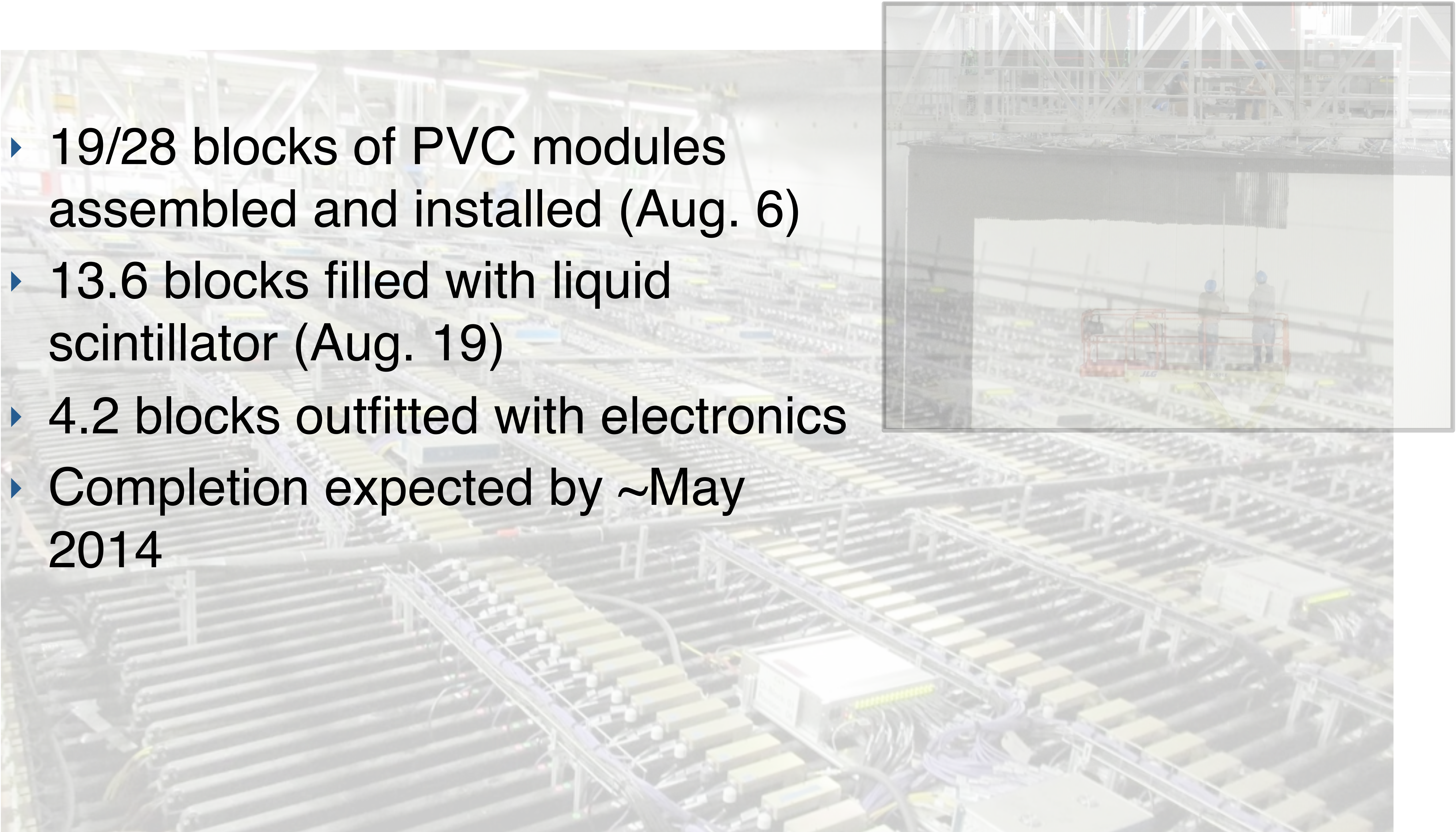
NOνA Far Detector Construction Progress



Far Detector, August 2013

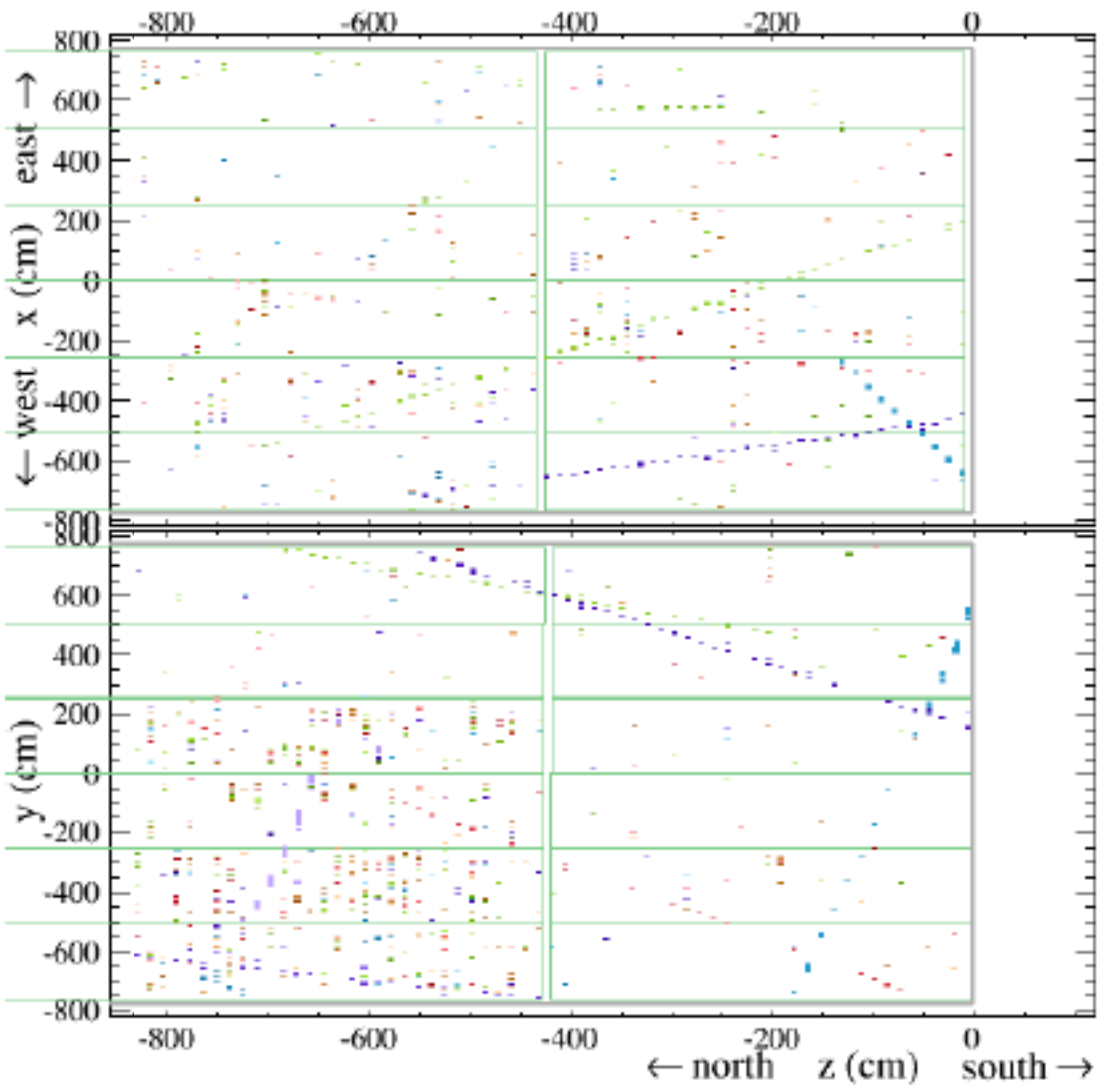
NOνA Far Detector Construction Progress

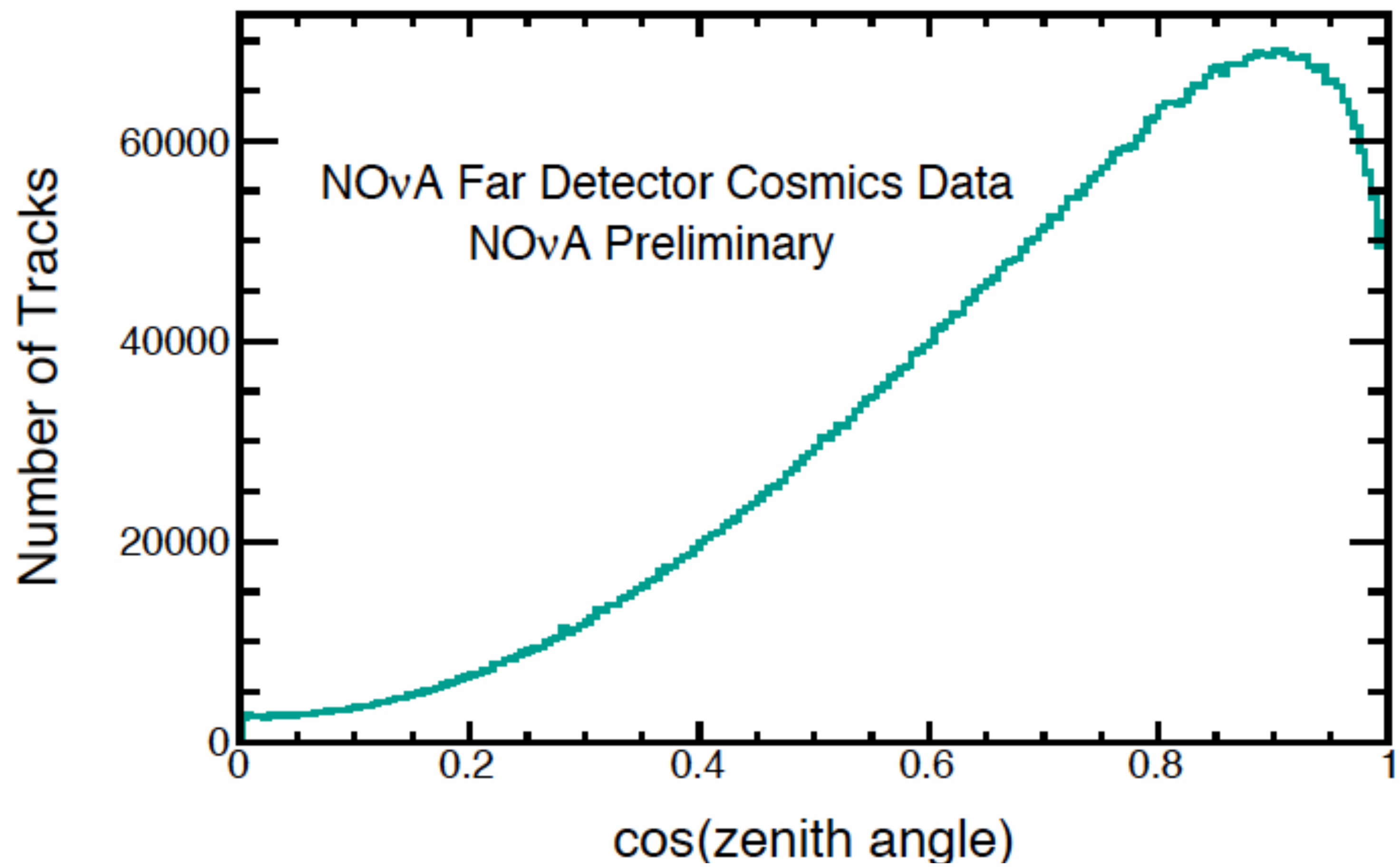
- 19/28 blocks of PVC modules assembled and installed (Aug. 6)
- 13.6 blocks filled with liquid scintillator (Aug. 19)
- 4.2 blocks outfitted with electronics
- Completion expected by ~May 2014

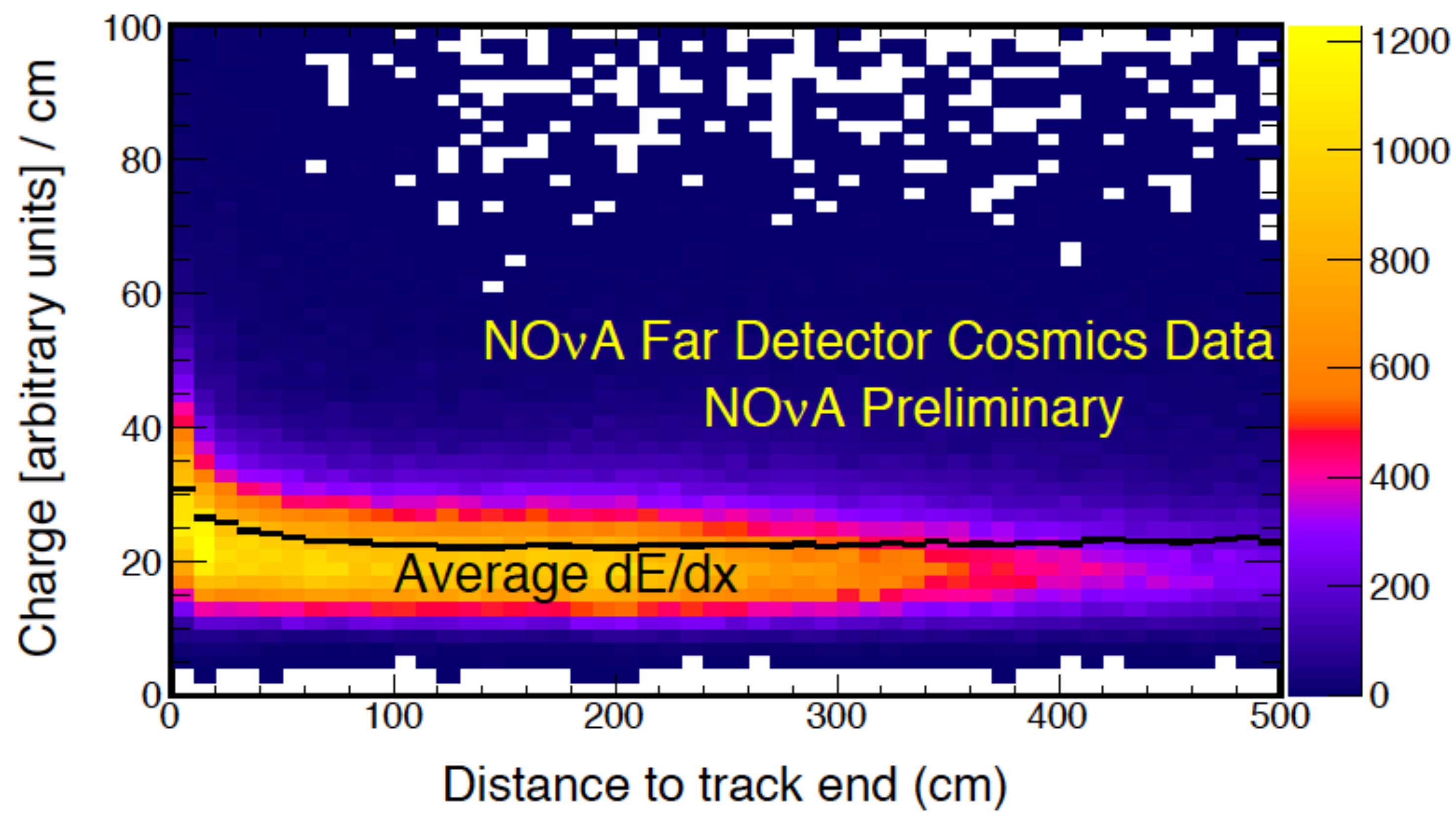


Far Detector, August 2013

NOνA Far Detector Commissioning



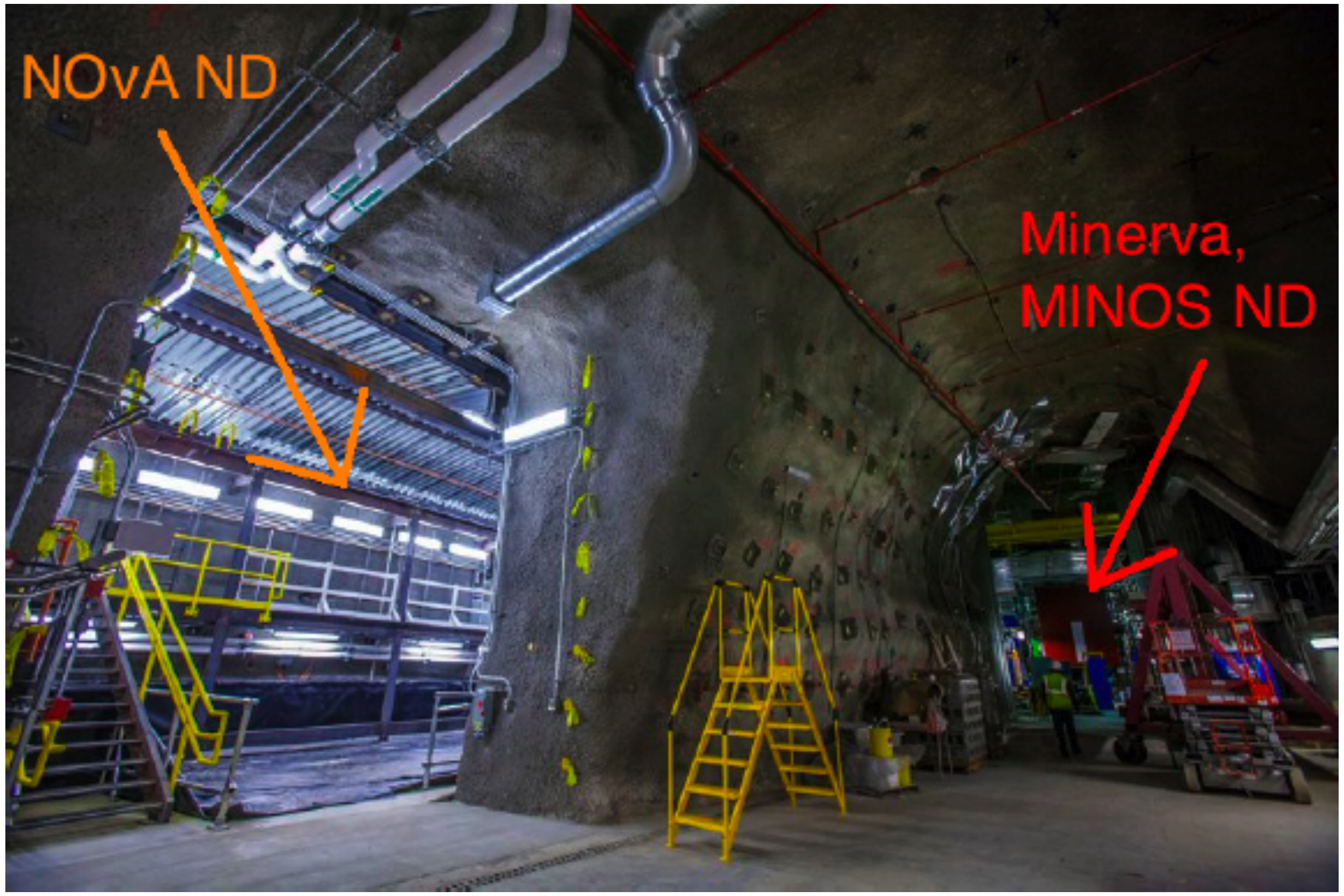


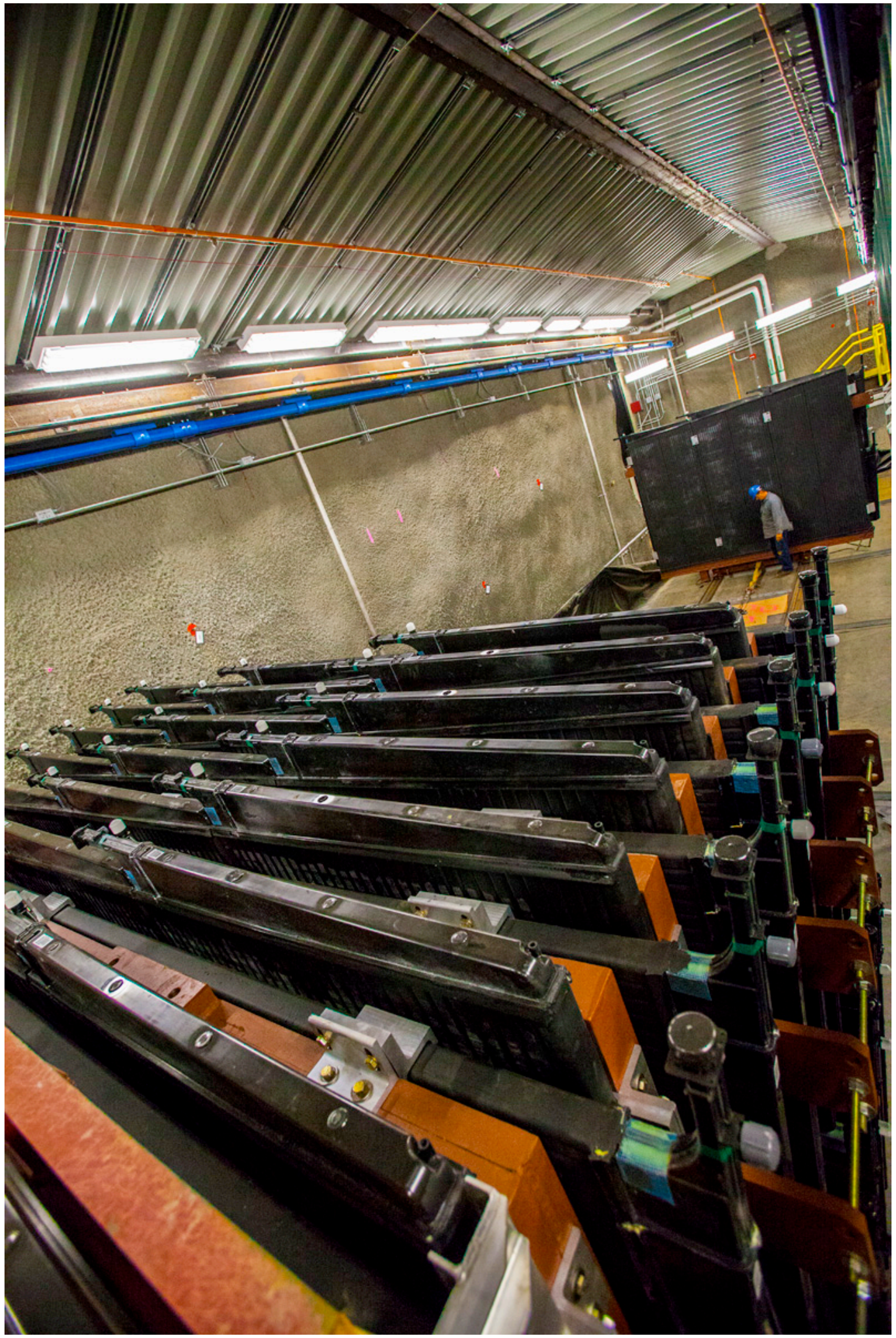


- Event display with 1st 4 blocks instrumented
- cosθ distribution from first two blocks, 30 min. live time
- Energy loss w.r.t. distance from end of track for stopping muons (> 2m)

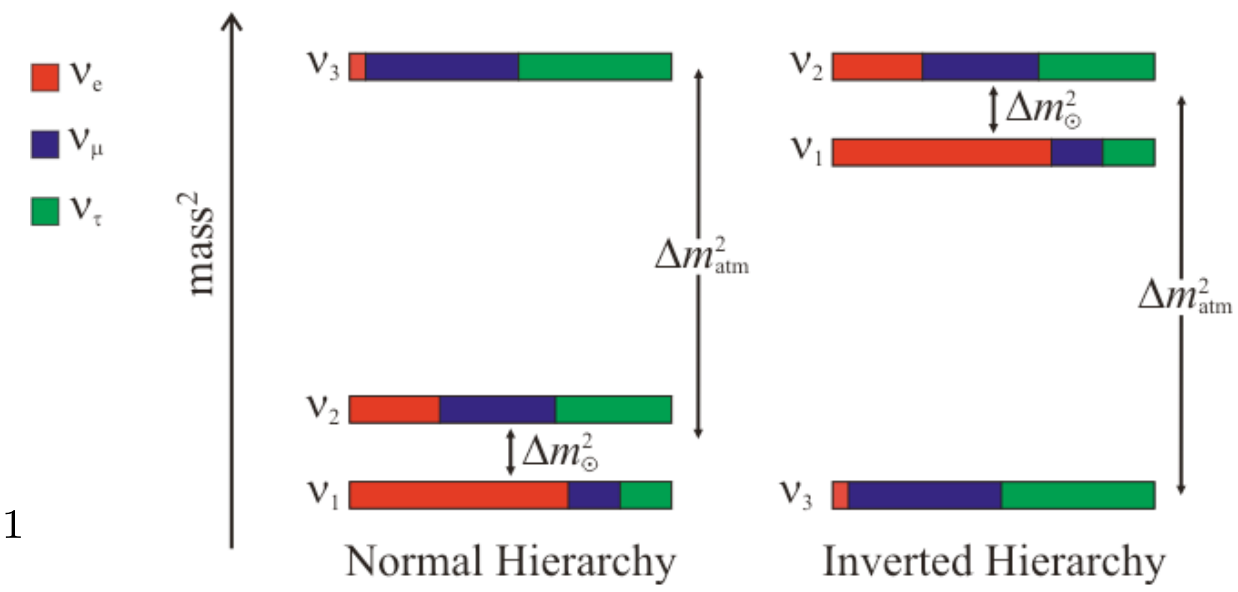
NOνA Near Detector Construction Progress

- Muon catcher installed Aug. 1, 2013
- First half of Near Detector to be installed by end of this year
- Second half of Near Detector to be installed by summer of 2014





$\nu_\mu \to \nu_e$ Oscillations in Long-Baseline Experiments



- Long-baseline $\nu_\mu \to \nu_e$ experiments have the potential to simultaneously measure θ_{13}, δ_{CP}, sign(Δm_{31}^2), sign(θ_{23}-45°):

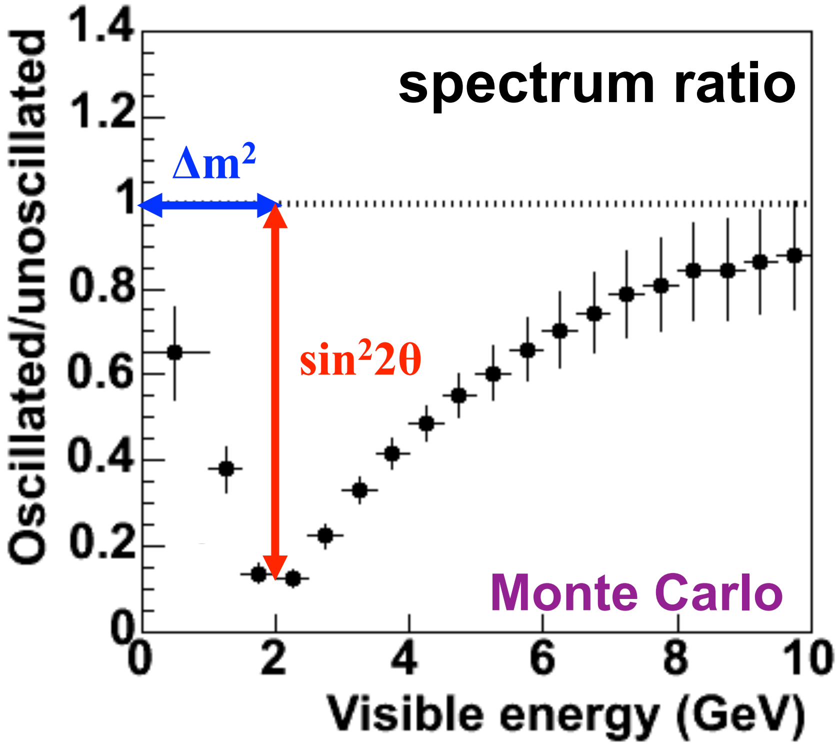
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \sin\Delta_{32}$$

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

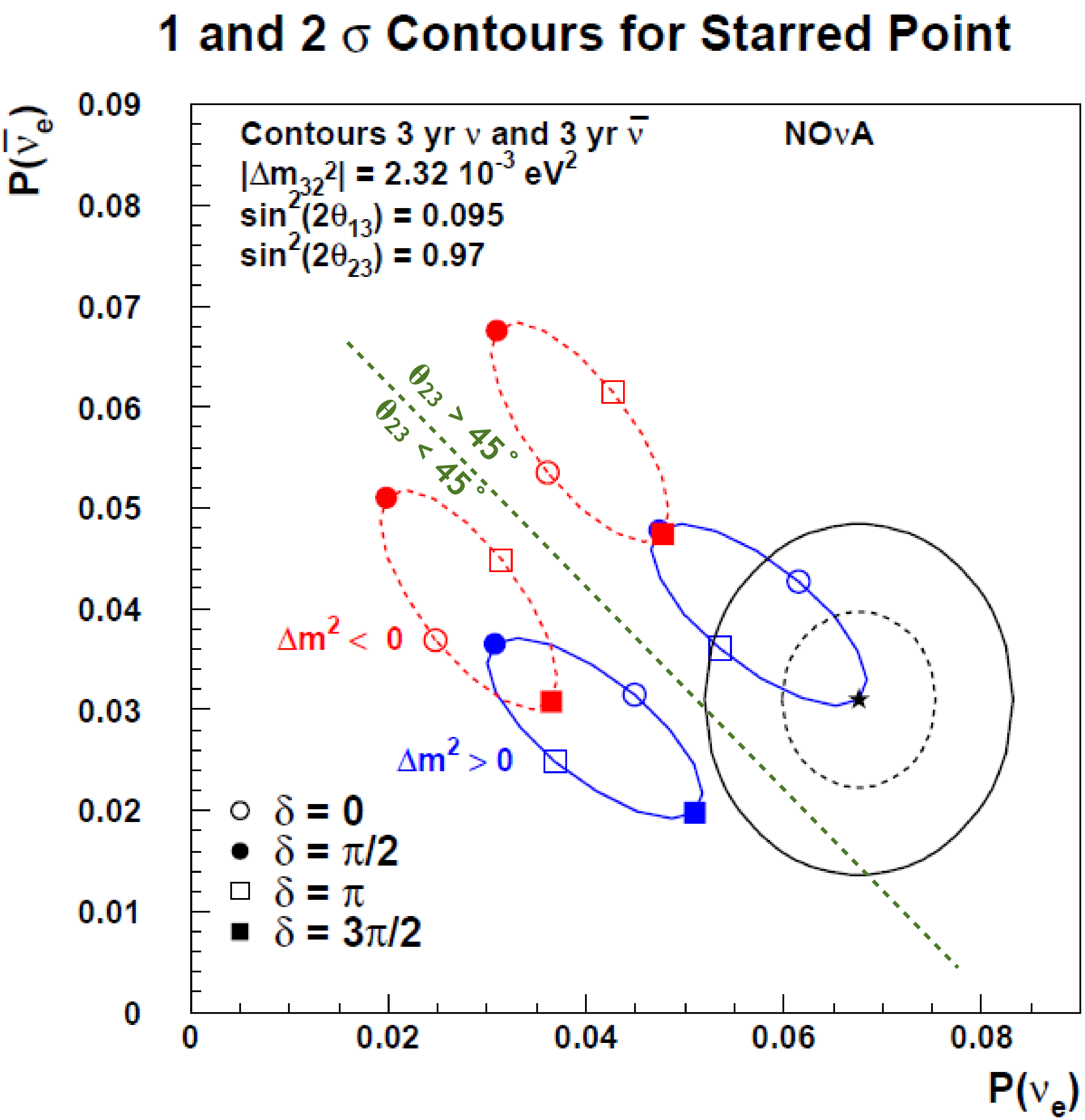
$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$ eg, in NOvA: $aL \simeq 0.23$

- Separate measurement of $\nu_\mu \to \nu_\mu$ gives access to $\sin^2(2\theta_{23})$ and Δm^2_{32}:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.27\Delta m^2_{32} \frac{L}{E}\right)$$

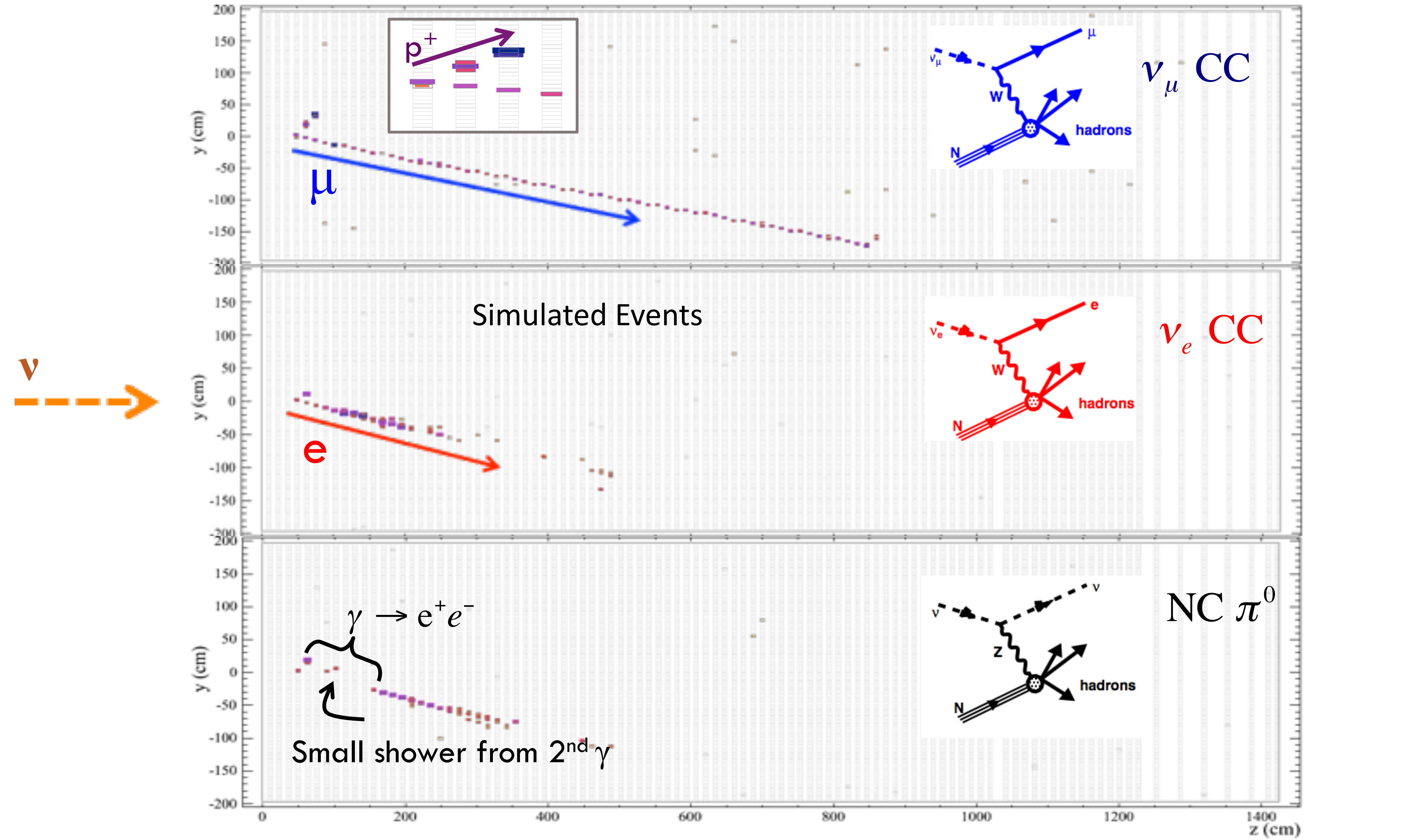


NOνA Measurements

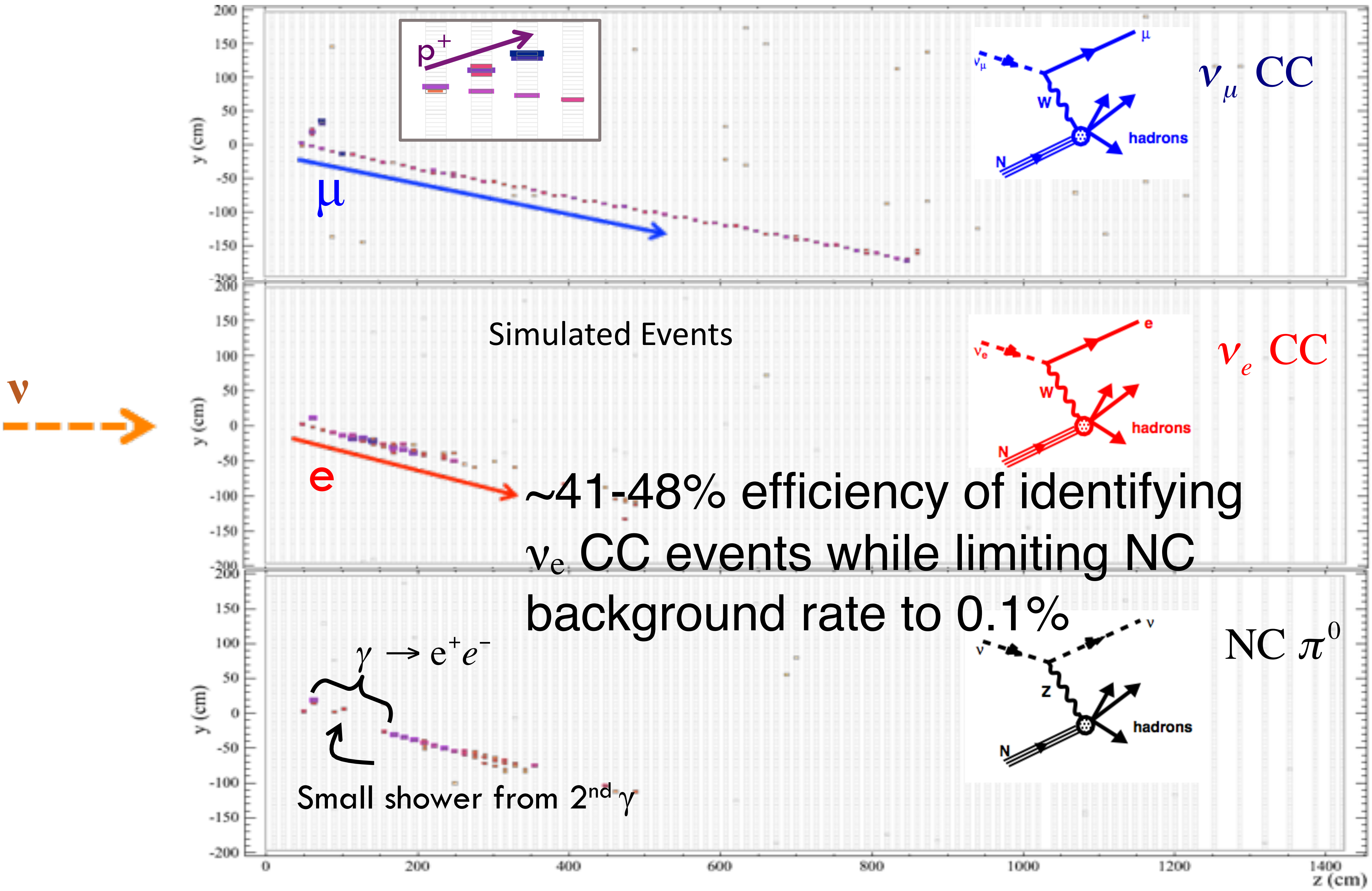


- The strategy in NOνA is to compare the oscillation probability of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ to extract mass hierarchy and first information on δ_{CP}
- Precision measurement of $\sin^2(2\theta_{23})$ from $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$
- If θ_{23} is non-maximal, then we also have the capability of determining the octant; this tells us whether or not ν_μ couples more strongly to ν_2 or ν_3.

Distinguishing Neutrino Events in NOνA

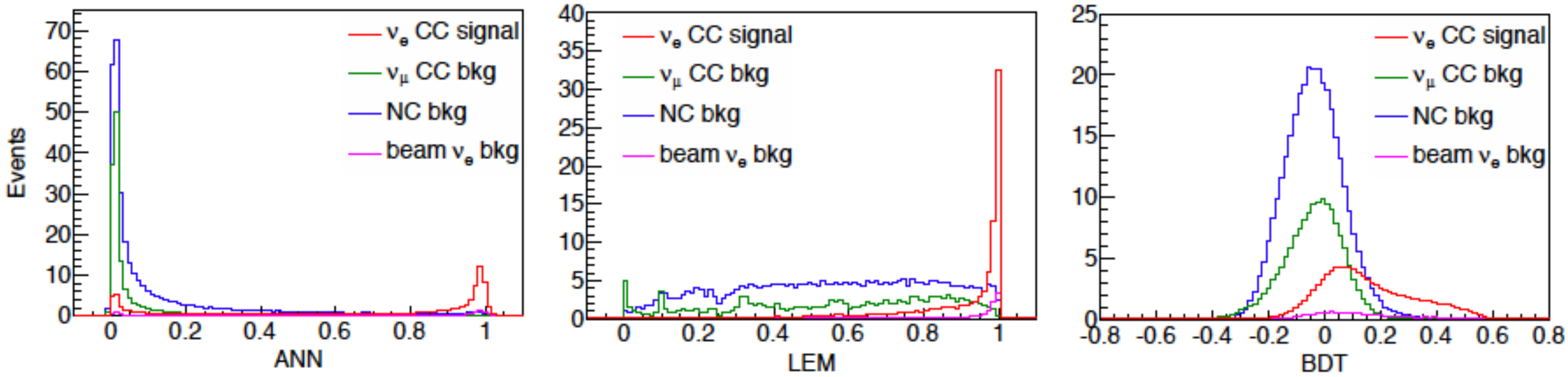


Distinguishing Neutrino Events in NOνA

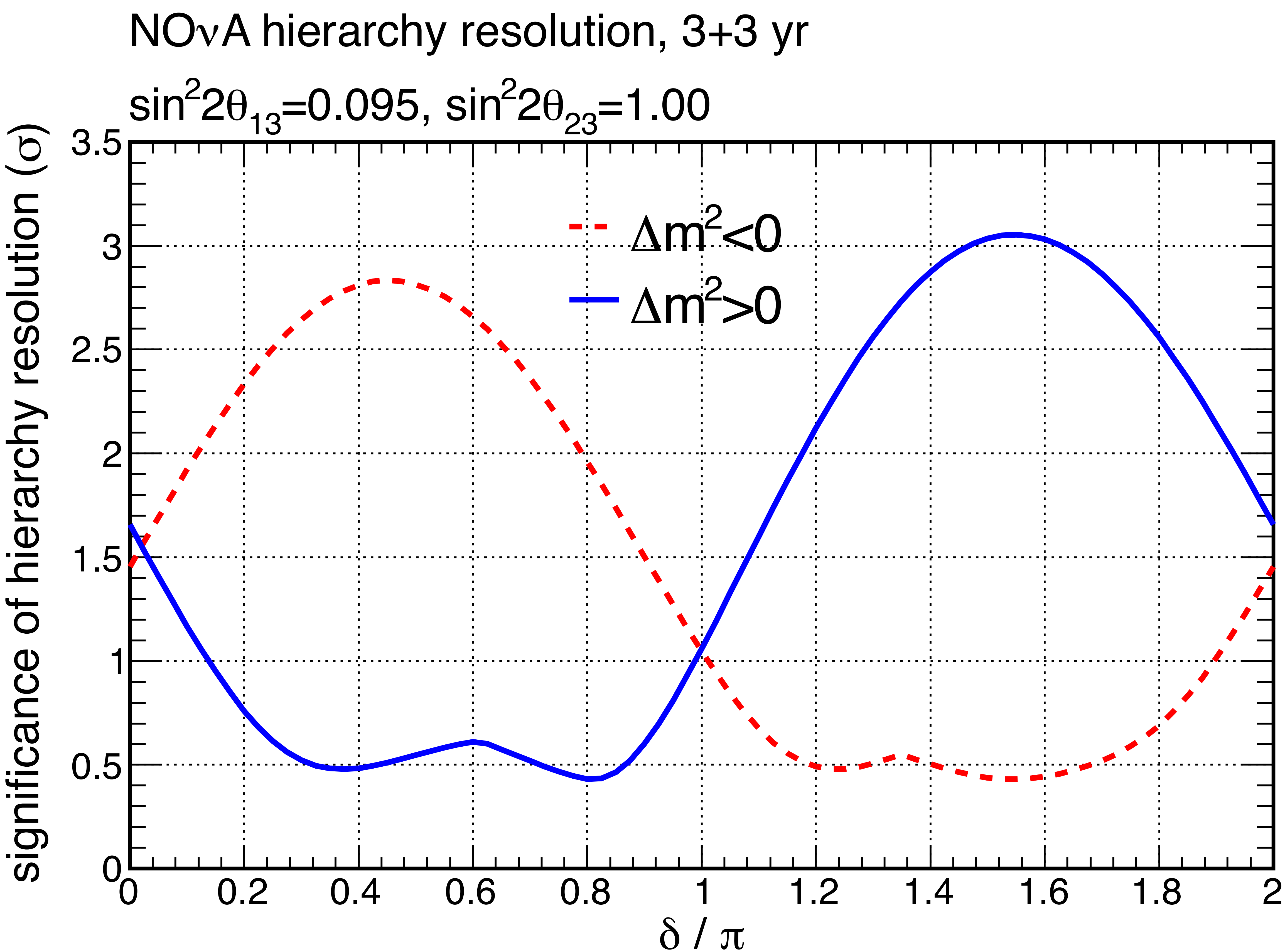


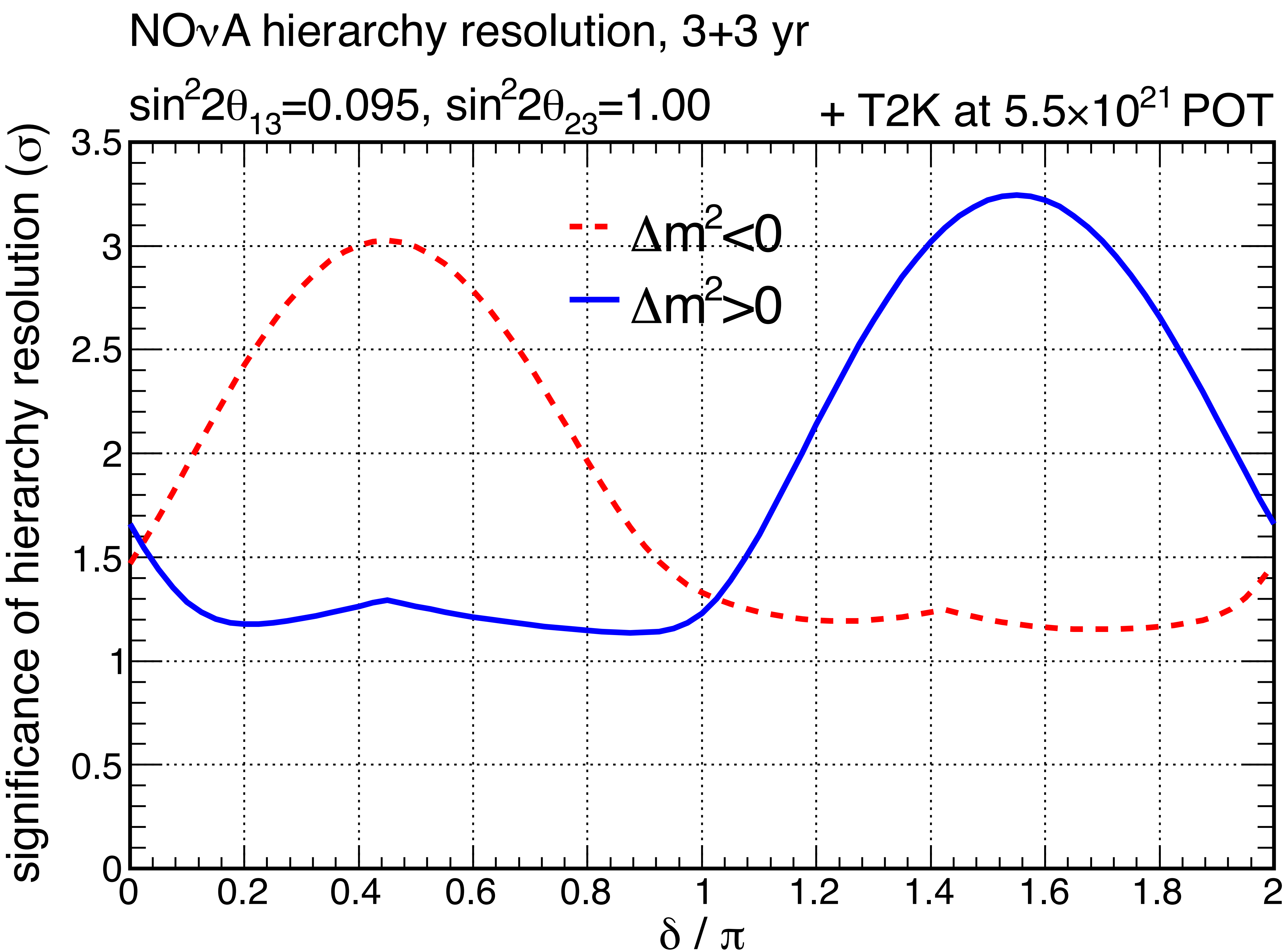
~41-48% efficiency of identifying ν_e CC events while limiting NC background rate to 0.1%

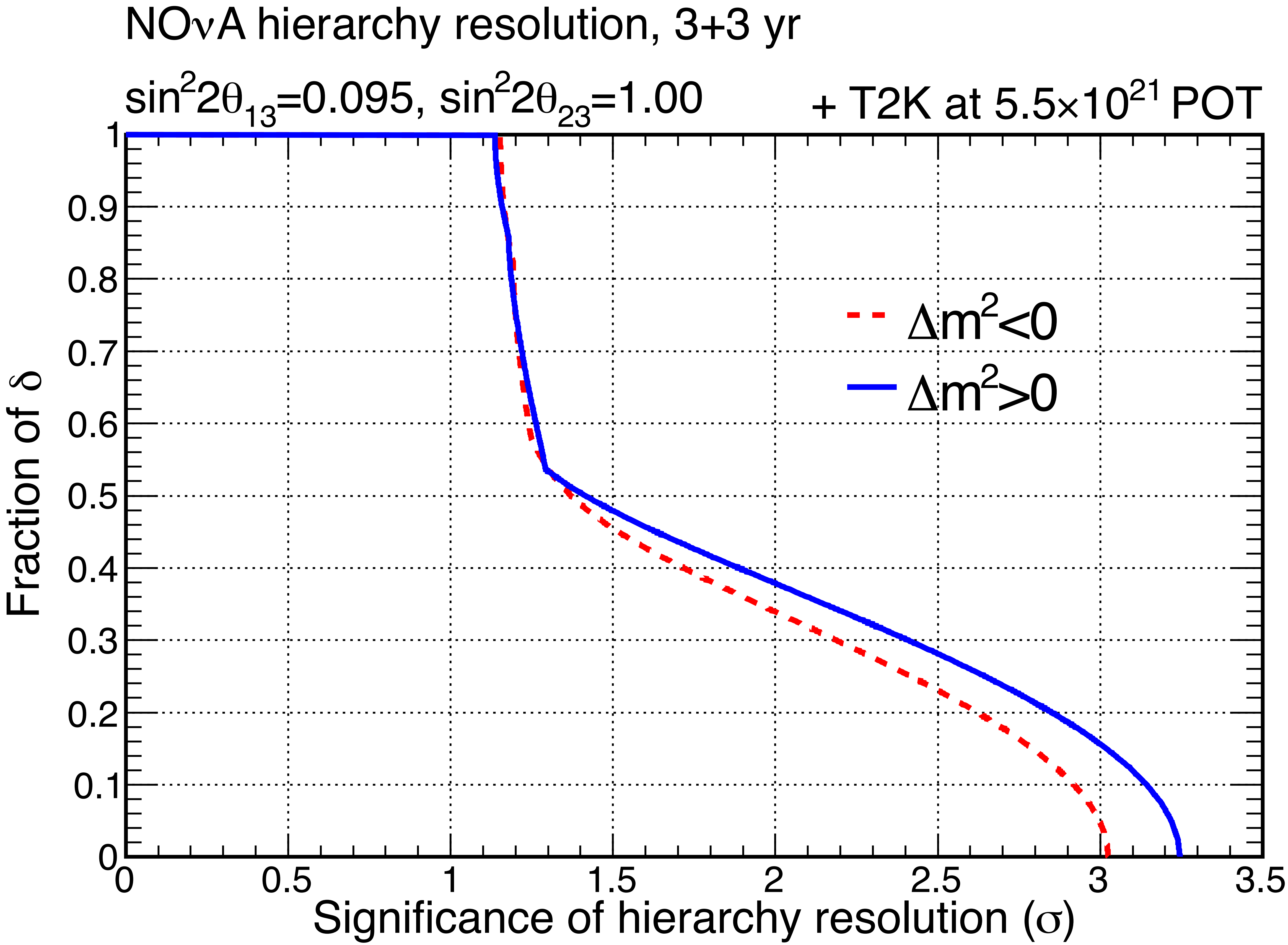
Distinguishing ν_e Events in NOνA

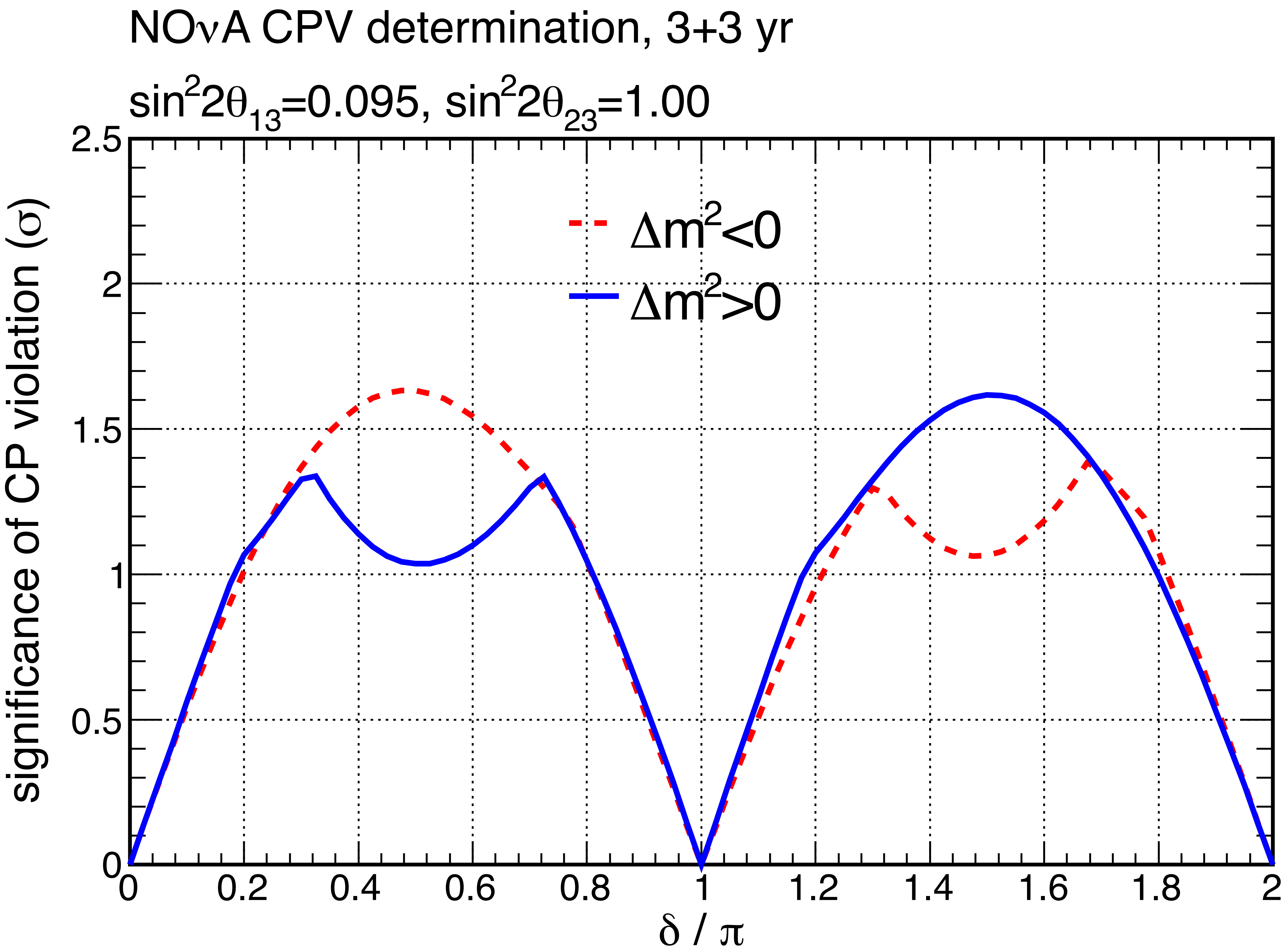


- With a 3+3 year run, $N(\nu_e) \simeq 68$ (statistics limited!)
- Several event identification algorithms have been developed to separate the small ν_e signal from various backgrounds:
  - ANN: artificial neural network using shower shape-based likelihood for particle hypotheses.
  - LEM: library event matching, match to library of MC events
  - BDT: boosted decision tree on simple reconstructed quantities
- Typical $S/(S+B)^{1/2} \simeq 6.5$

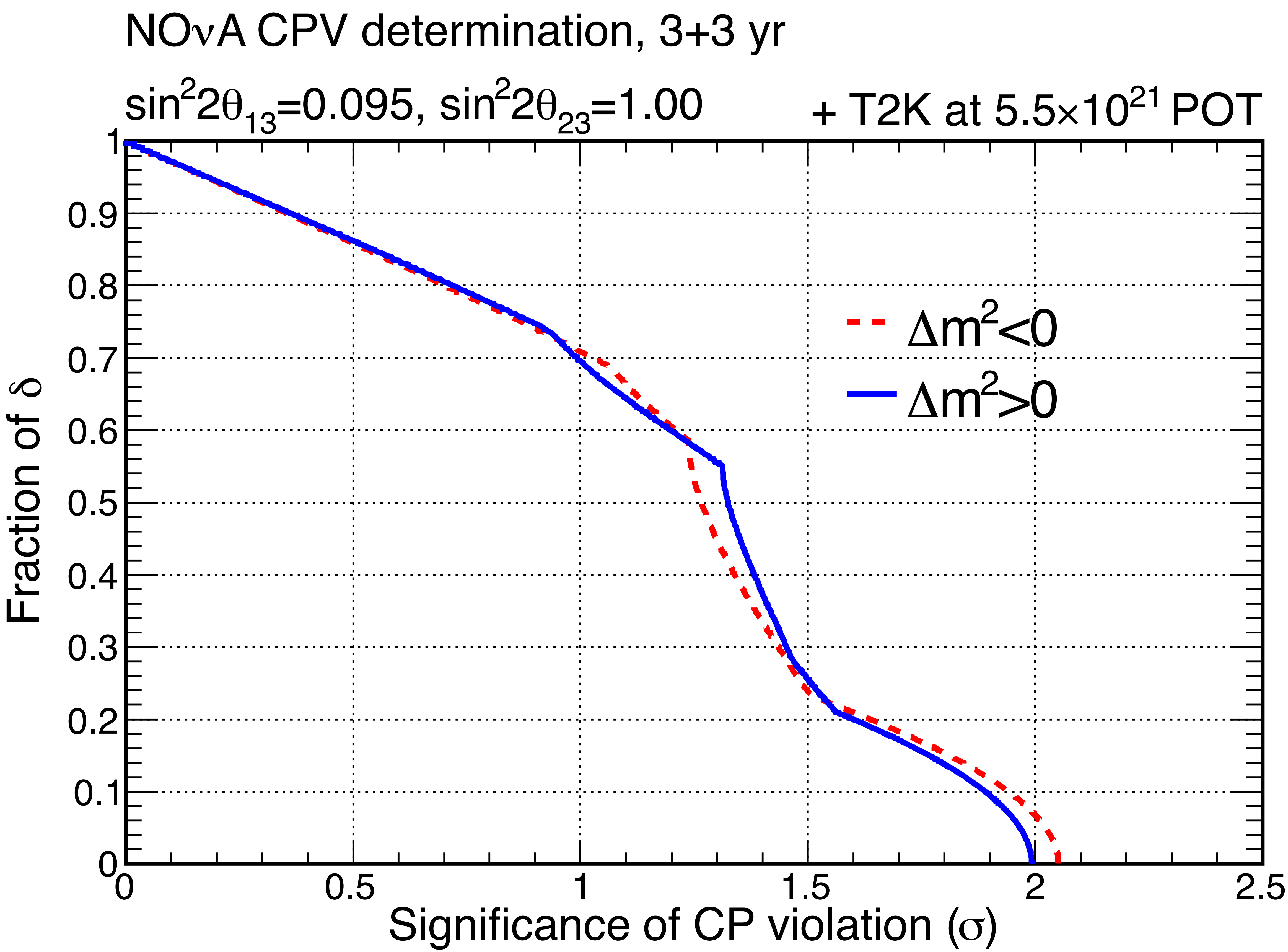

NOνA hierarchy resolution, 3+3 yr
sin²2θ₁₃=0.095, sin²2θ₂₃=1.00
Δm²<0
Δm²>0
significance of hierarchy resolution (σ)
δ / π
0
0.5
1
1.5
2
2.5
3
3.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


NOνA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
+ T2K at 5.5×10²¹ POT
significance of hierarchy resolution (σ)
δ / π
Δm²<0
Δm²>0
0
0.5
1
1.5
2
2.5
3
3.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8

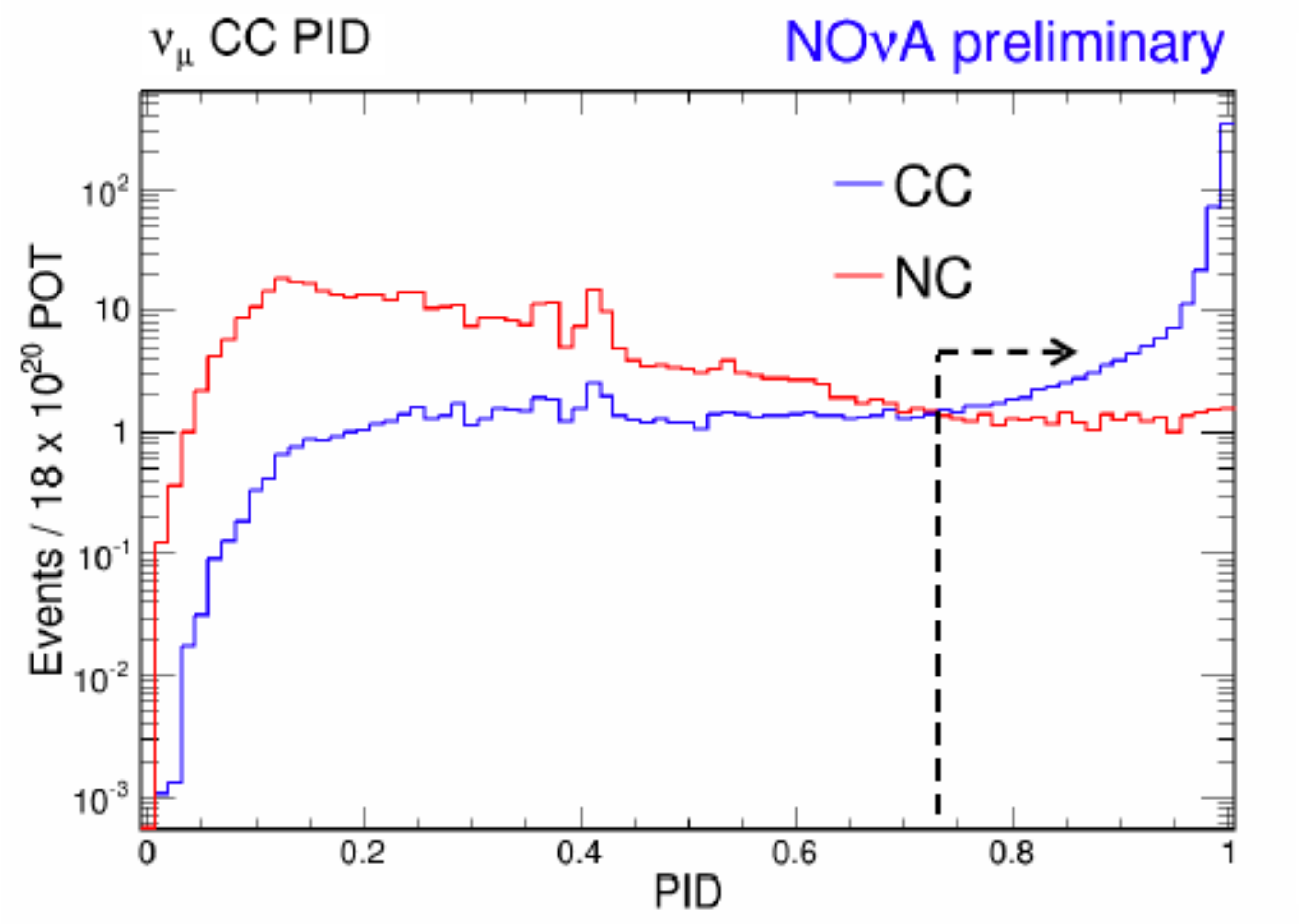

NOνA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
+ T2K at 5.5×10²¹ POT
Δm²<0
Δm²>0
Fraction of δ
Significance of hierarchy resolution (σ)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.5
1.5
2
2.5
3
3.5



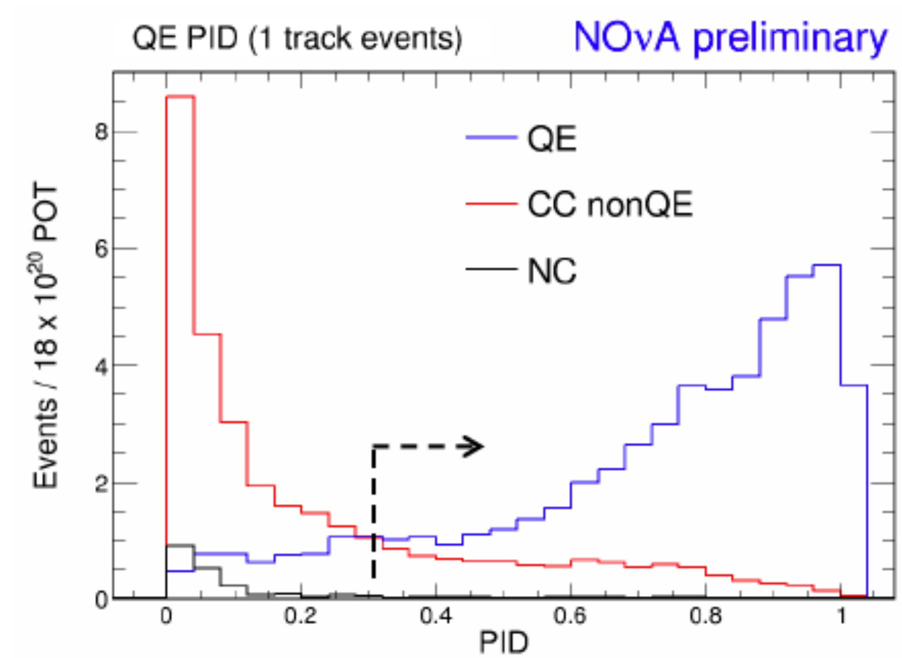
NOνA CPV determination, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
Δm²<0
Δm²>0
significance of CP violation (σ)
δ / π
0
0.5
1
1.5
2
2.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8

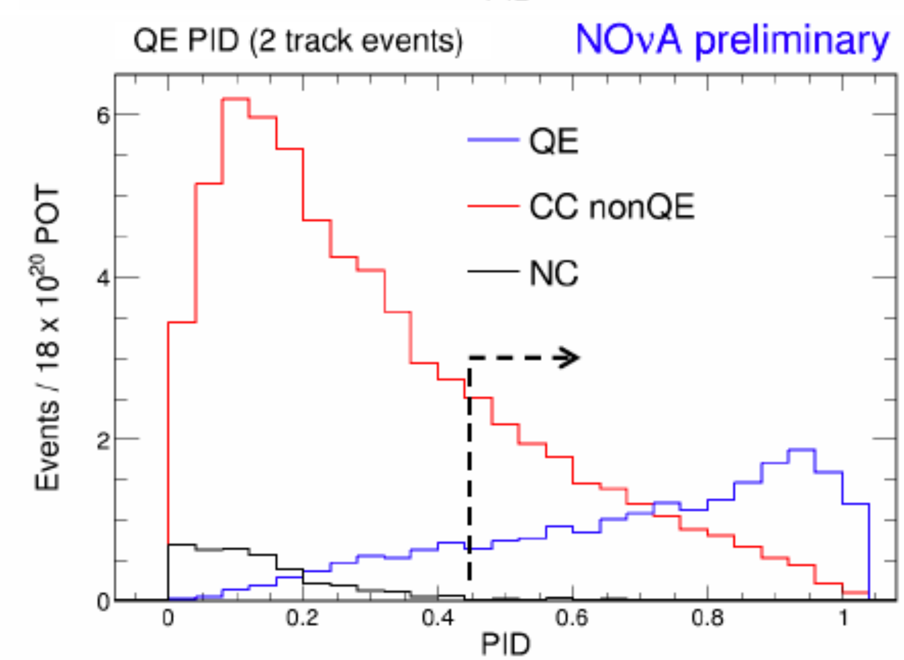

NOνA CPV determination, 3+3 yr
sin²2θ₁₃=0.095, sin²2θ₂₃=1.00
+ T2K at 5.5×10²¹ POT
Δm²<0
Δm²>0
Fraction of δ
Significance of CP violation (σ)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5

Distinguishing ν_μ Events in NOνA

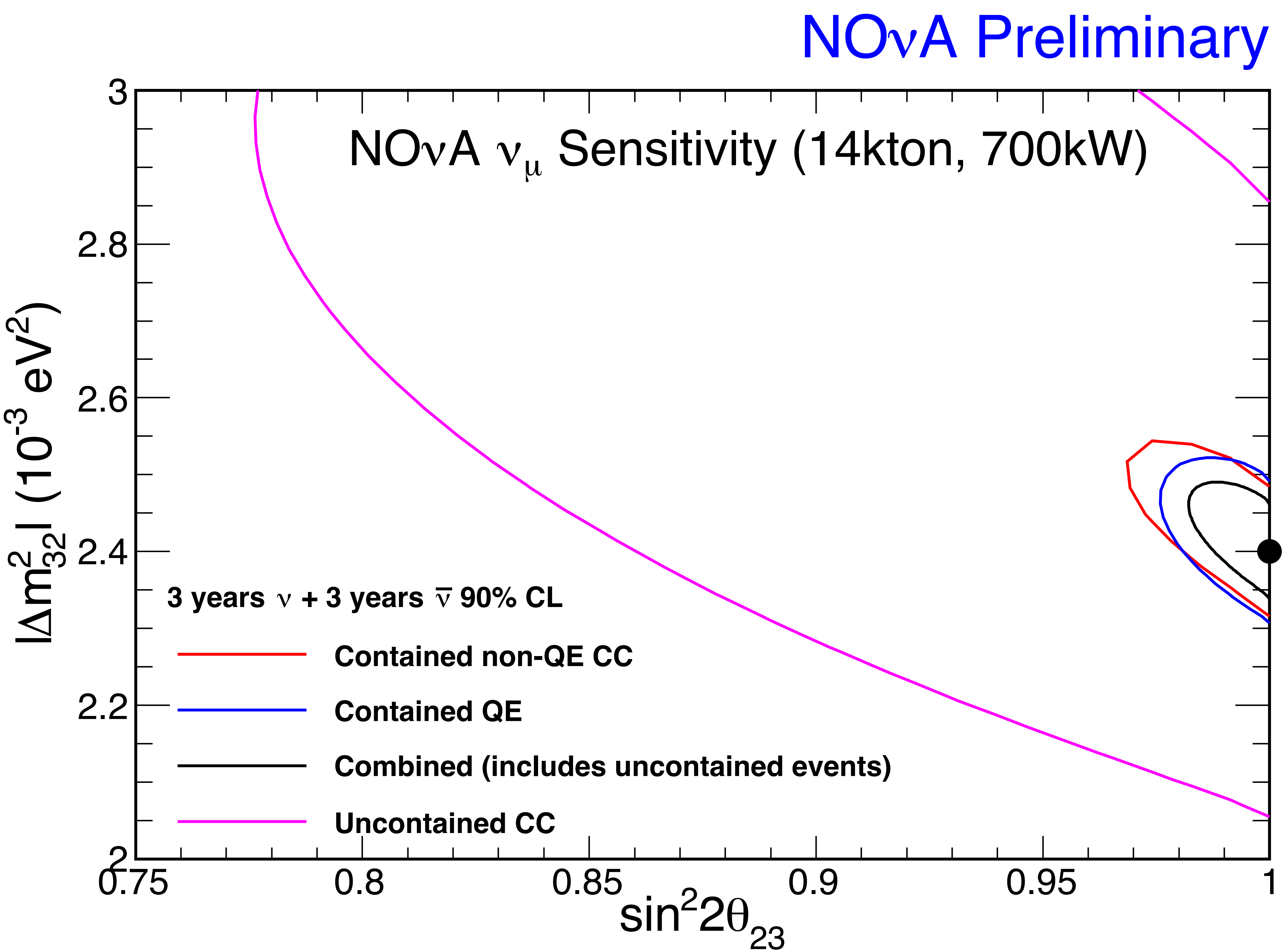


- Muon tracks identified using a multivariate analysis based on reconstructed dE/dx, track length, scattering



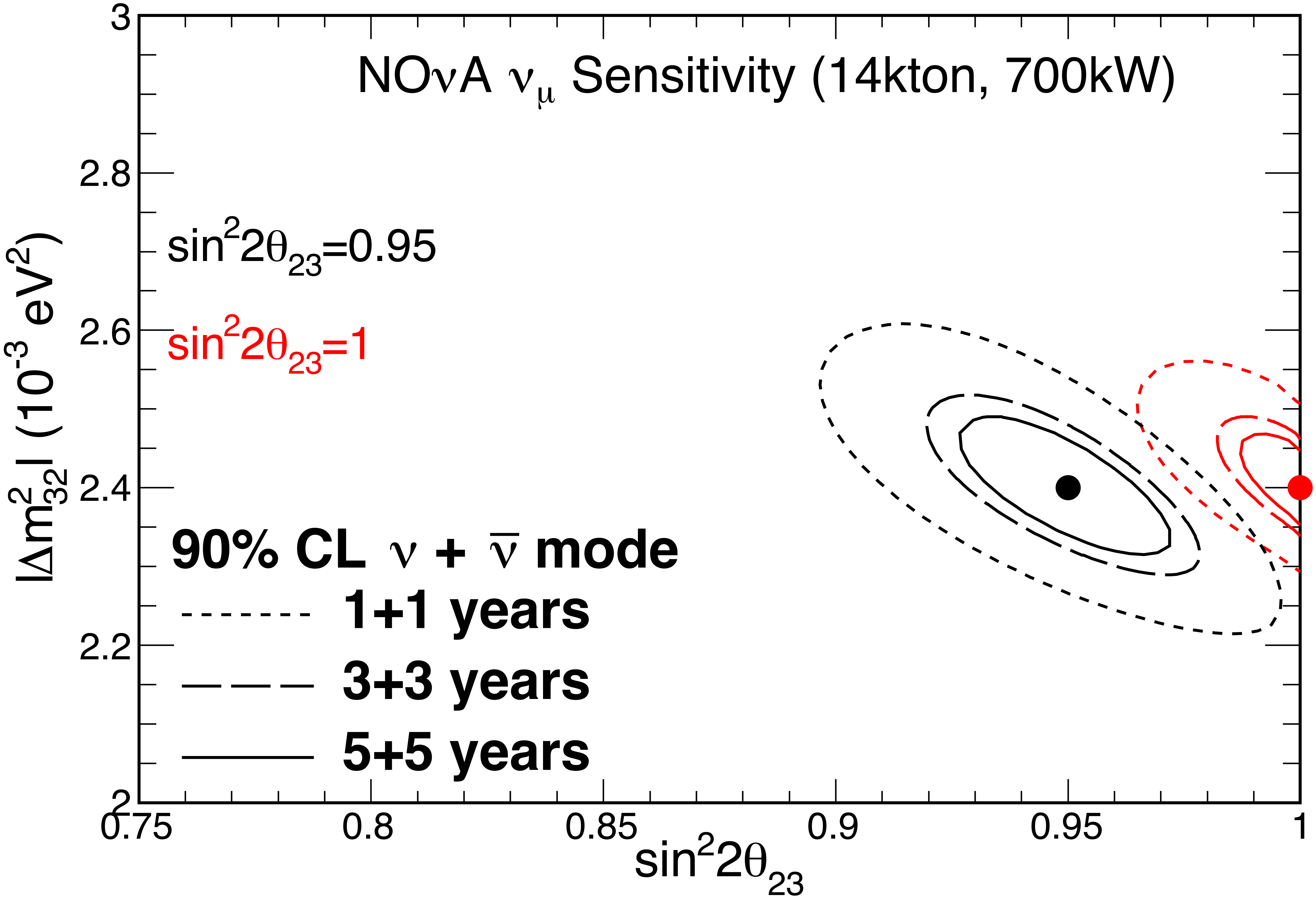


- QE events have much higher energy resolution.
- QE and non-QE events separated using multivariate analysis based on energy distribution in the event.



NOνA Preliminary
NOνA νμ Sensitivity (14kton, 700kW)
3 years ν + 3 years ν̄ 90% CL
Contained non-QE CC
Contained QE
Combined (includes uncontained events)
Uncontained CC
|Δm²₃₂| (10⁻³ eV²)
sin²2θ₂₃
3
2.8
2.6
2.4
2.2
2
0.75
0.8
0.85
0.9
0.95
1

NOνA Preliminary

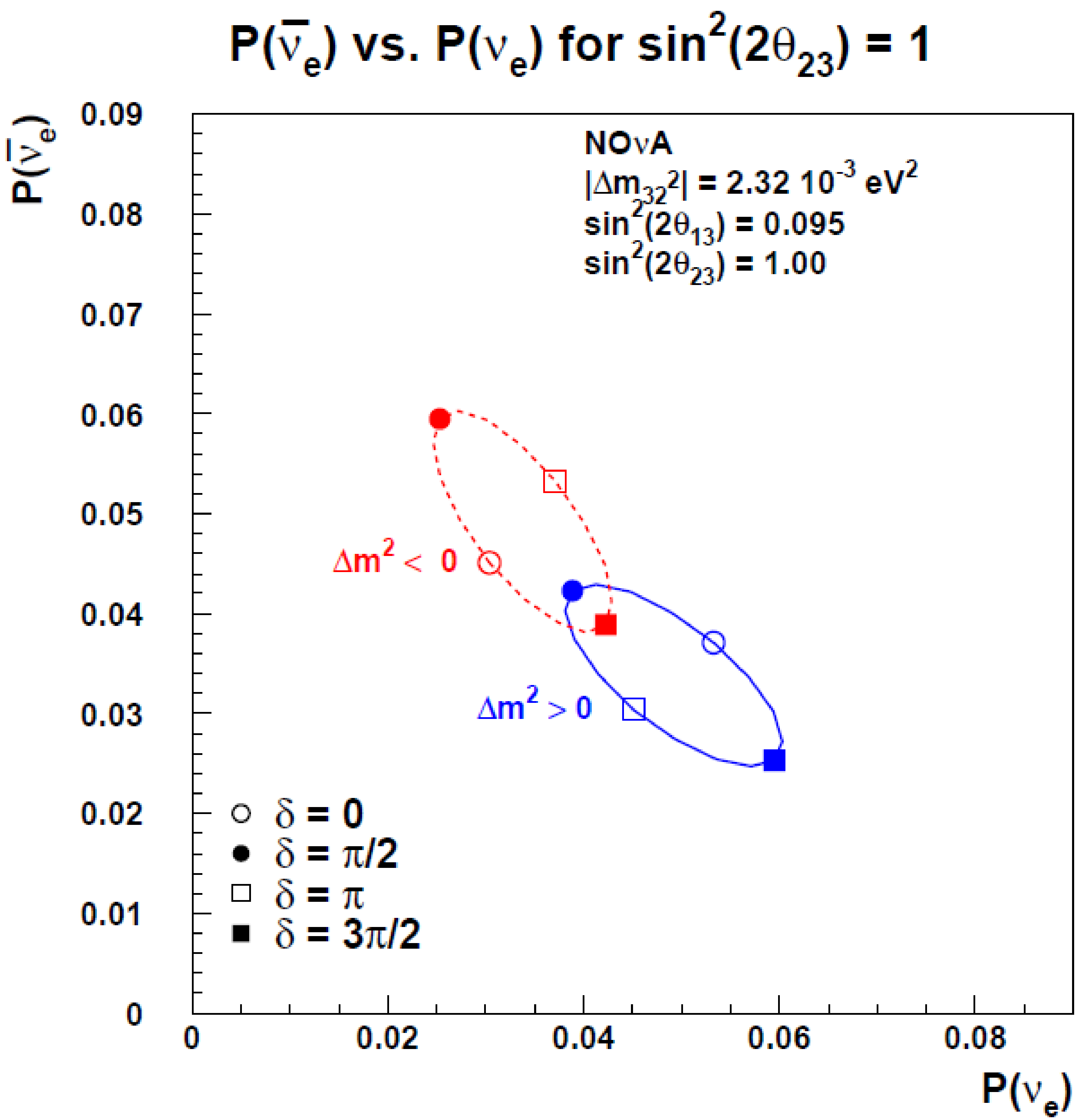


Summary

- NOνA will make many important contributions to neutrino physics:
  - Measurement of θ_{13}
  - Important first information on the neutrino mass hierarchy and CP violating phase
  - More precise measurement of $\sin^2(2\theta_{23})$ and determination of the θ_{23} octant
- First far detector blocks have been installed and now collecting cosmic ray data
- Near detector muon catcher installed, first half of detector will be completed by end of this calendar year
- NuMI beam expected to return within the next few weeks
- Collaboration is very focused on commissioning of far detector
- Reconstruction and analysis tools are in place for first results in summer of 2014.

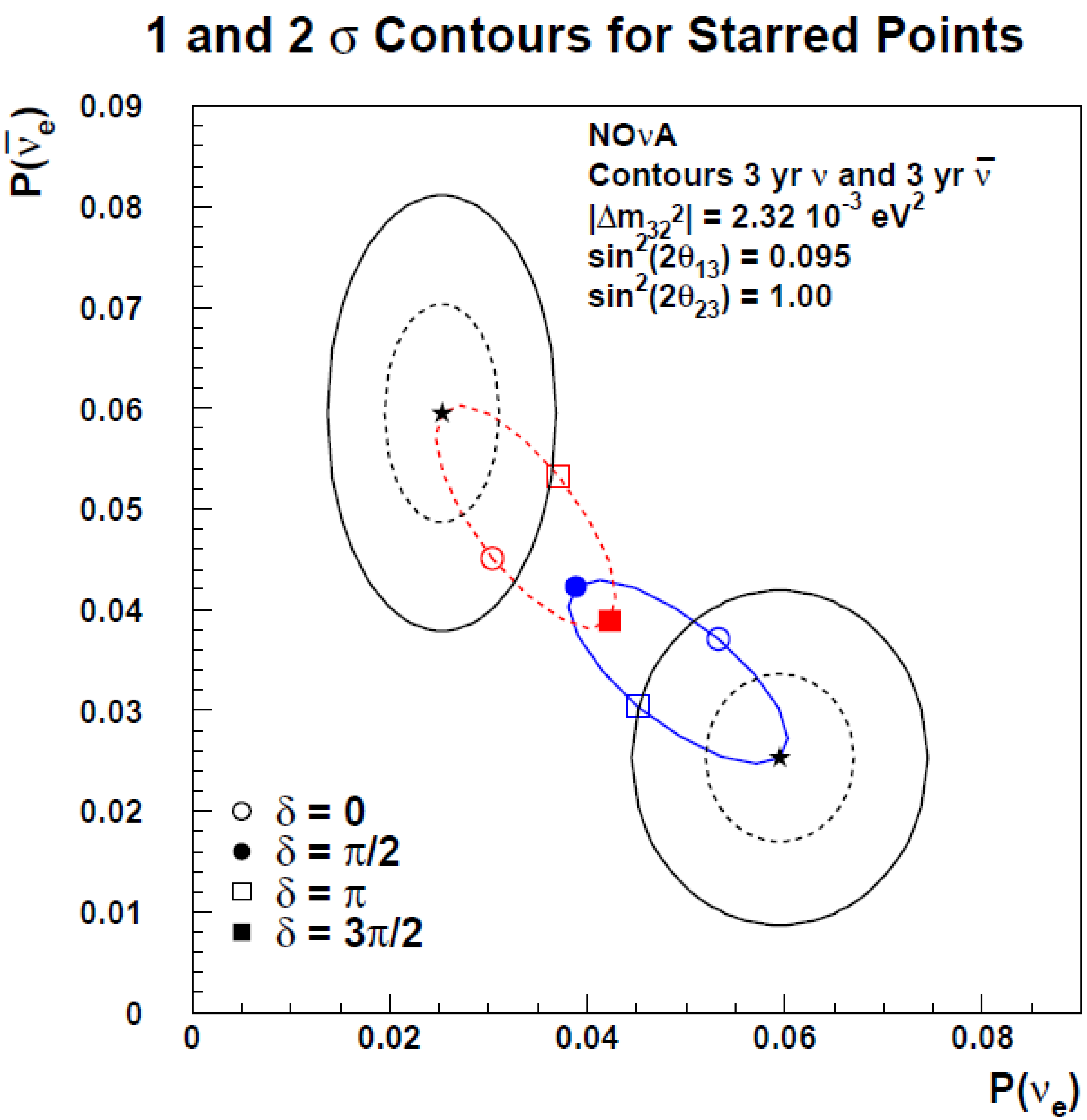
BACKUP

NOνA Measurements



- The strategy in NOνA is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

NOνA Measurements



- The strategy in NOνA is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
- These cases represent best-case scenarios for determining the mass hierarchy after 3 years of running each mode each. Contours are 1- and 2-sigma measurements.