Status of the NOvA Experiment

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Rencontres du Vietnam, 2014
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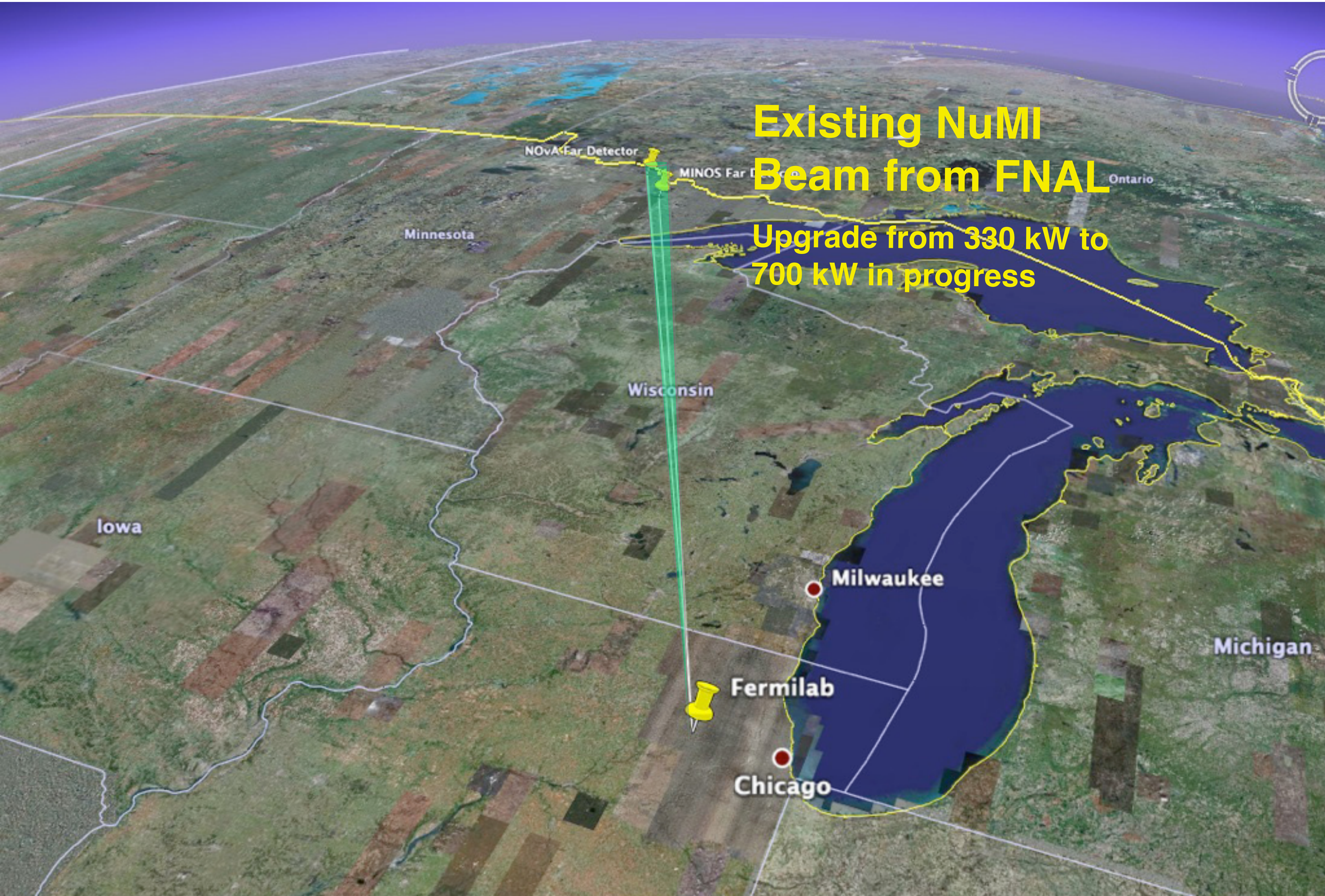
The NuMI Off-Axis ν_e Appearance (NOvA) Experiment

A growing collaboration of over 200 scientists and engineers from 38 institutions and 7 countries.

The NuMI Off-Axis ν_e Appearance (NOvA) Experiment



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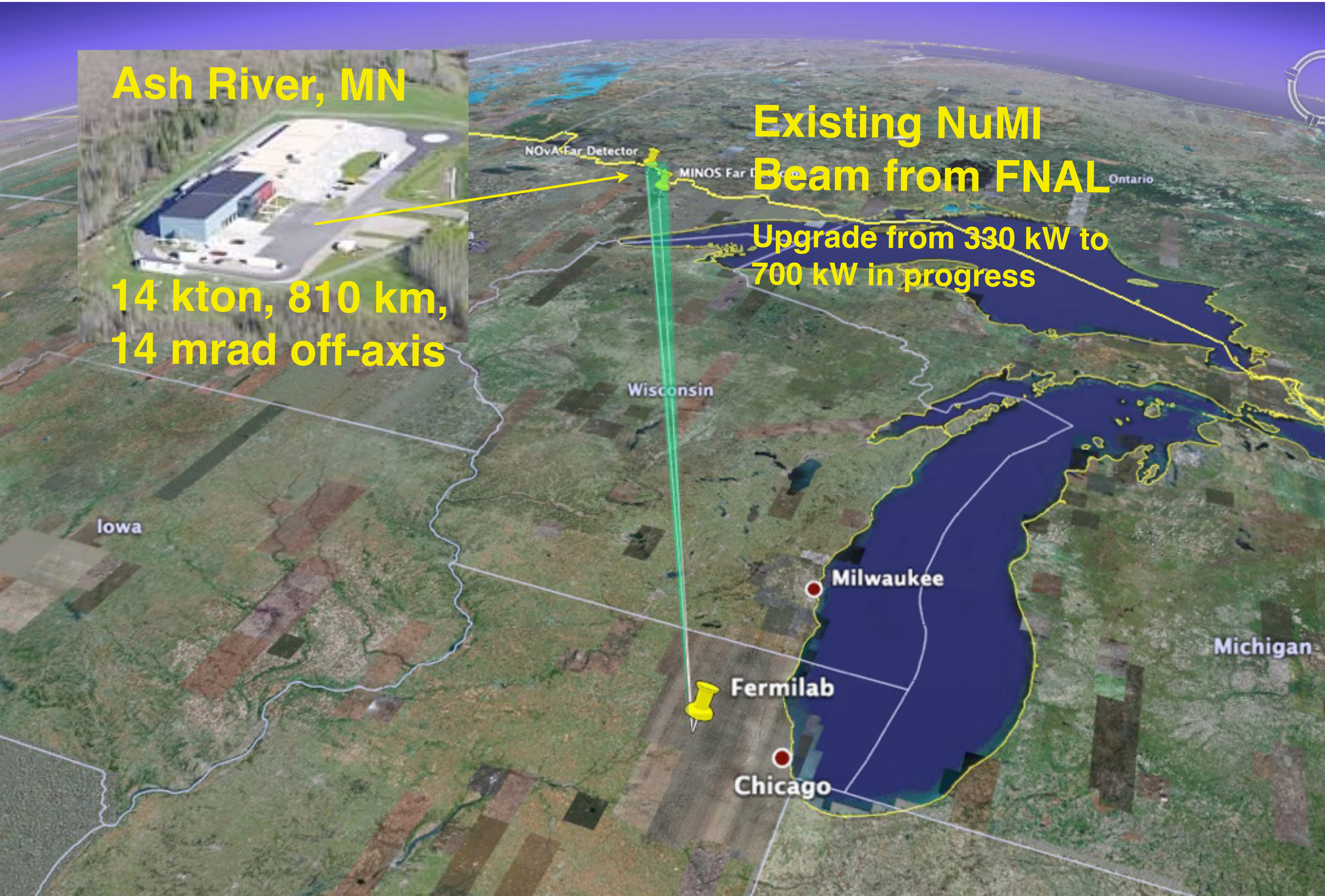
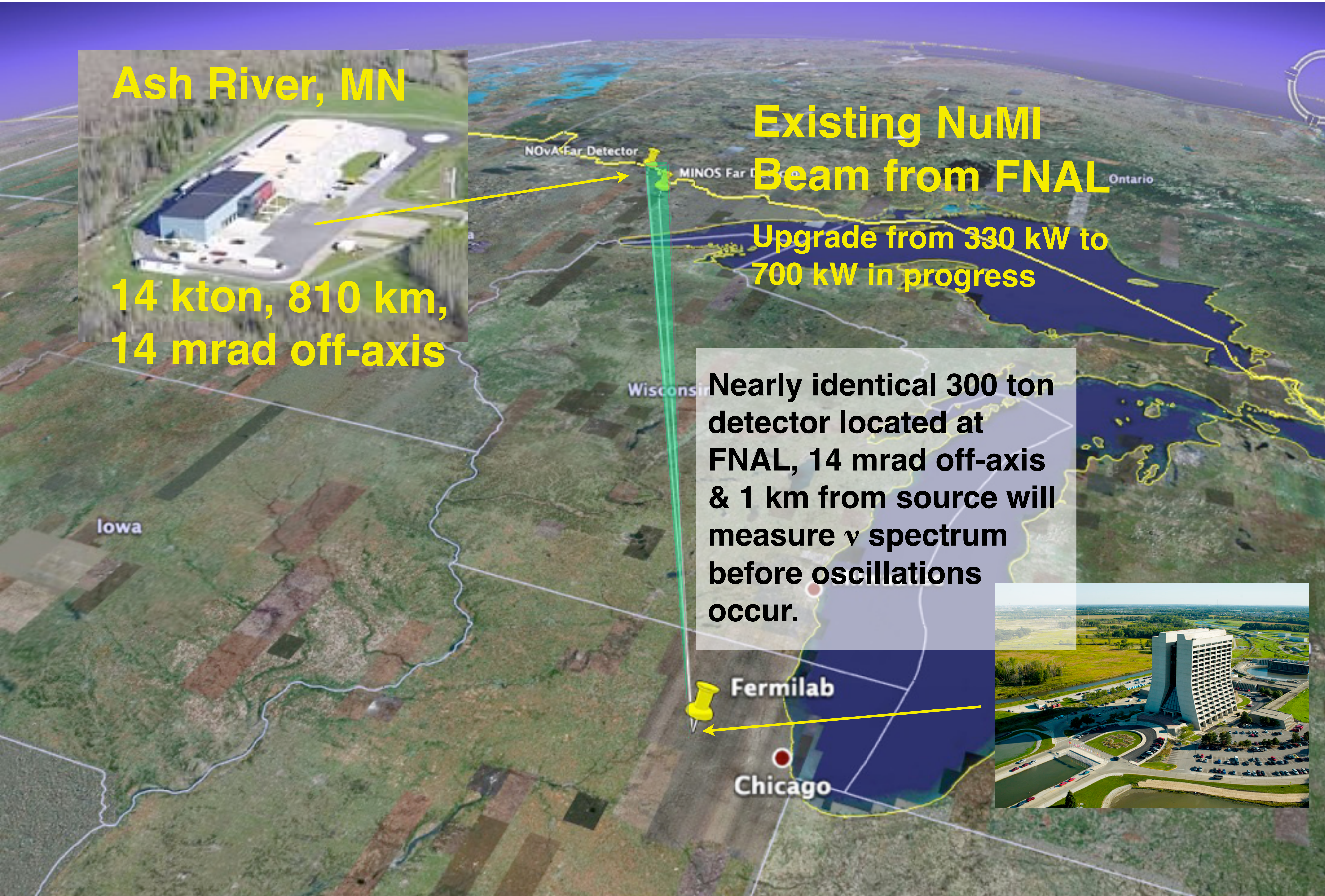


The NuMI Off-Axis ν_e Appearance (NOvA) Experiment



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.

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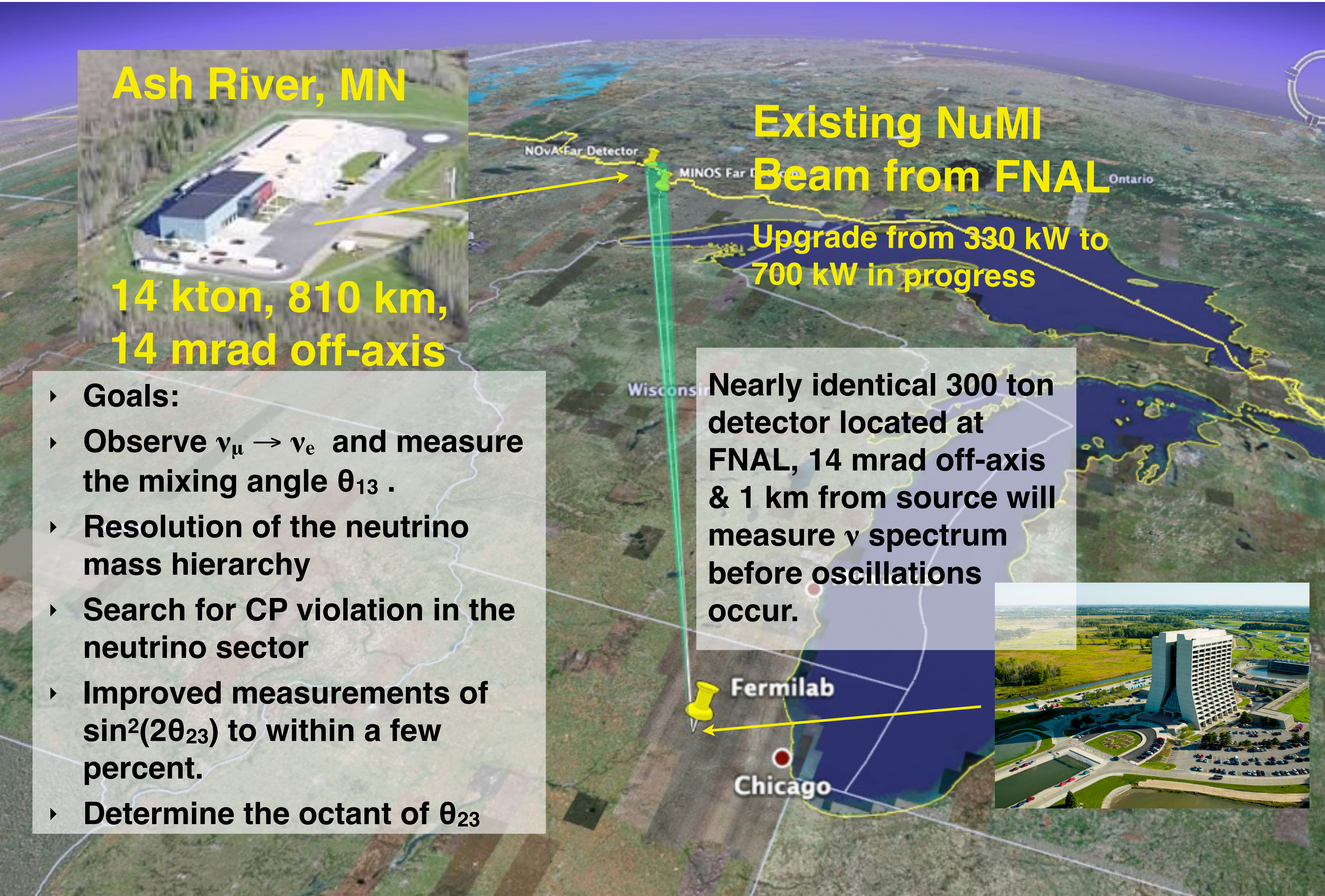


Ash River, MN

14 kton, 810 km,
14 mrad off-axis

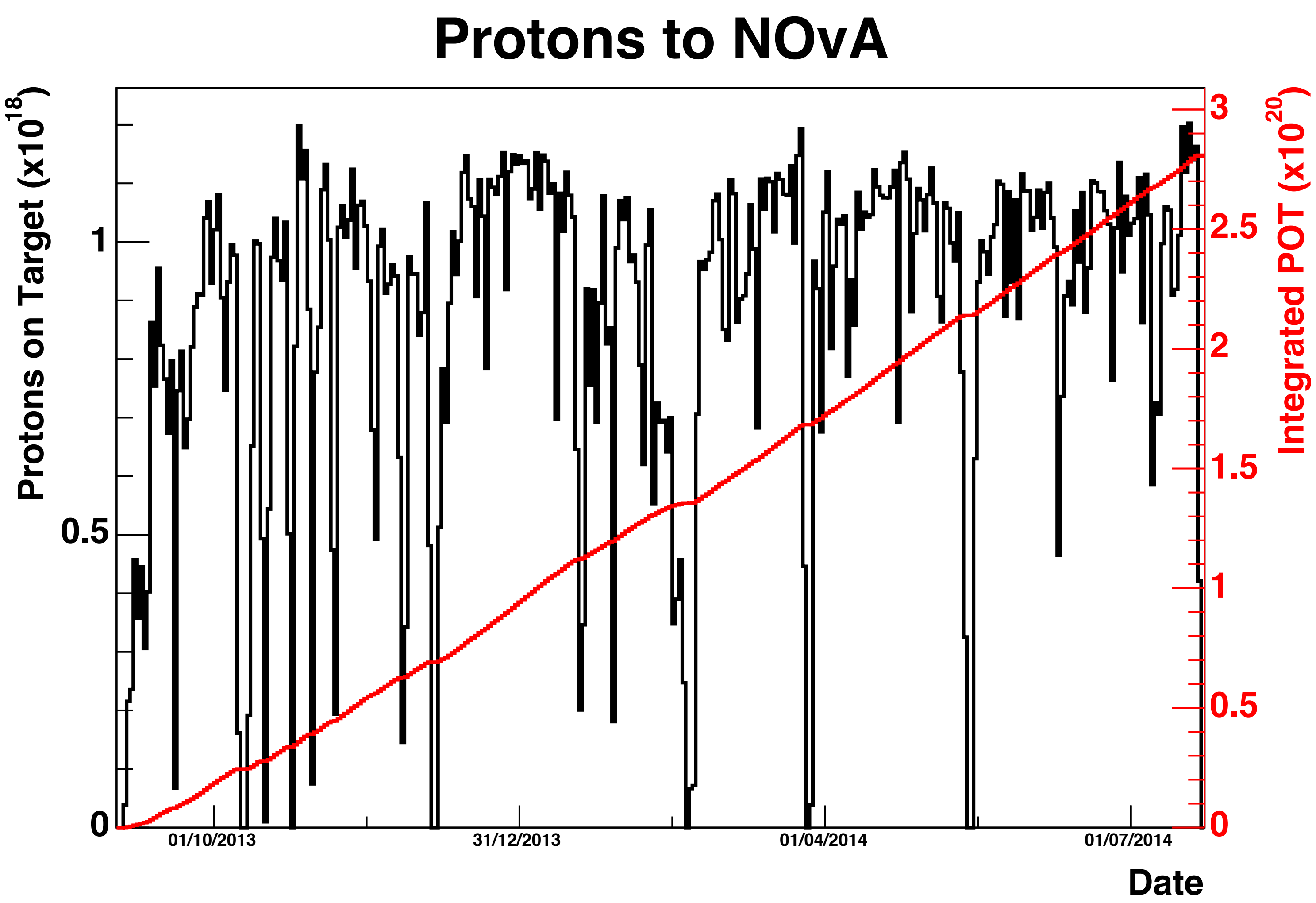
Existing NuMI Beam from FNAL

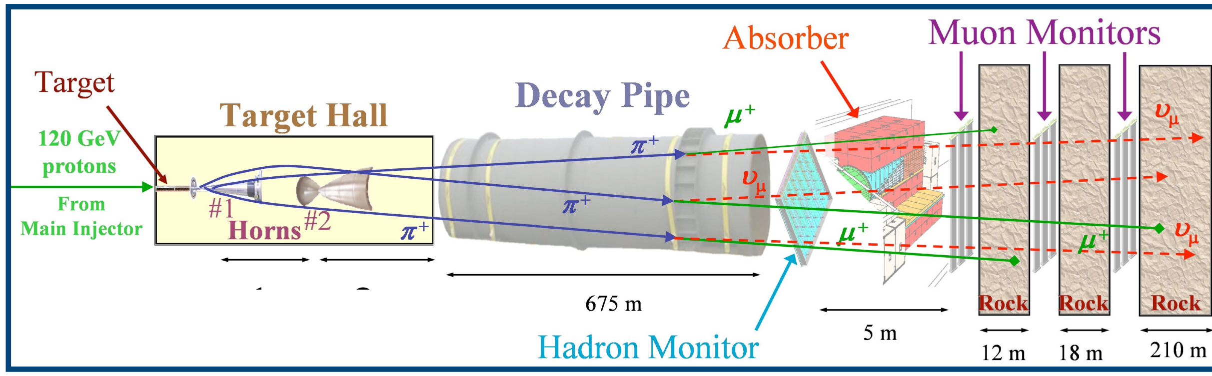
Upgrade from 330 kW to 700 kW in progress

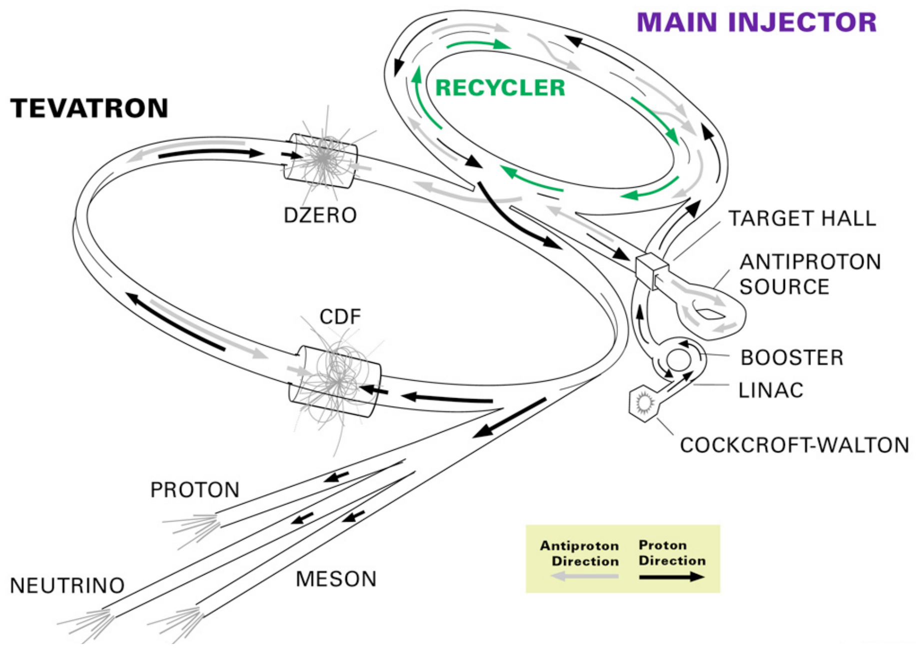
- **Goals:**
- **Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13} .**
- **Resolution of the neutrino mass hierarchy**
- **Search for CP violation in the neutrino sector**
- **Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.**
- **Determine the octant of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

Accelerator Upgrades and Performance

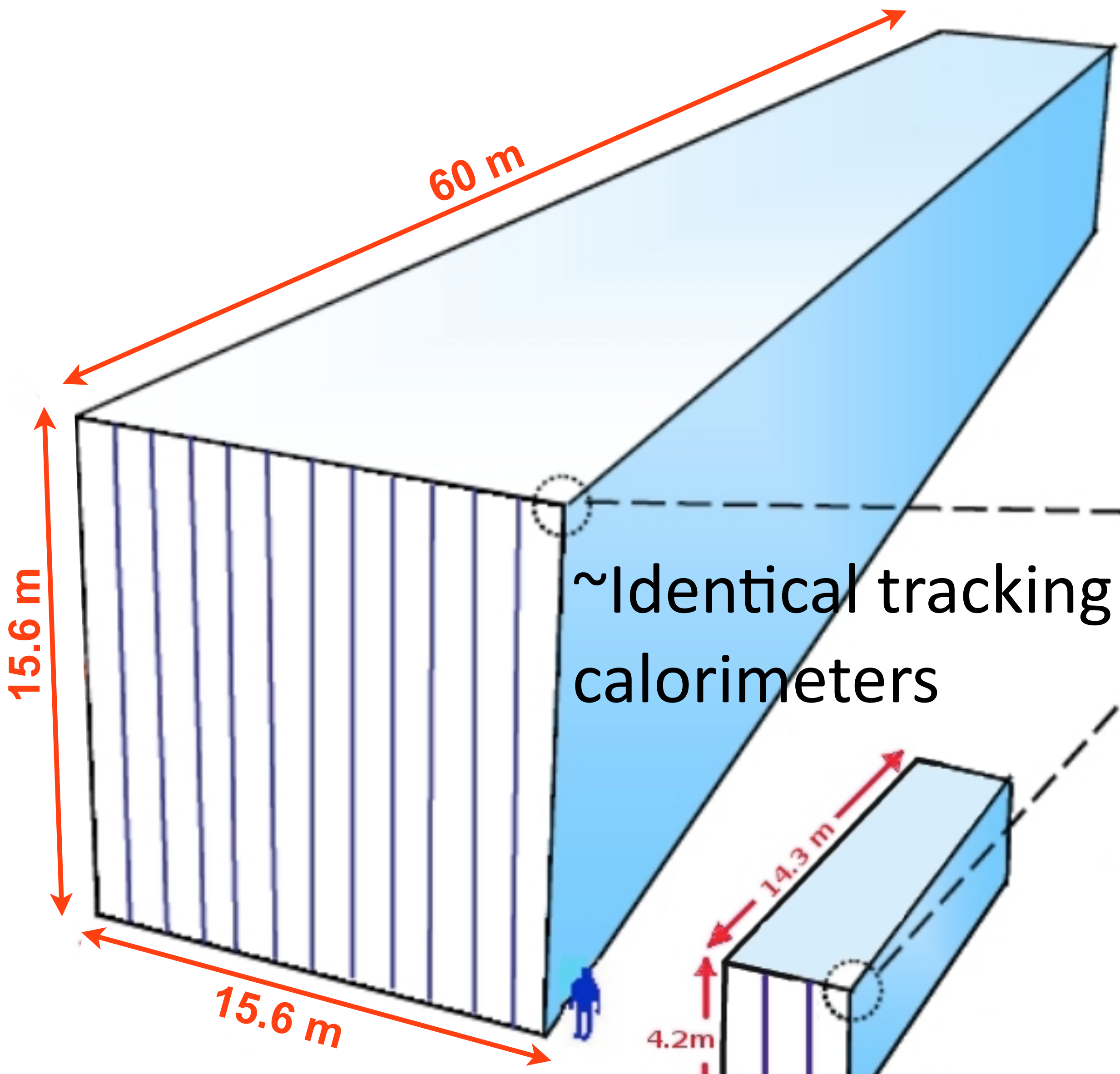






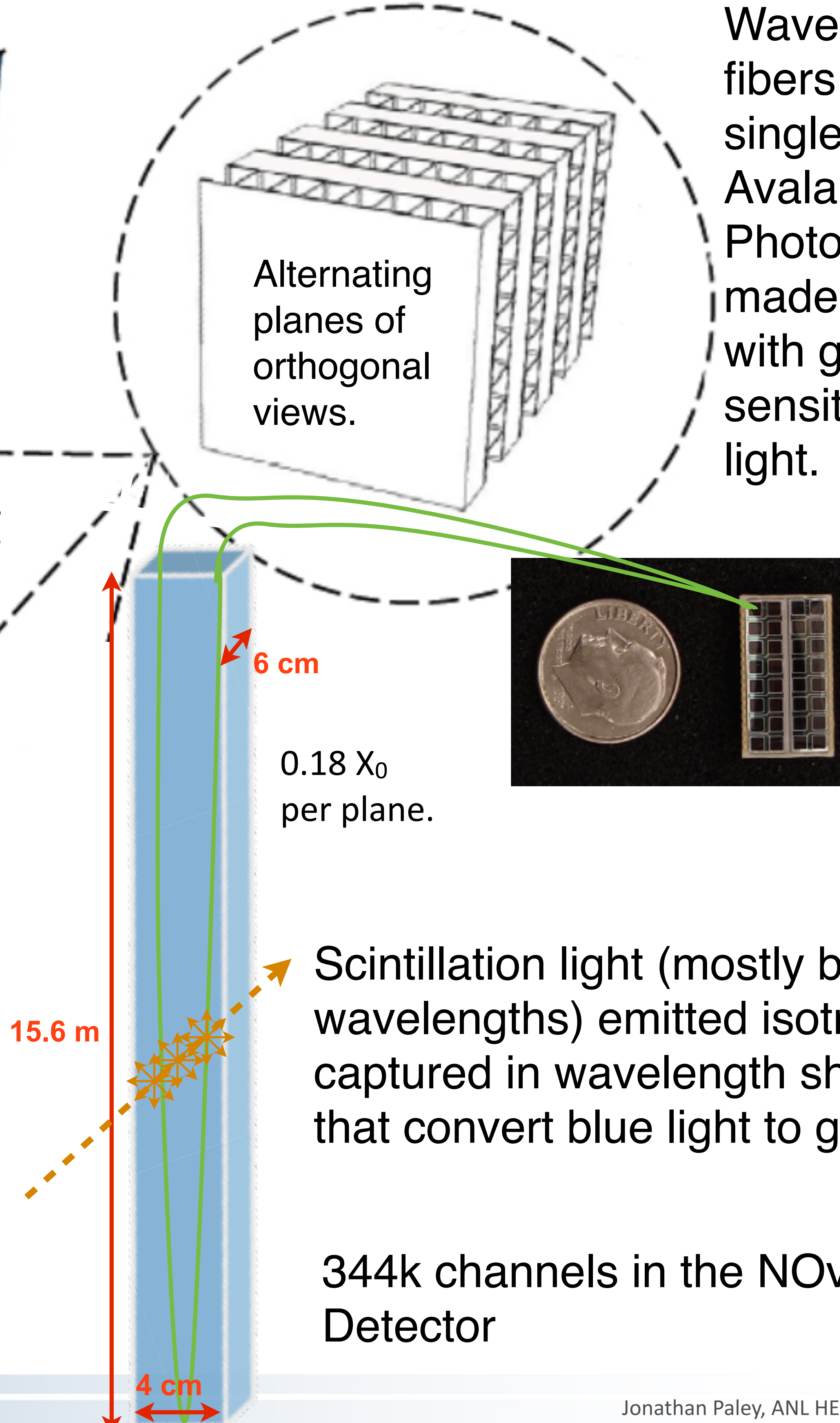
- Spill repetition rate already increased from 2.1 to 1.33 s/spill
- Target station upgraded to handle the increased power and provide the desired neutrino energy beam
- Currently average beam power is ~280 kW
- Hope to ramp to 500 kW through end of 2014 by use of recycler accelerator
- Limited in short-term to 500 kW until Booster RF system upgrades are complete.

The NOvA 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.

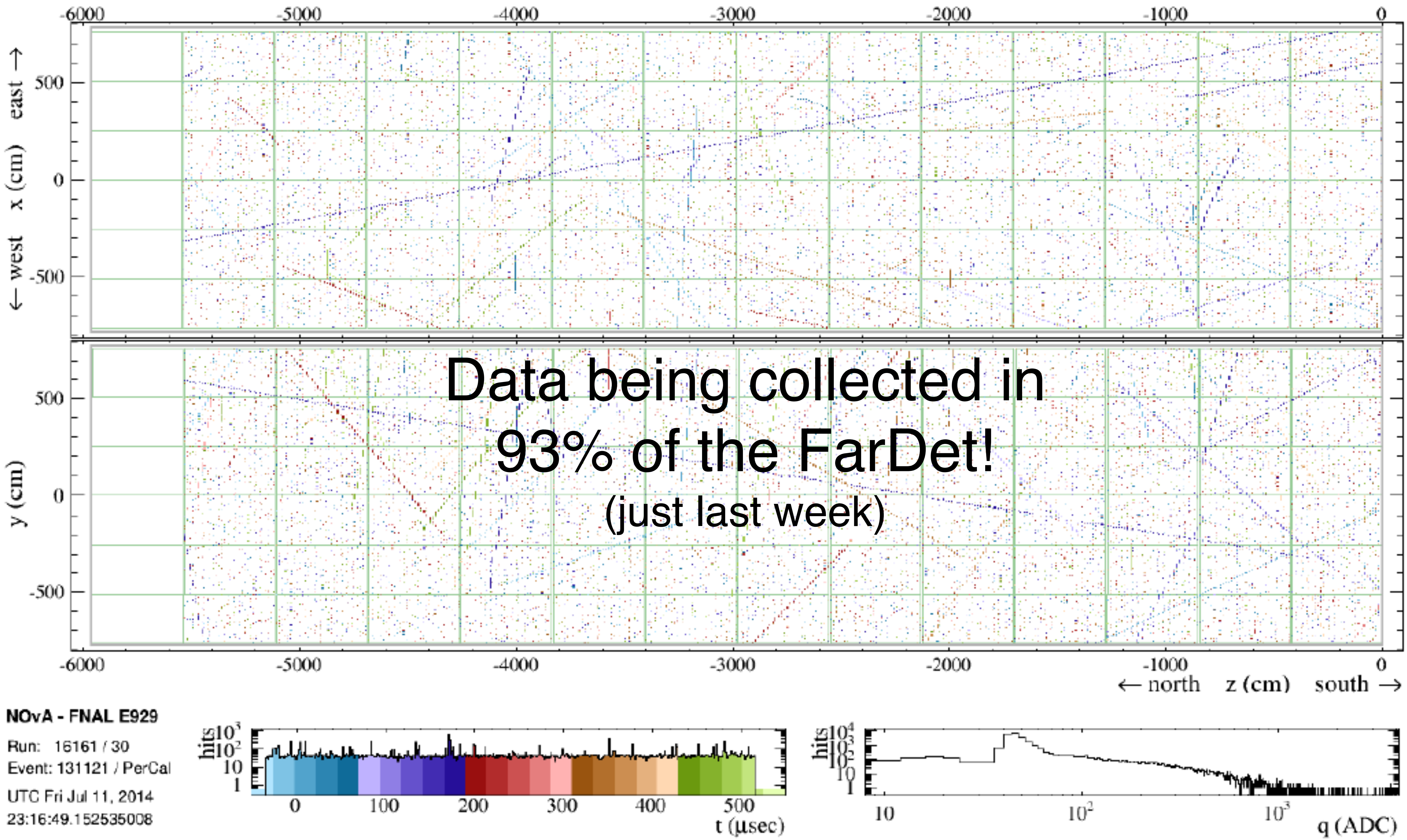
Scintillation light (mostly blue wavelengths) emitted isotropically and captured in wavelength shifting fibers that convert blue light to green.

344k 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

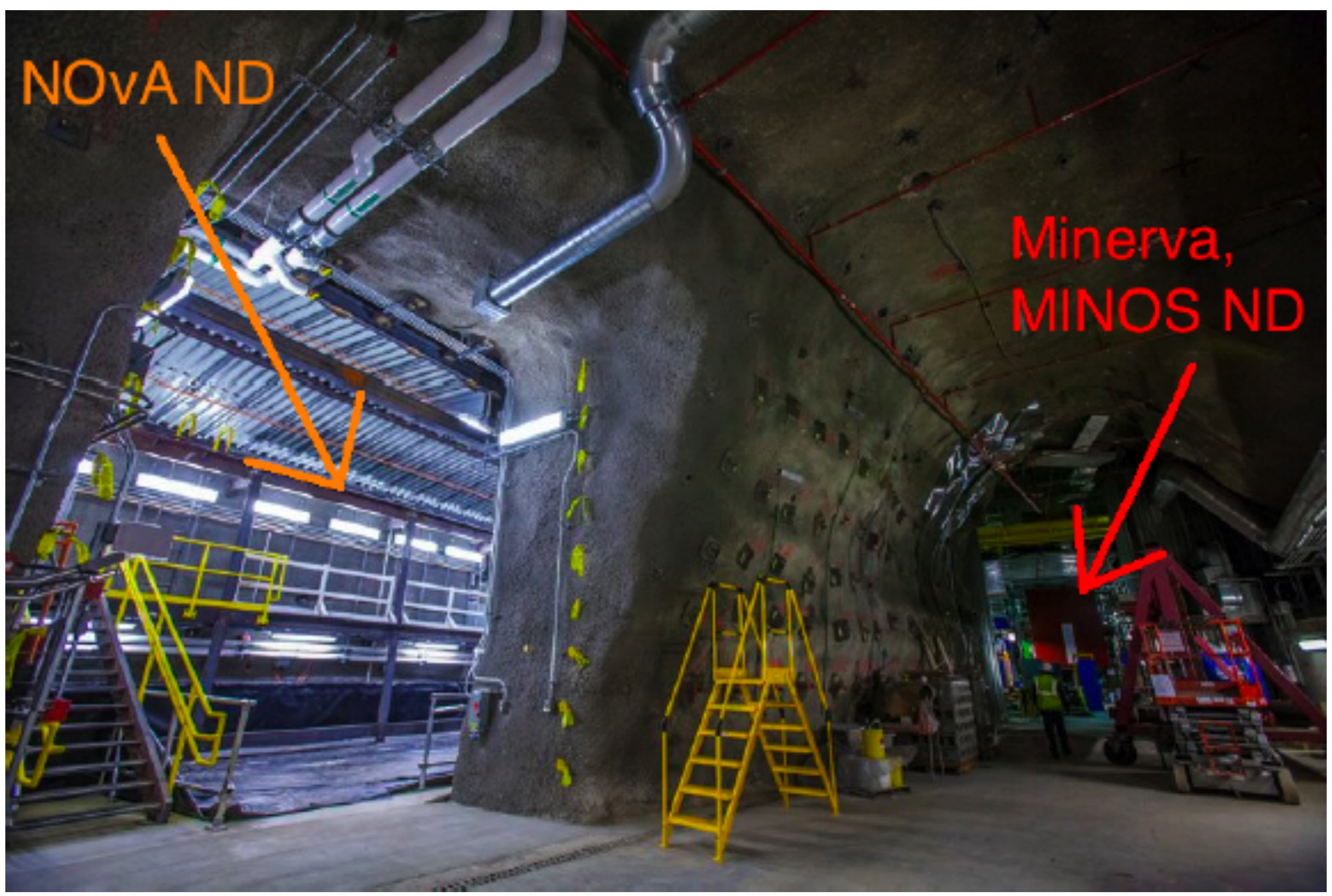
NOvA Far Detector - Nearly Complete!



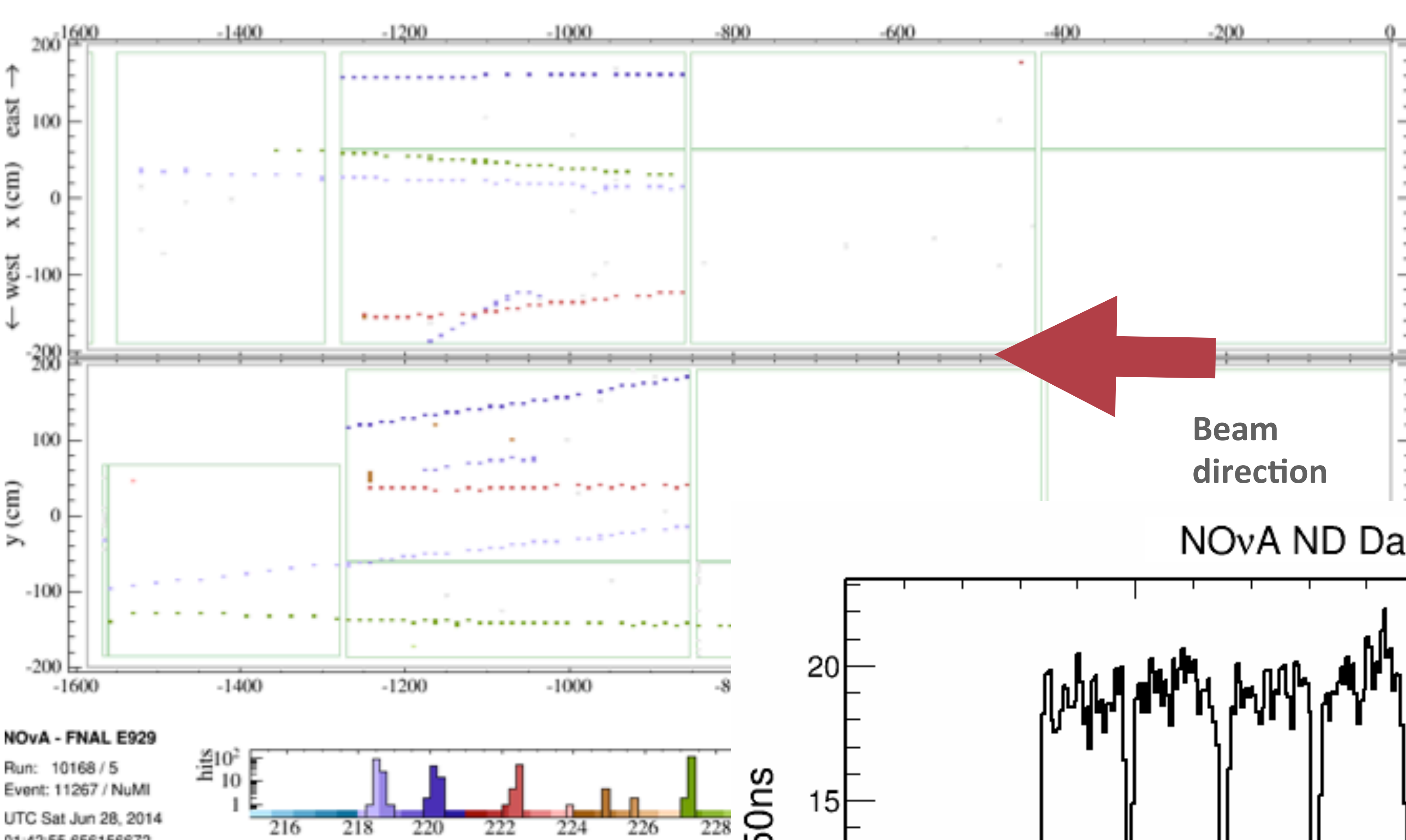
NOvA Far Detector - Complete!

NOvA Near Detector Construction

- Detector construction complete
- FEB installation complete
- APD installation nearly complete, expect to have a few weeks of a full NearDet operating before the upcoming accelerator shutdown.

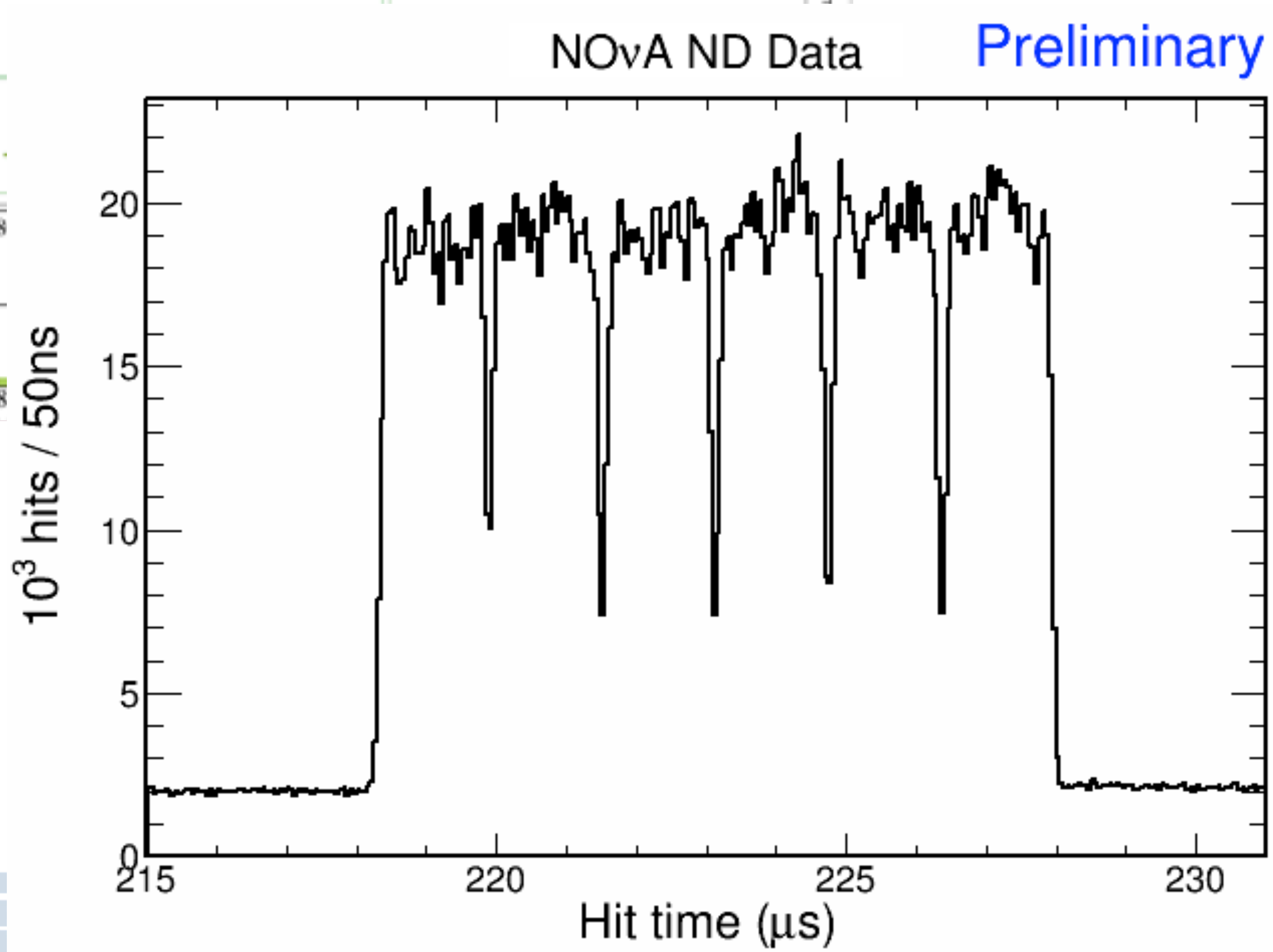


Neutrinos in the NOvA Near Detector

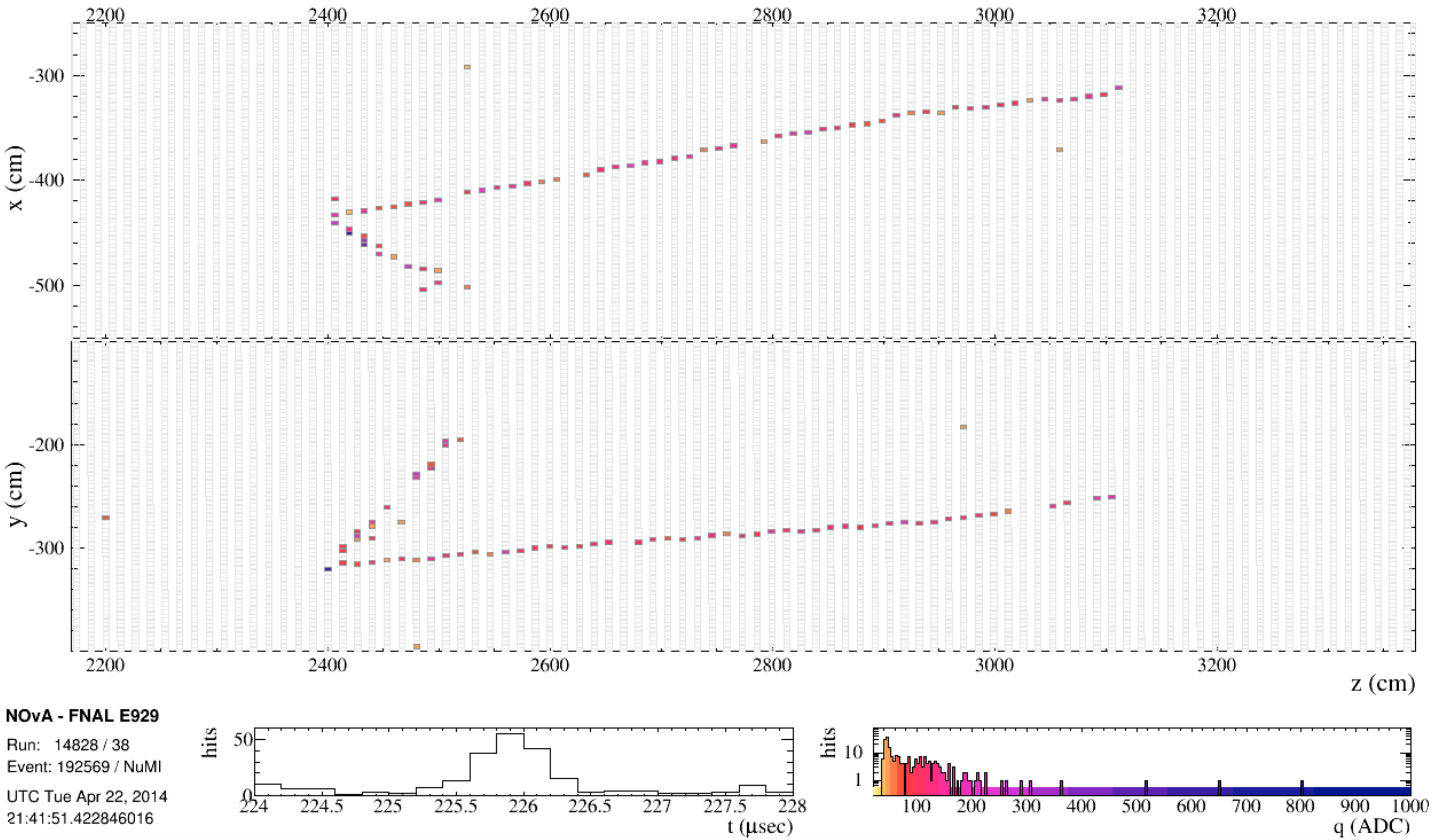


- Only part of the detector instrumented and read out
- APD gains 25x less than FarDet

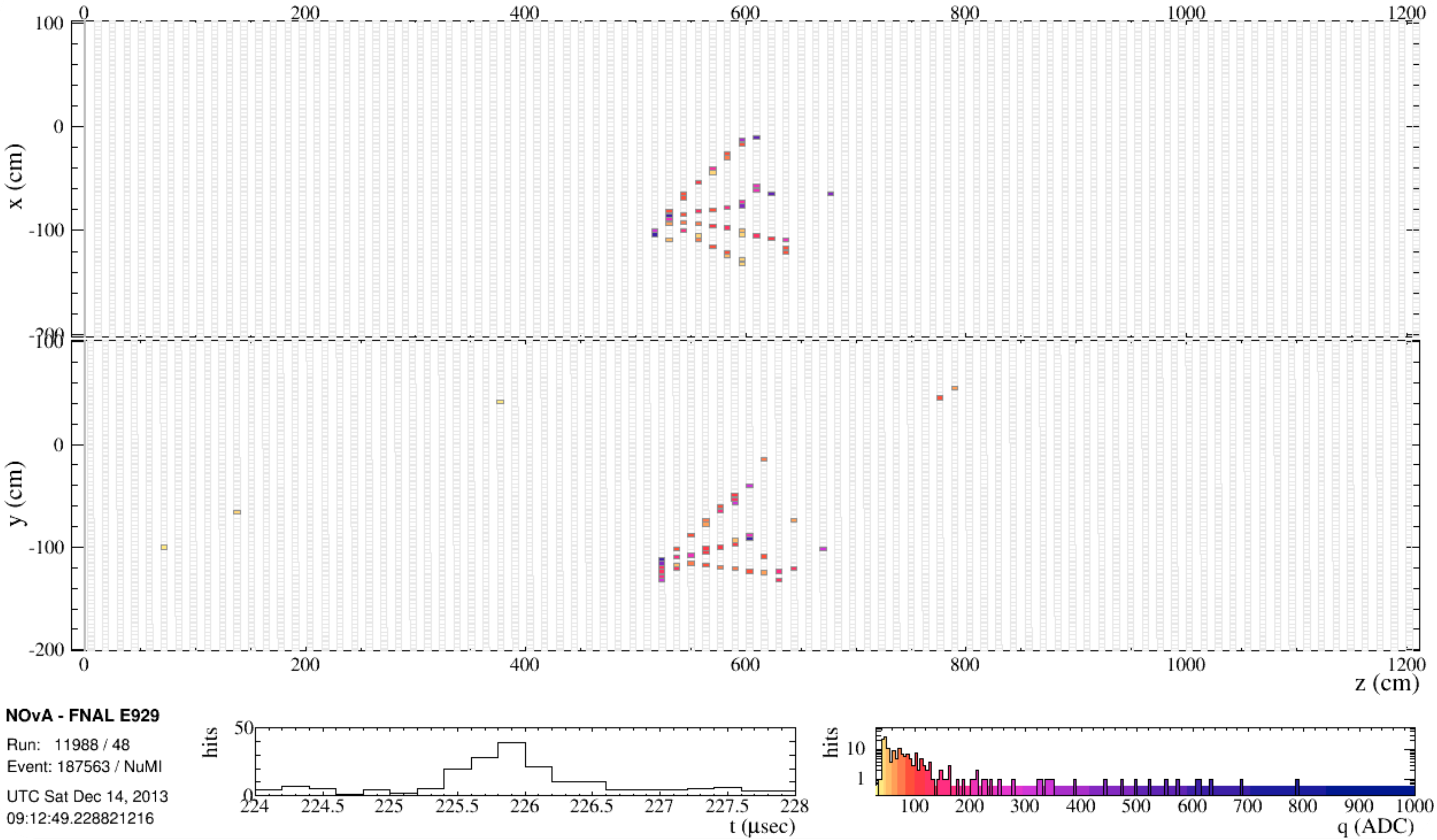
- Raw hit multiplicities
- Pulse shape information used for accurate timing
- Beam spill structure observed within just a few hours of running



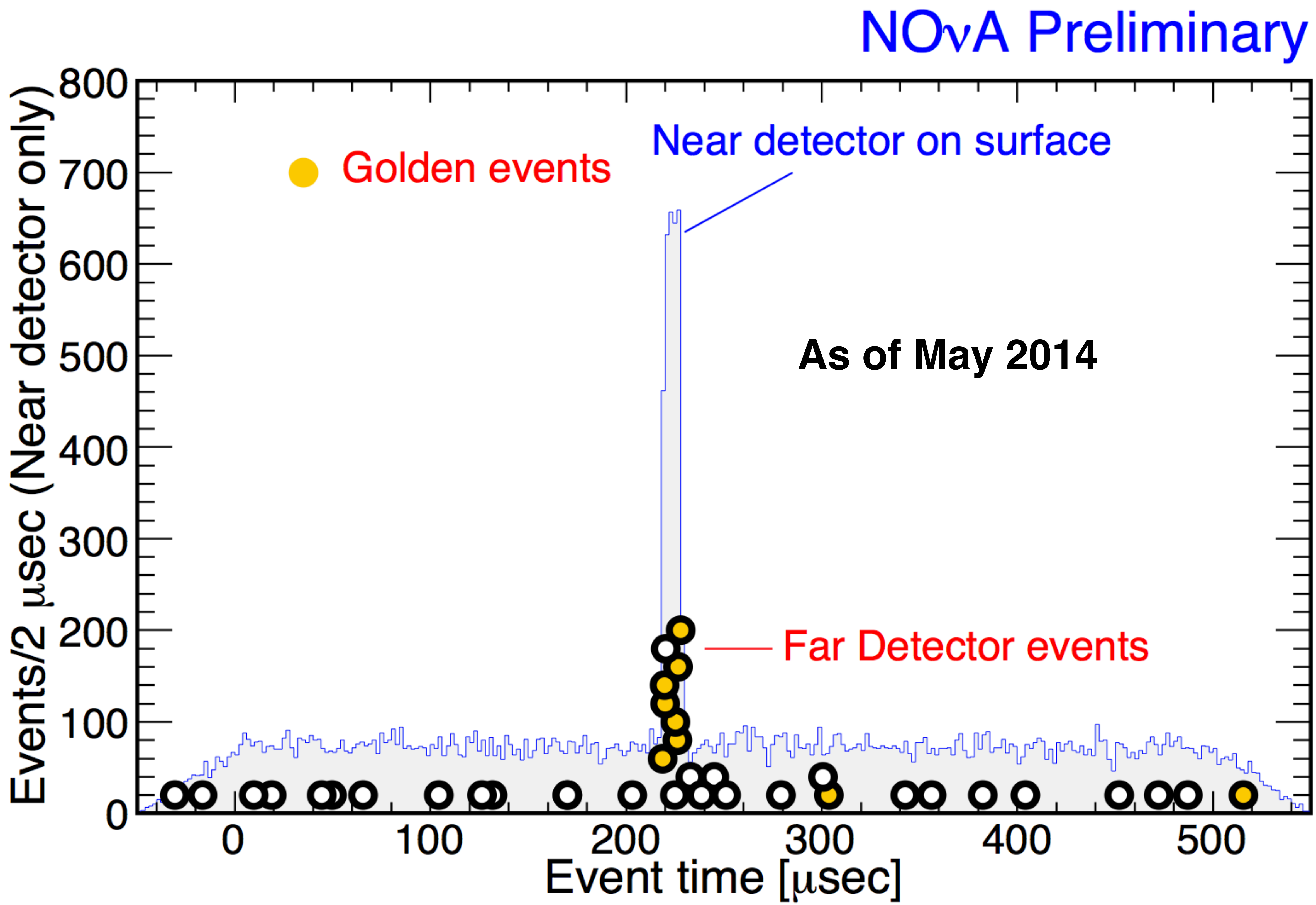
Neutrino Candidates in the NOvA Far Detector



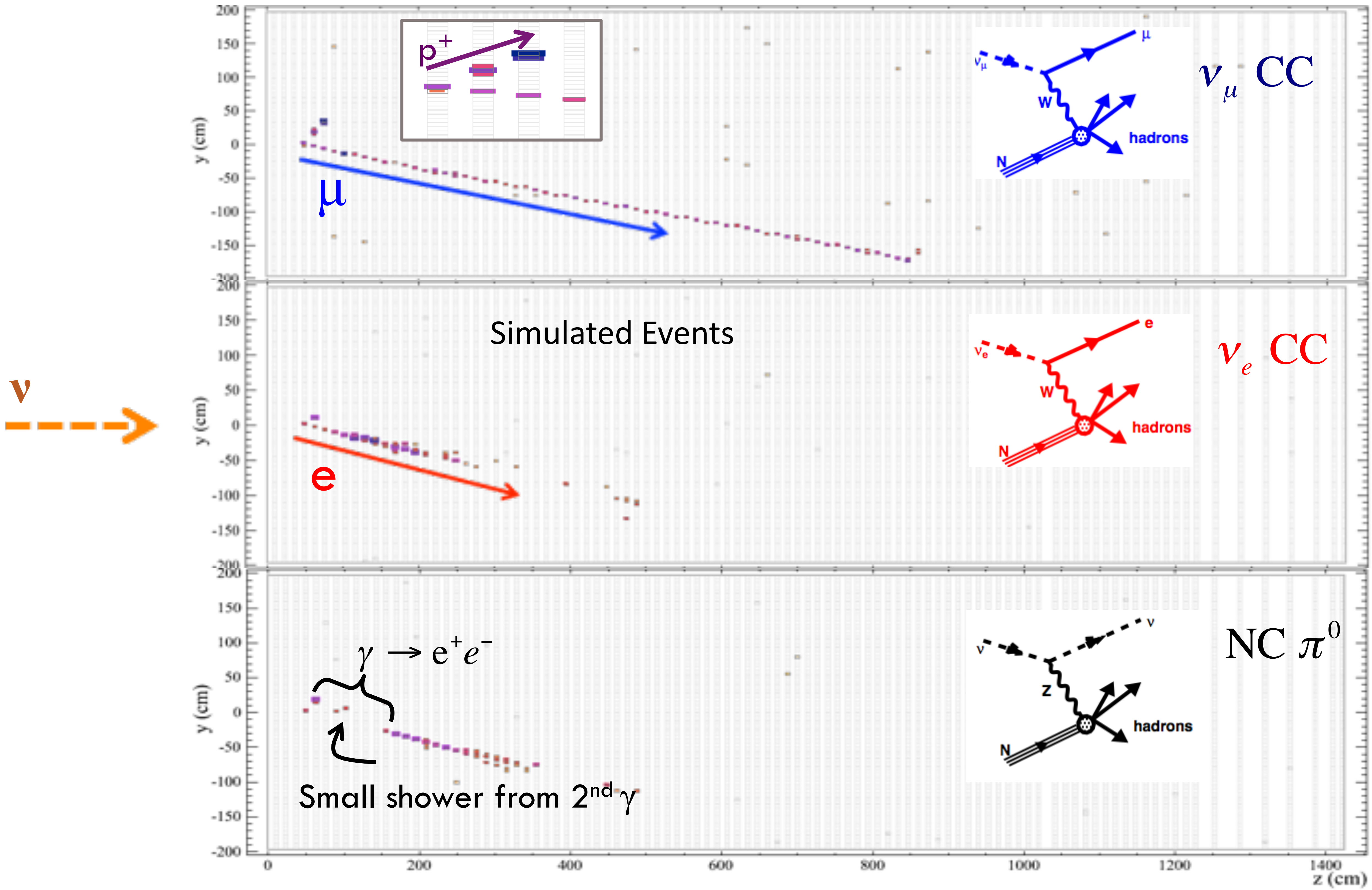
Neutrino Candidates in the NOvA Far Detector



Time Distribution of Neutrino Candidates in the NOvA Far Detector



Distinguishing Neutrino Events in NOvA



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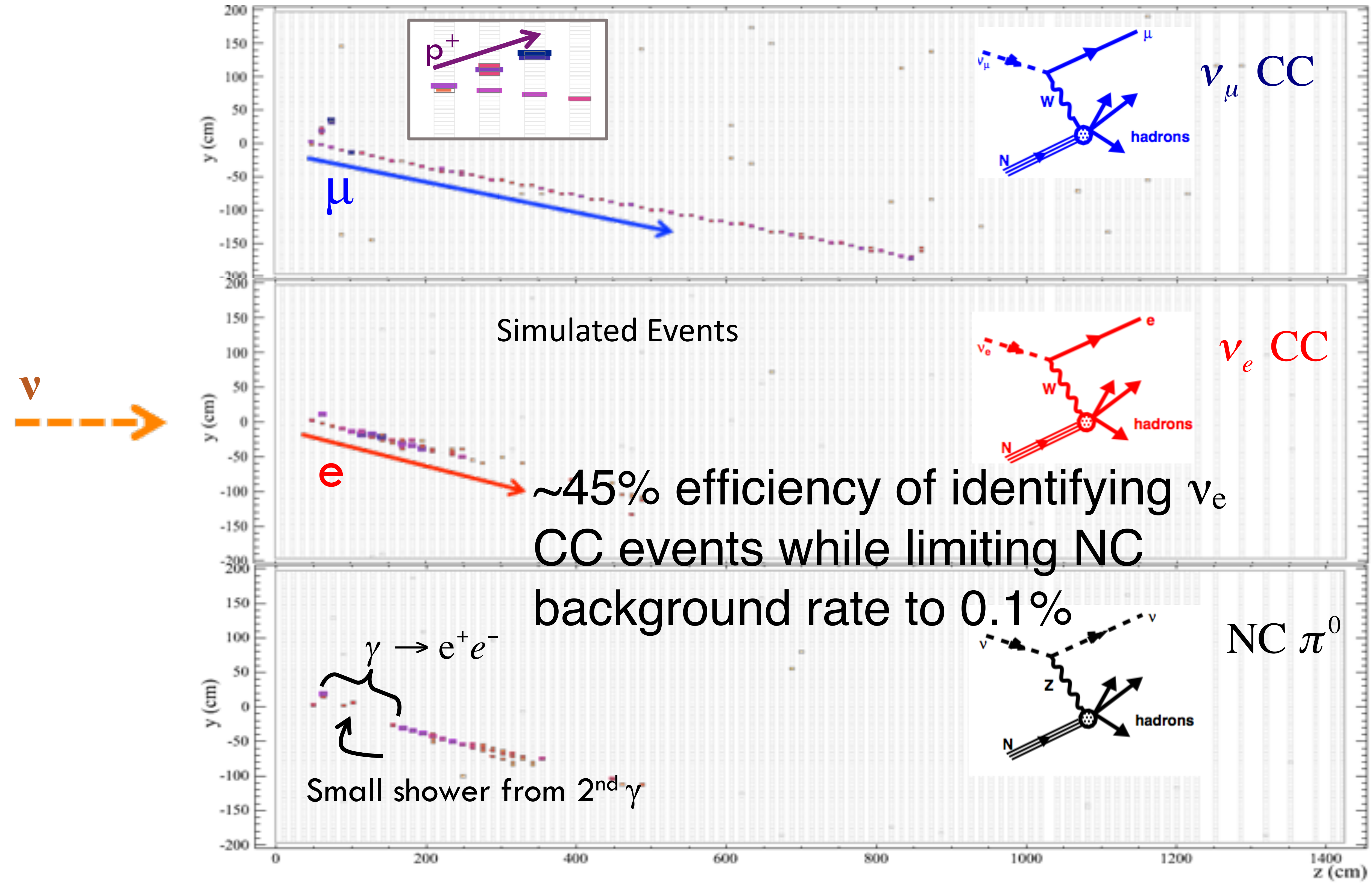
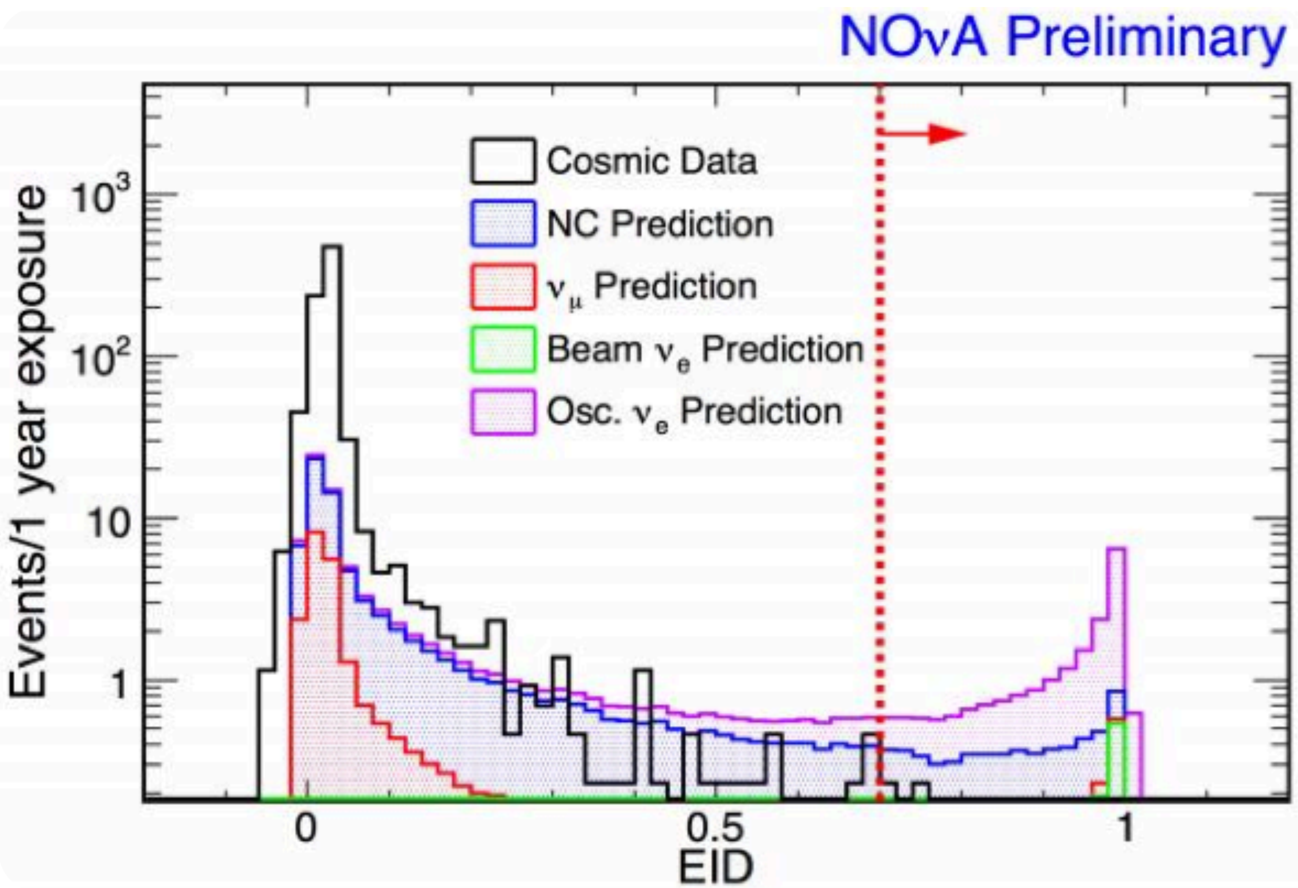
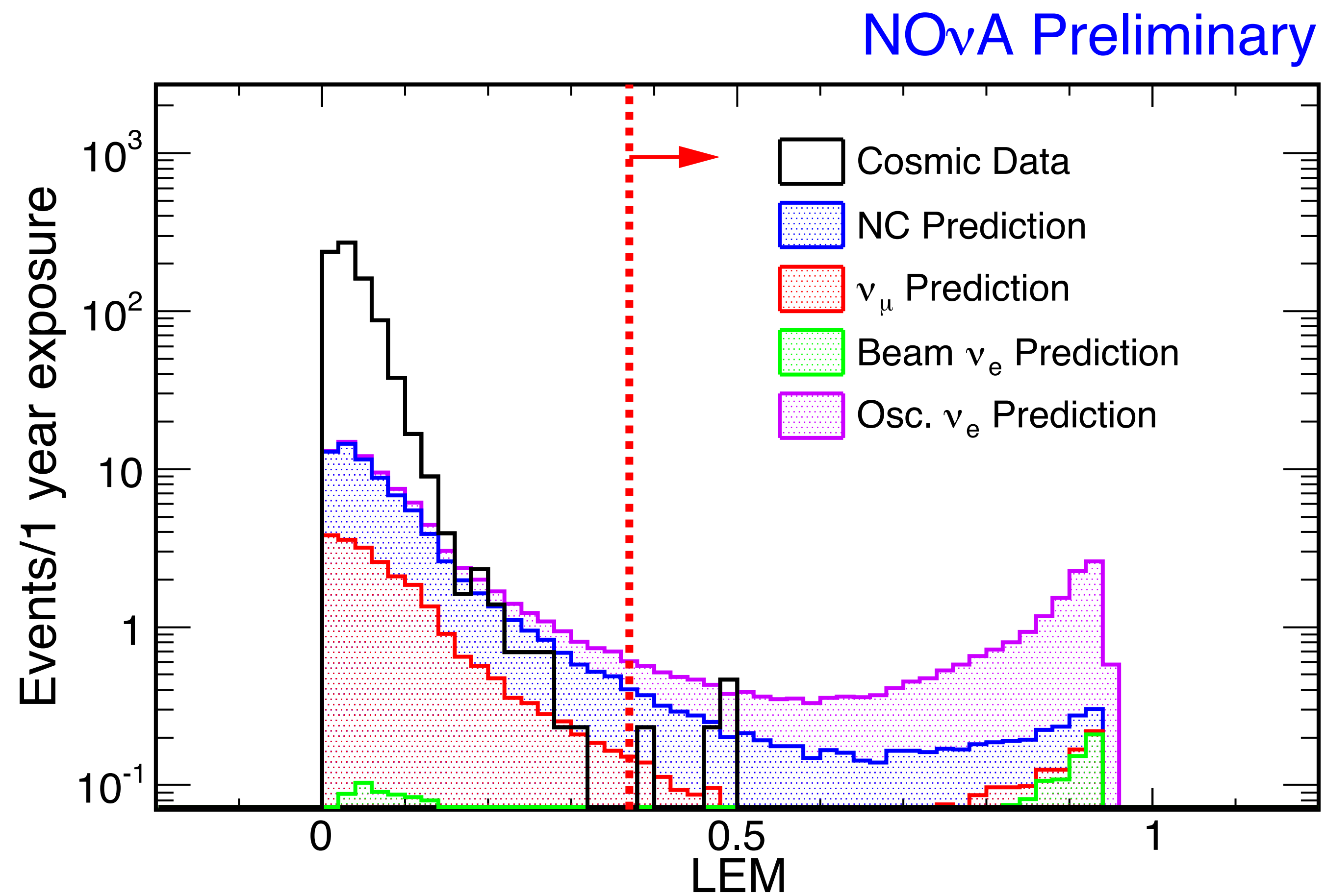


~45% efficiency of identifying ν_e CC events while limiting NC background rate to 0.1%

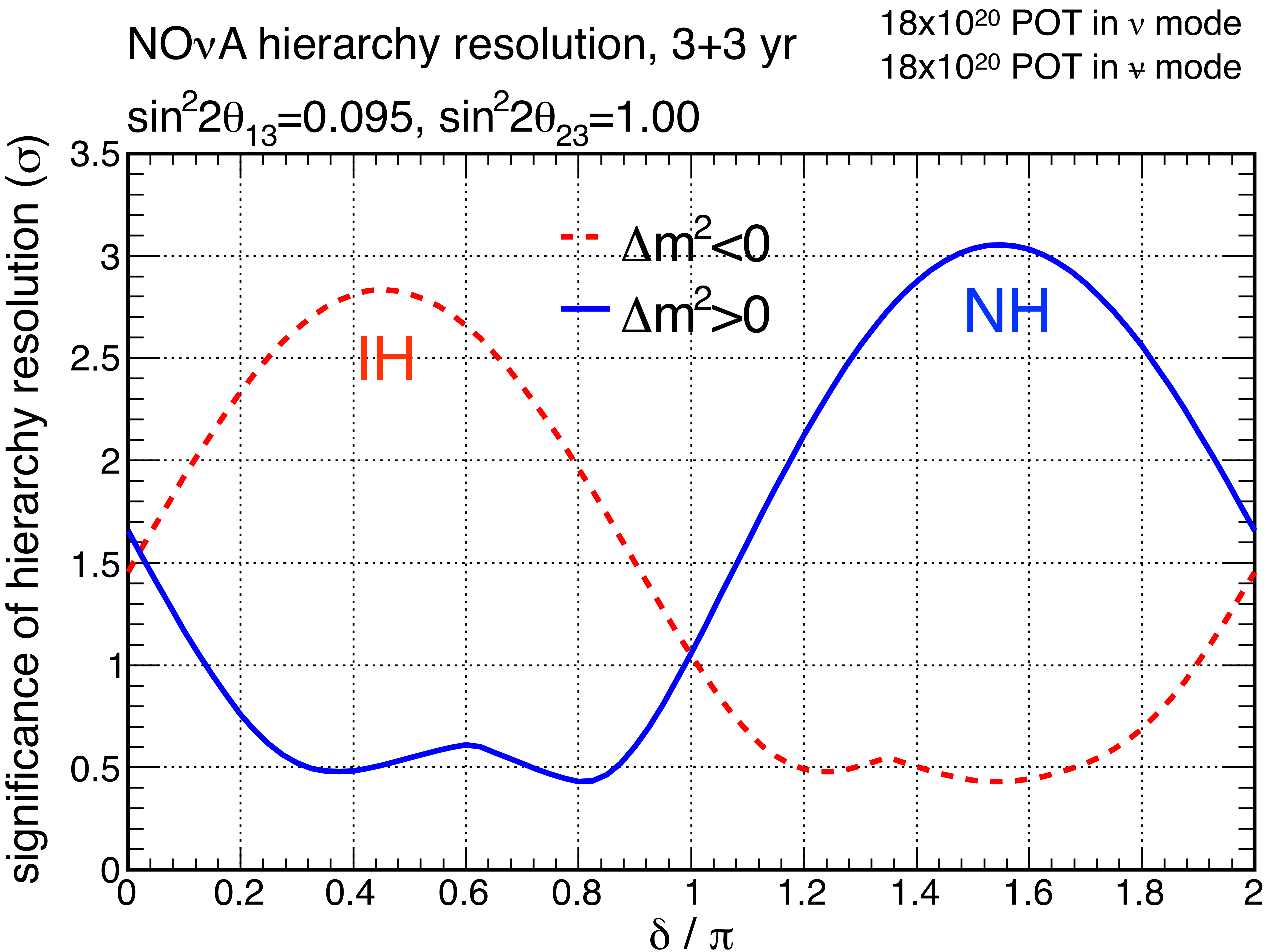
Distinguishing ν_e Events in NOvA



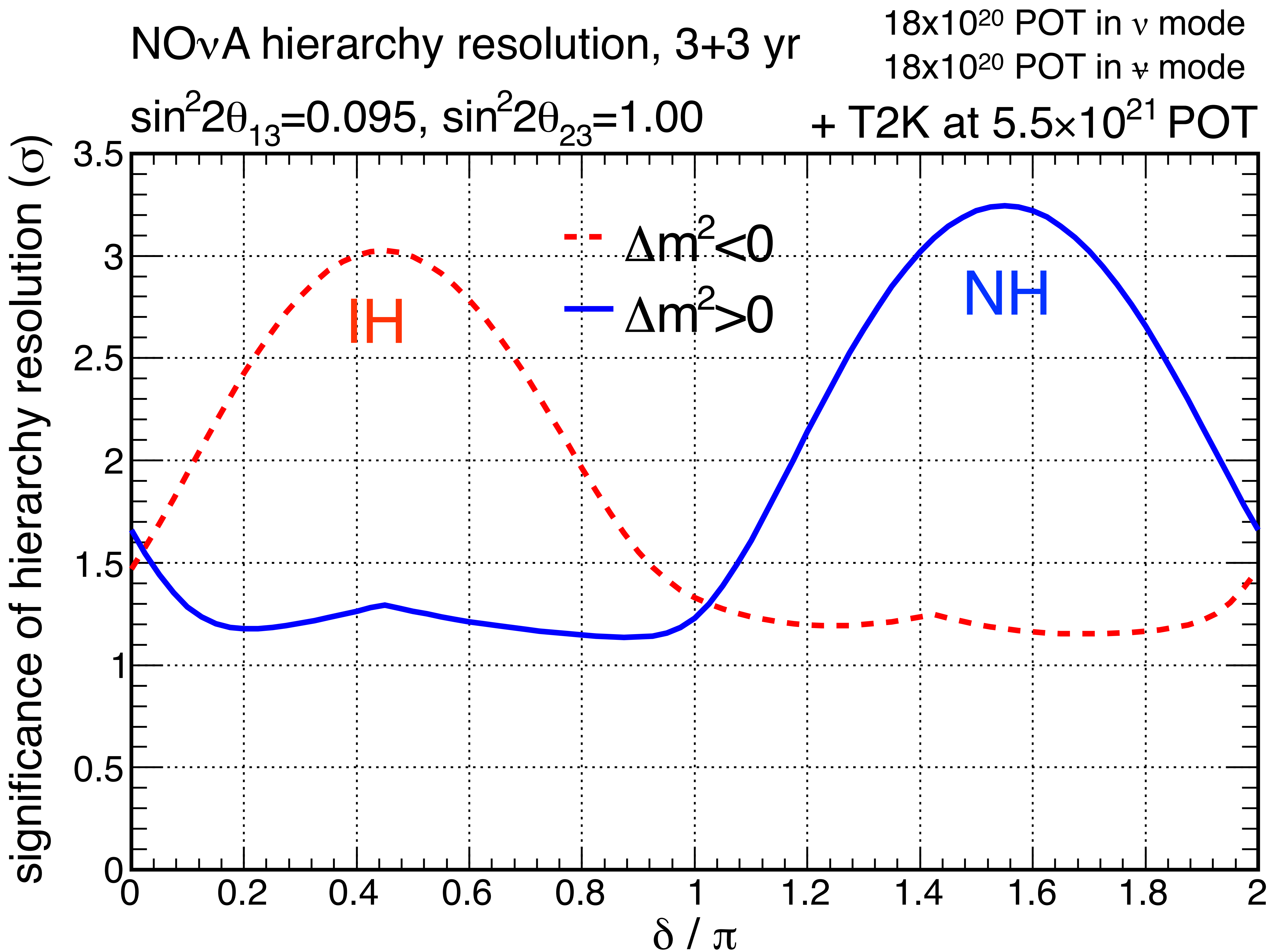


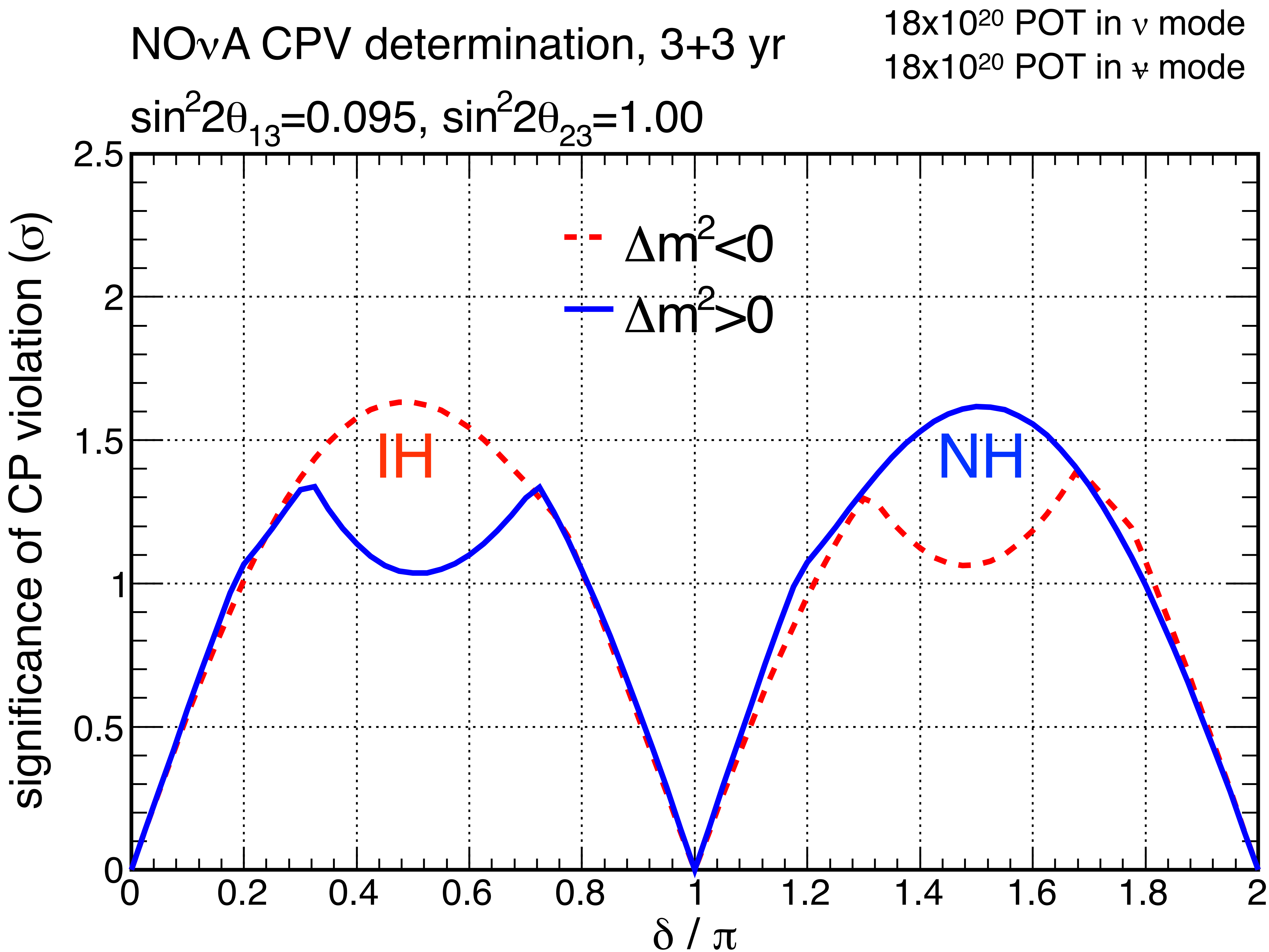
	Osc ν_eCC	Beam Bkg	Cosmic Bkg
1 yr Nominal Exposure			
	36.7	965	19M
Containment & quailty	24.7	106	55k
Cosmic Rejection	21.2	82.9	834
ν_e selection	13.9	6.0	0.46

- Cosmic ray background rejection of $40\text{x}10^6$:1 achieved using a variety of cuts
- Several event identification algorithms have been developed to separate the small ν_e signal from various backgrounds, all with similar performance
- With a 3+3 year run, N(ν_e) ≃ 68 (statistics limited!)

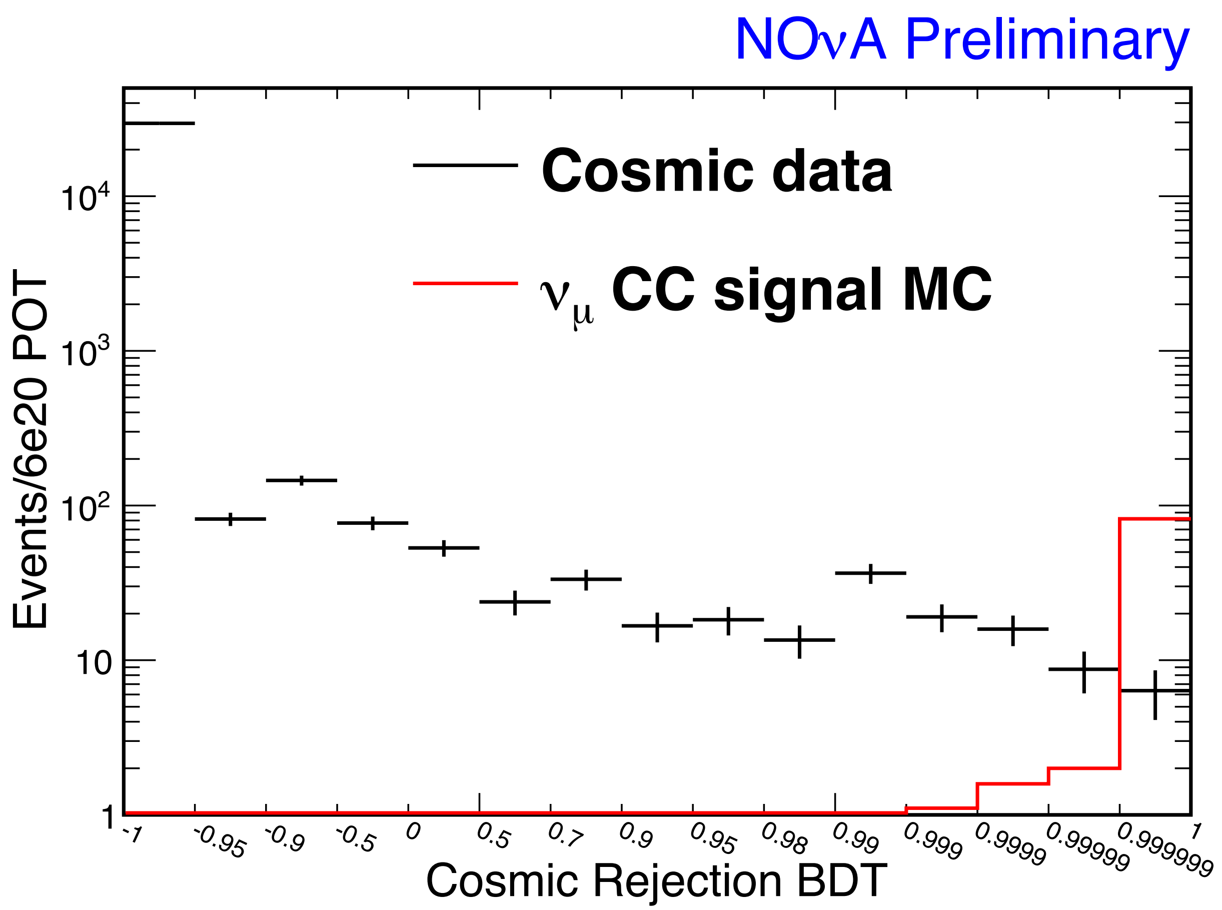


NOνA hierarchy resolution, 3+3 yr
$\sin^2 2\theta_{13}$=0.095, $\sin^2 2\theta_{23}$=1.00
18x10[20] POT in ν mode
18x10[20] POT in $\bar{\nu}$ mode
$\Delta m^2<0$
$\Delta m^2>0$
IH
NH
significance of hierarchy resolution (σ)
δ / π

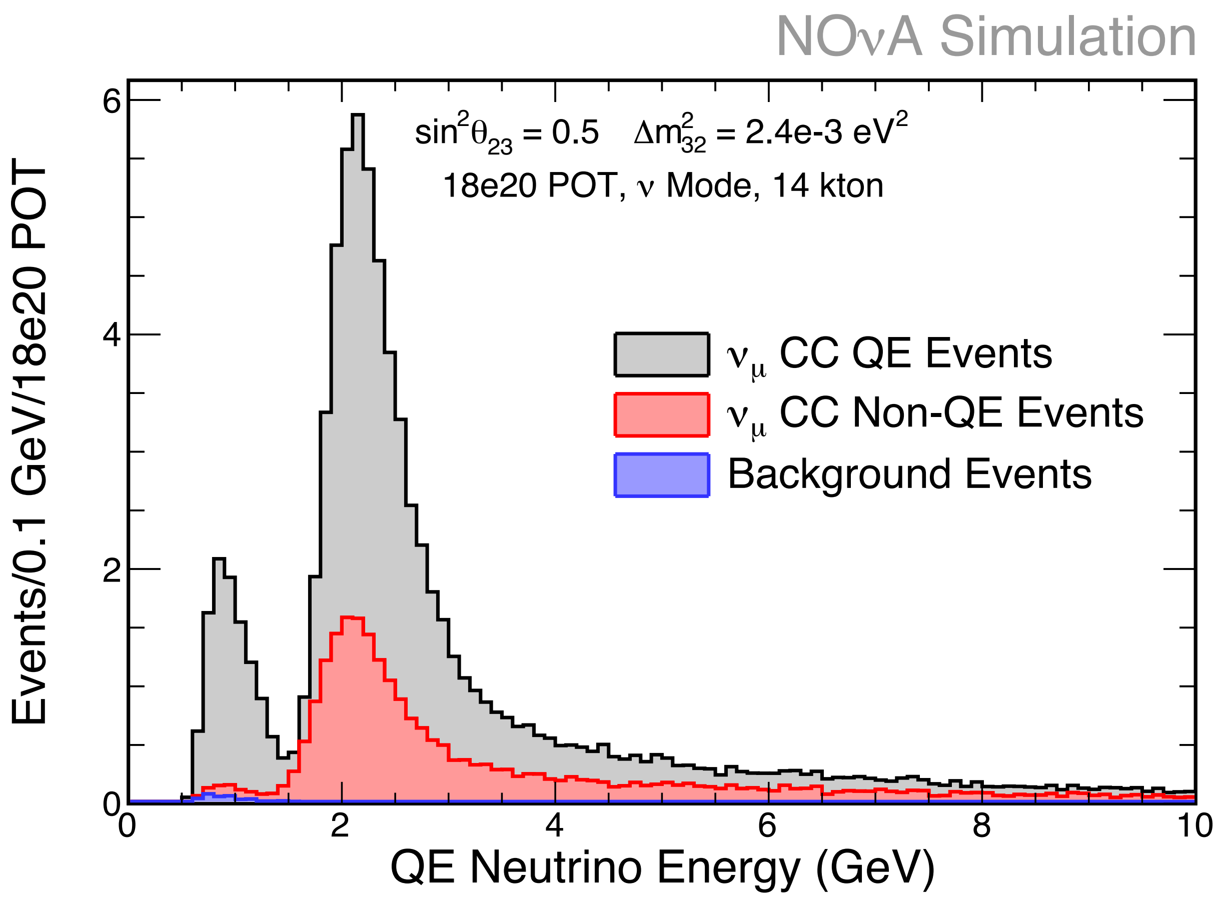

NOνA hierarchy resolution, 3+3 yr
18x10^20 POT in ν mode
18x10^20 POT in ν̄ mode
sin²2θ13=0.095, sin²2θ23=1.00
+ T2K at 5.5×10^21 POT
Δm²<0
Δm²>0
IH
NH
significance of hierarchy resolution (σ)
δ / π
0
0.5
1
1.5
2
2.5
3
3.5
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8


NOνA CPV determination, 3+3 yr
$\sin^2 2\theta_{13}=0.095$, $\sin^2 2\theta_{23}=1.00$
18×10^{20} POT in ν mode
18×10^{20} POT in $\bar{\nu}$ mode
$\Delta m^2<0$
$\Delta m^2>0$
IH
NH
significance of CP violation (σ)
δ / π
0
0.5
1
1.5
2
2.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

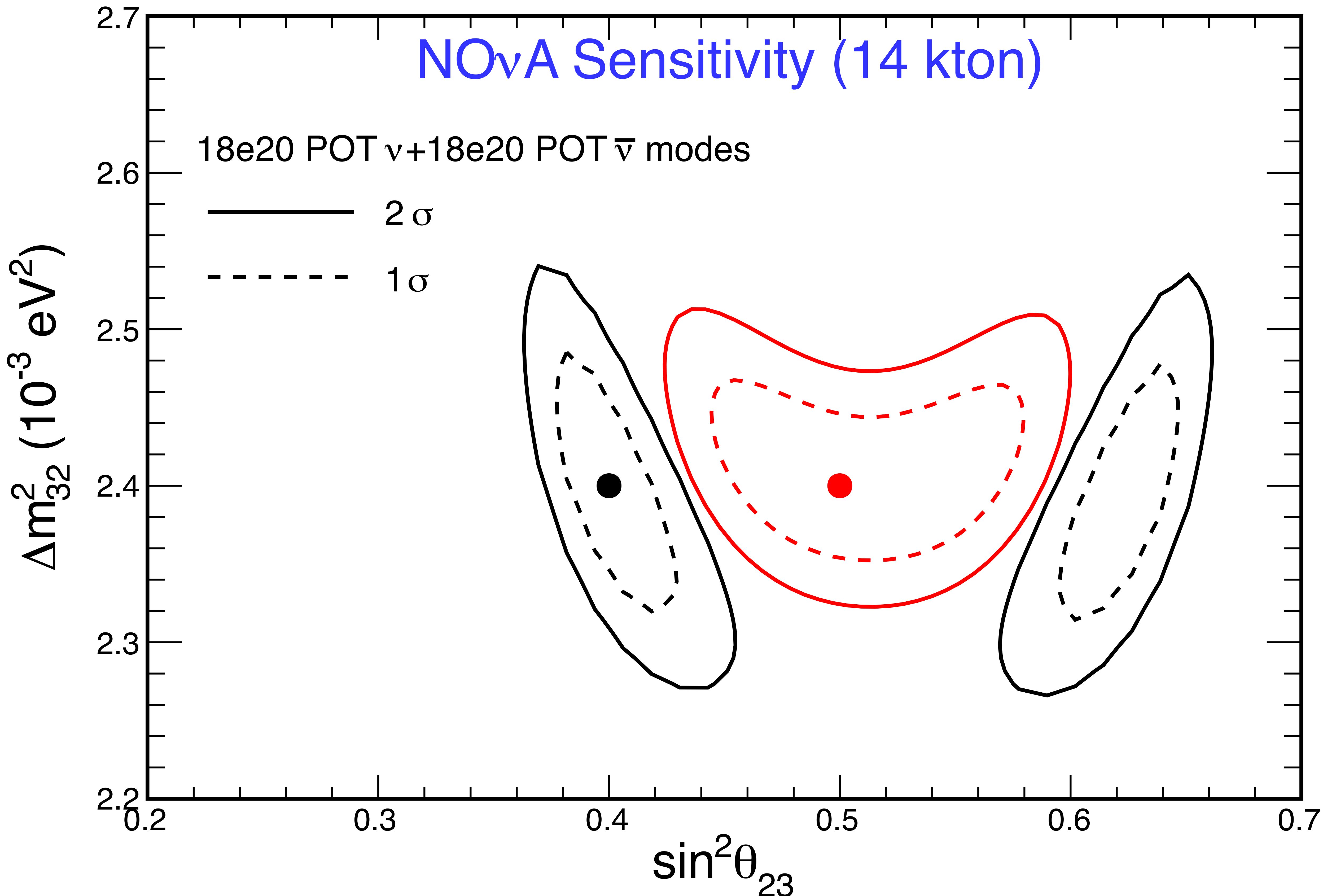
Distinguishing ν_μ Events in NOvA

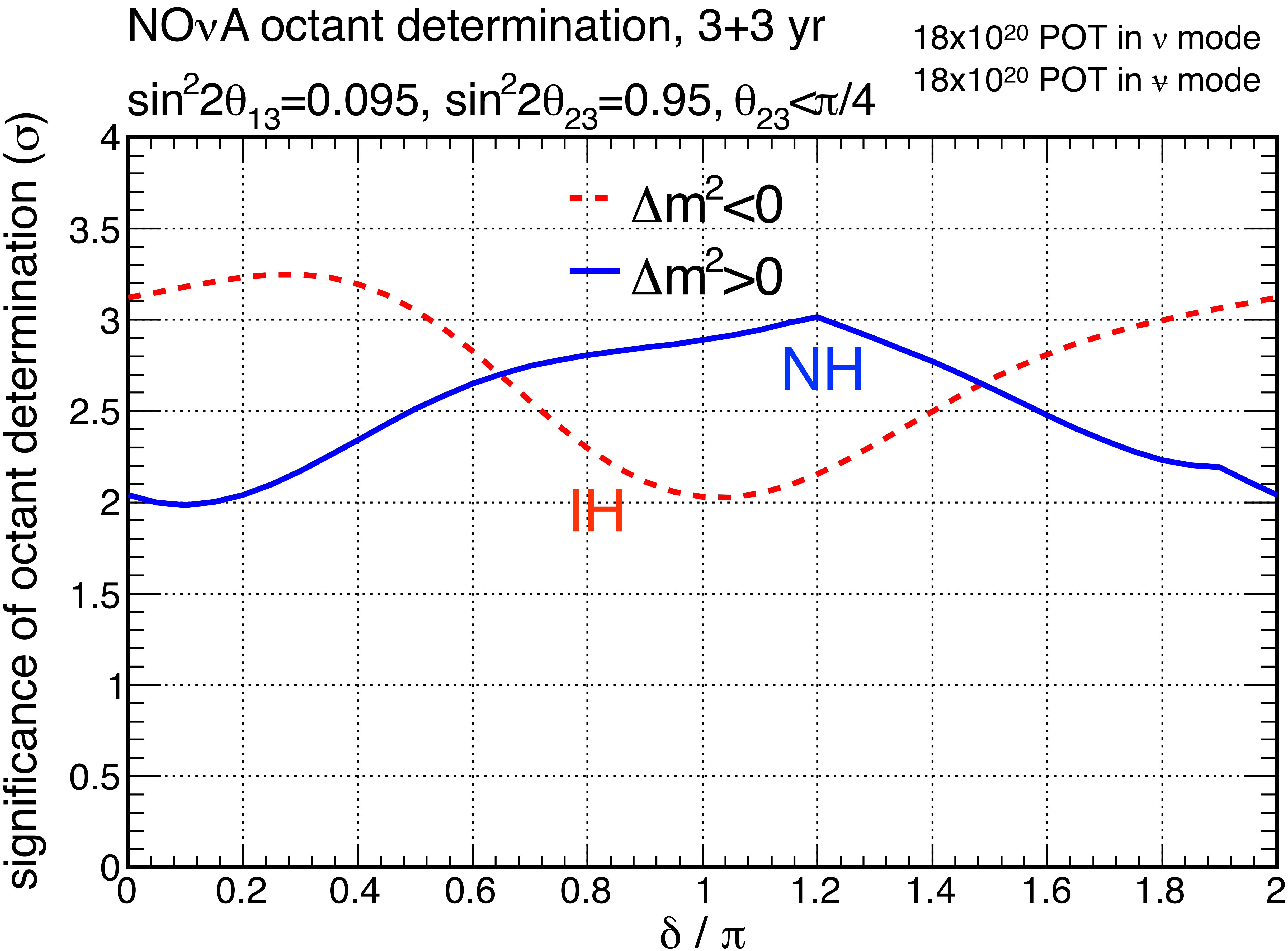


- Boosted decision tree used to reject cosmic ray backgrounds; 20M:1 rejection achieved.
- Muon tracks identified using a multivariate analysis based on reconstructed dE/dx, track length, scattering



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


NOνA Sensitivity (14 kton)
18e20 POT ν+18e20 POT ν̄ modes
2 σ
1 σ
Δm²₃₂ (10⁻³ eV²)
sin²θ₂₃
2.7
2.6
2.5
2.4
2.3
2.2
0.2
0.3
0.4
0.5
0.6
0.7



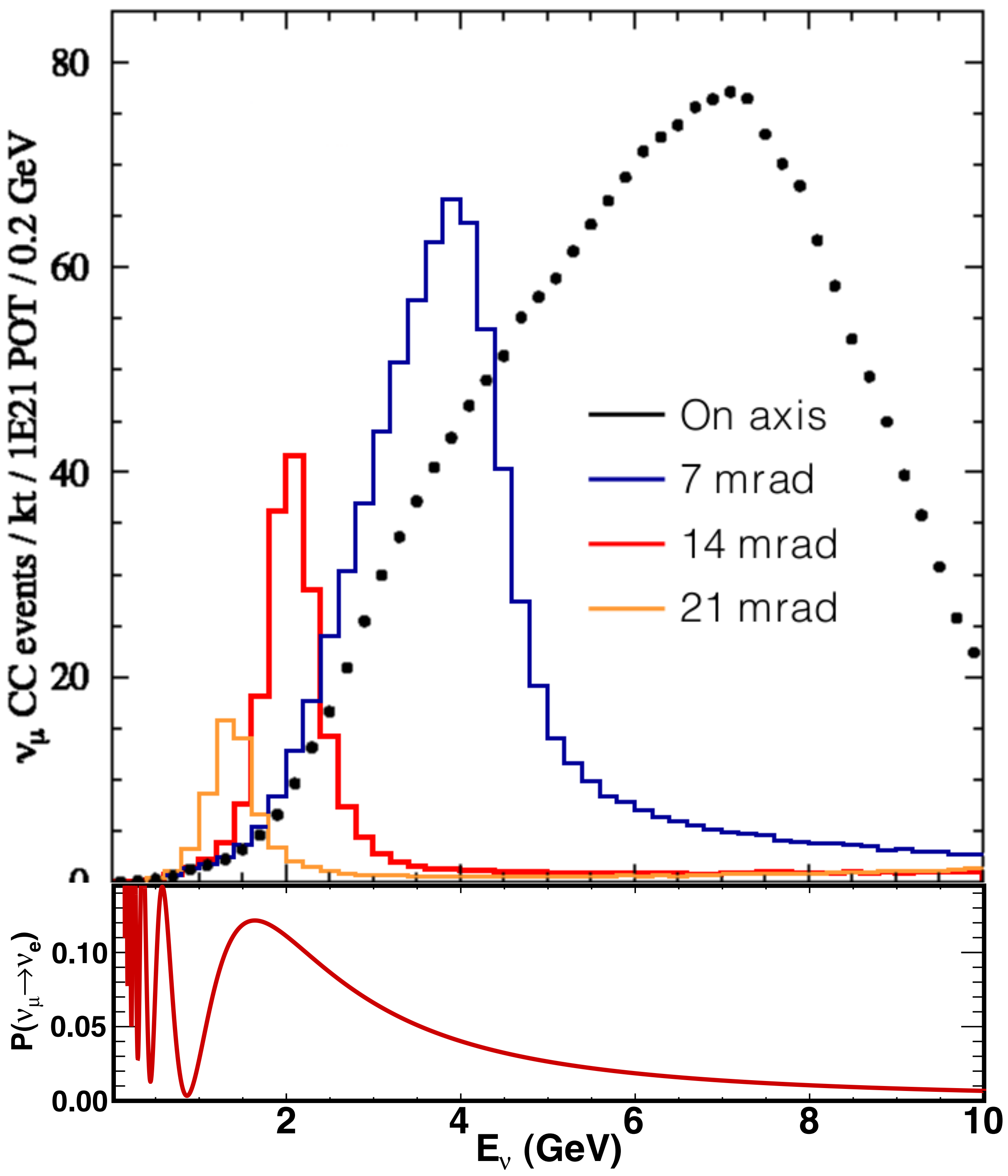
NOνA octant determination, 3+3 yr
sin²2θ₁₃=0.095, sin²2θ₂₃=0.95, θ₂₃<π/4
18x10²⁰ POT in ν mode
18x10²⁰ POT in ν̄ mode
Δm²<0
Δm²>0
NH
IH
significance of octant determination (σ)
δ / π
0
0.5
1
1.5
2
2.5
3
3.5
4
0.2
0.4
0.6
0.8
1.2
1.4
1.6
1.8

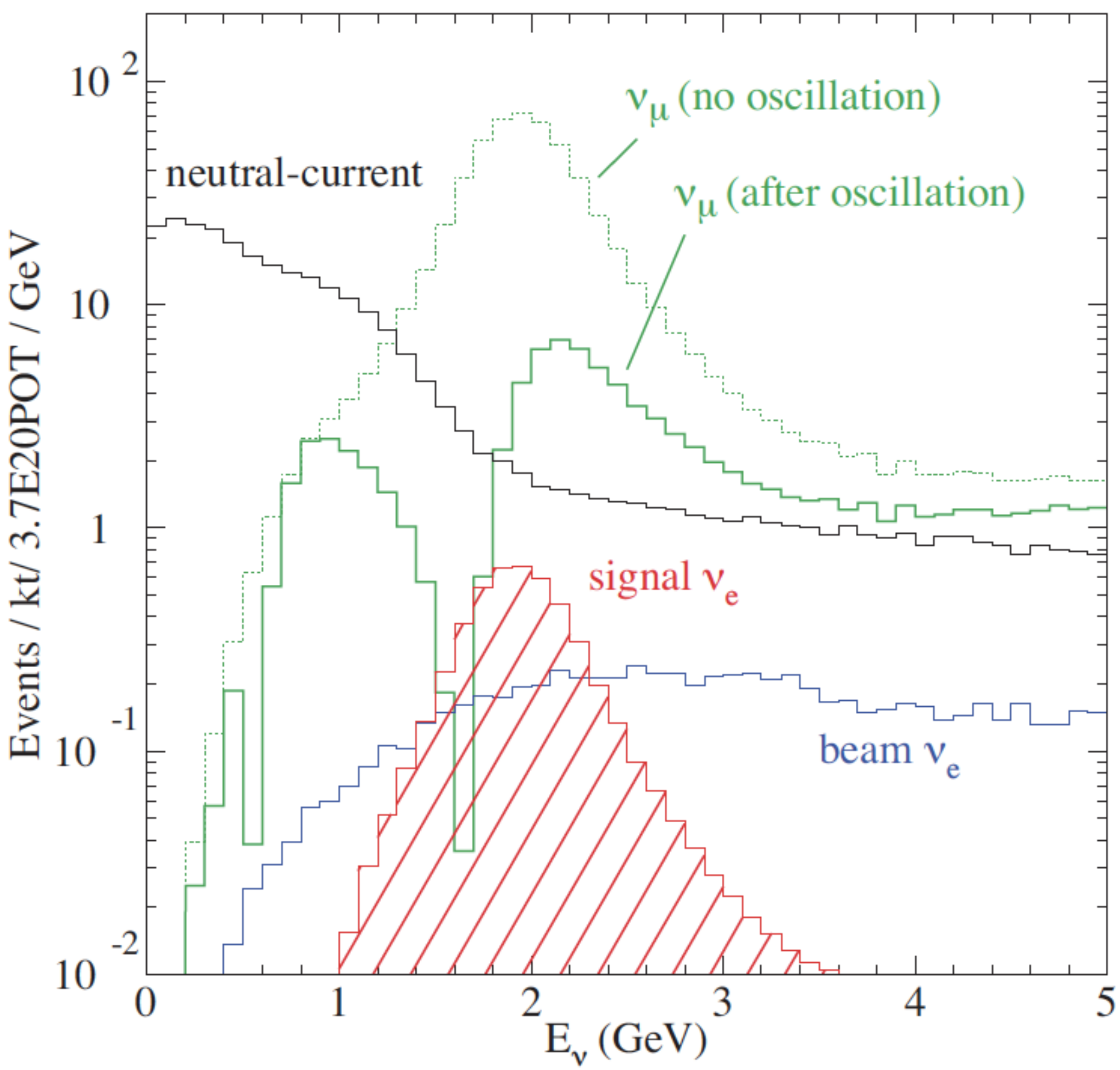
Summary

- NOvA 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
- Both Far and Near detectors are nearly complete
- First neutrinos have been observed in both detectors!
- Collaboration is very focused on commissioning of both detectors
- NuMI beam will be down for upgrades between September and October; when beam returns, we will have fully instrumented, commissioned and calibrated detectors
- Reconstruction and analysis tools are in place for first results in early 2015
- Stay tuned!

BACKUP

Why Go Off-Axis?

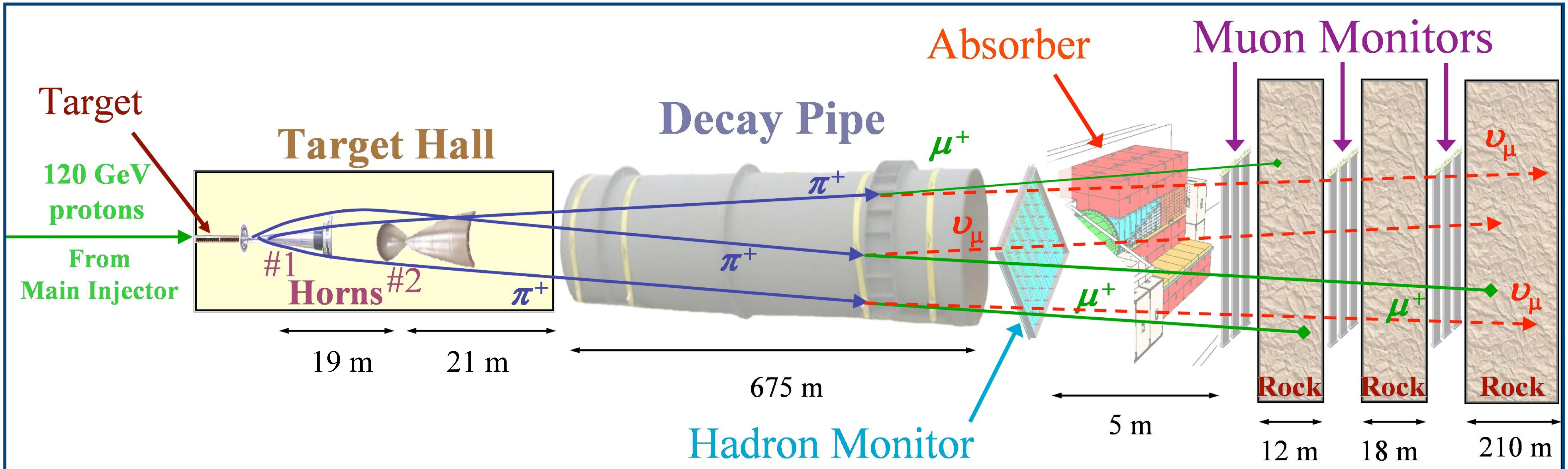




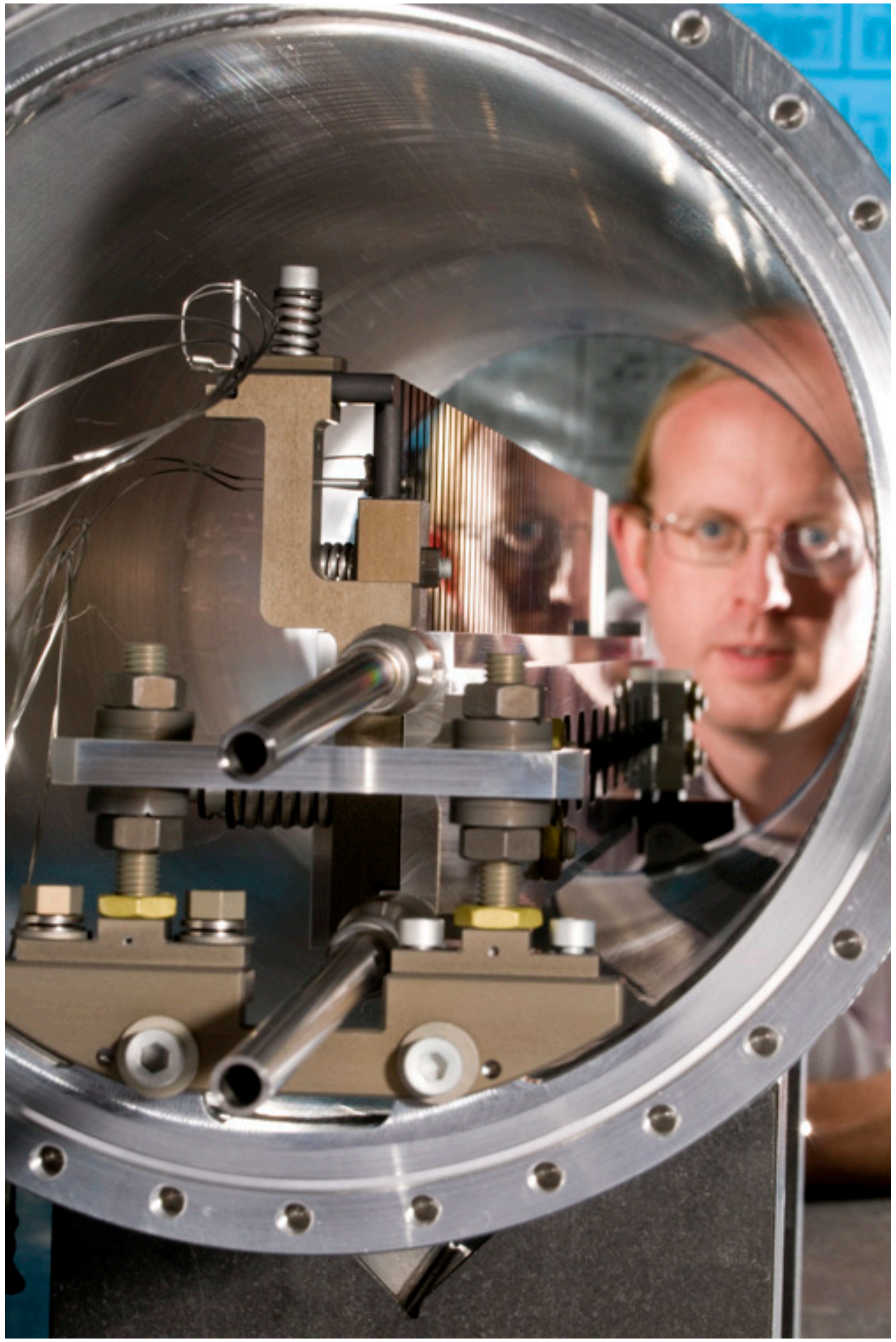
- Narrow-band beam, in conjunction with topology of final state particles, allows one to more easily reject potential backgrounds.

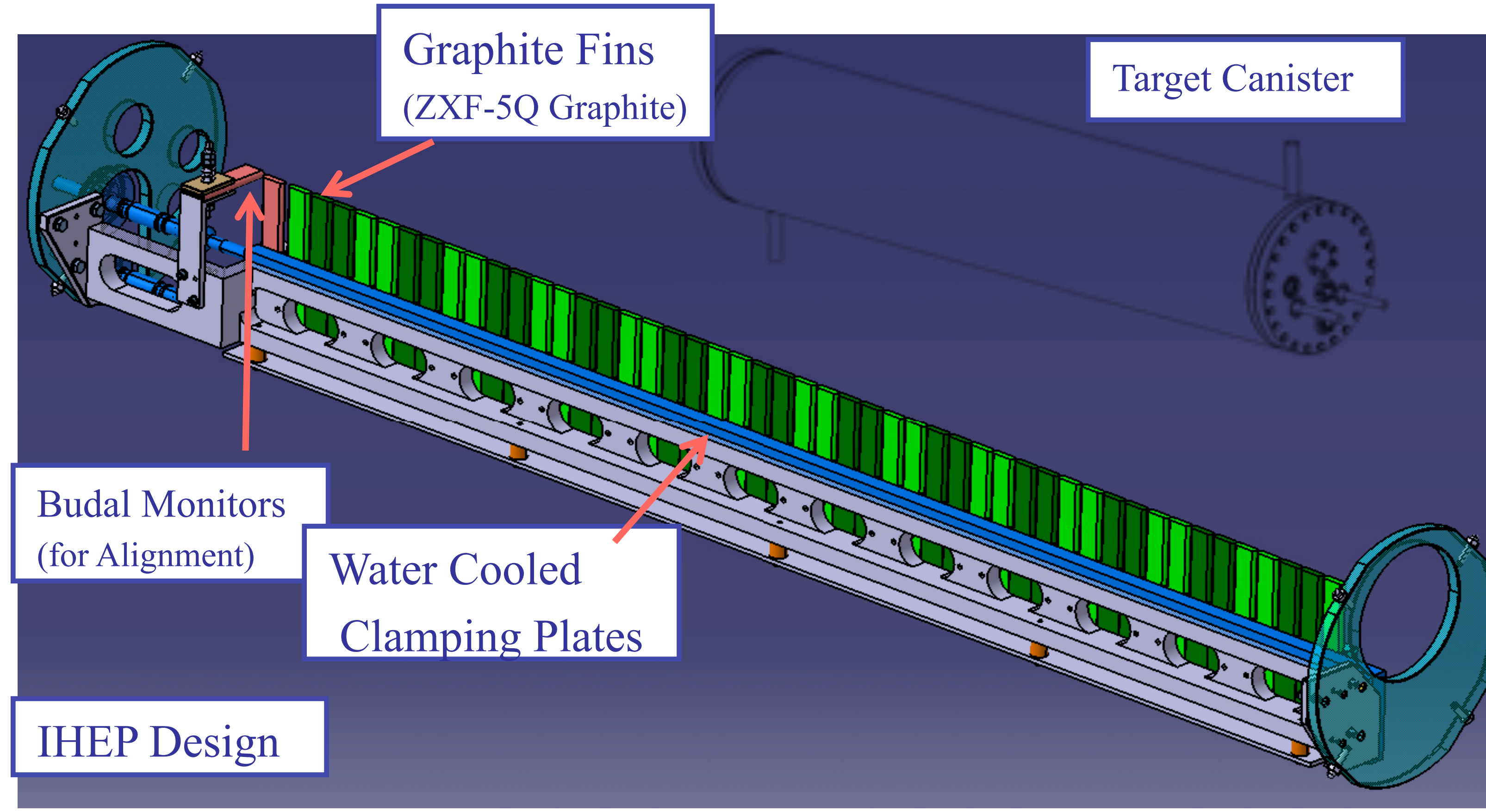
Accelerator Upgrades for NOvA

- 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



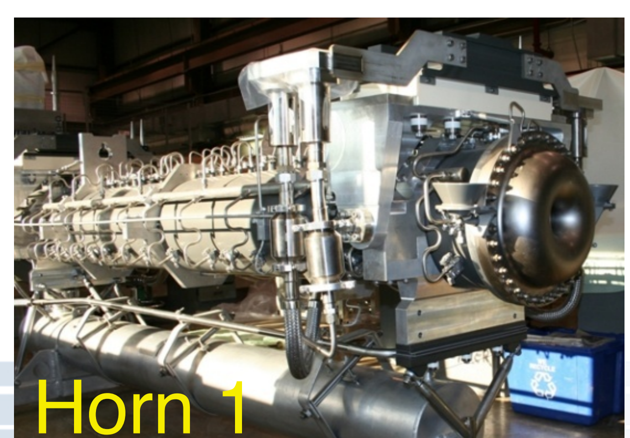
NuMI Target and Horns for the NOvA Era



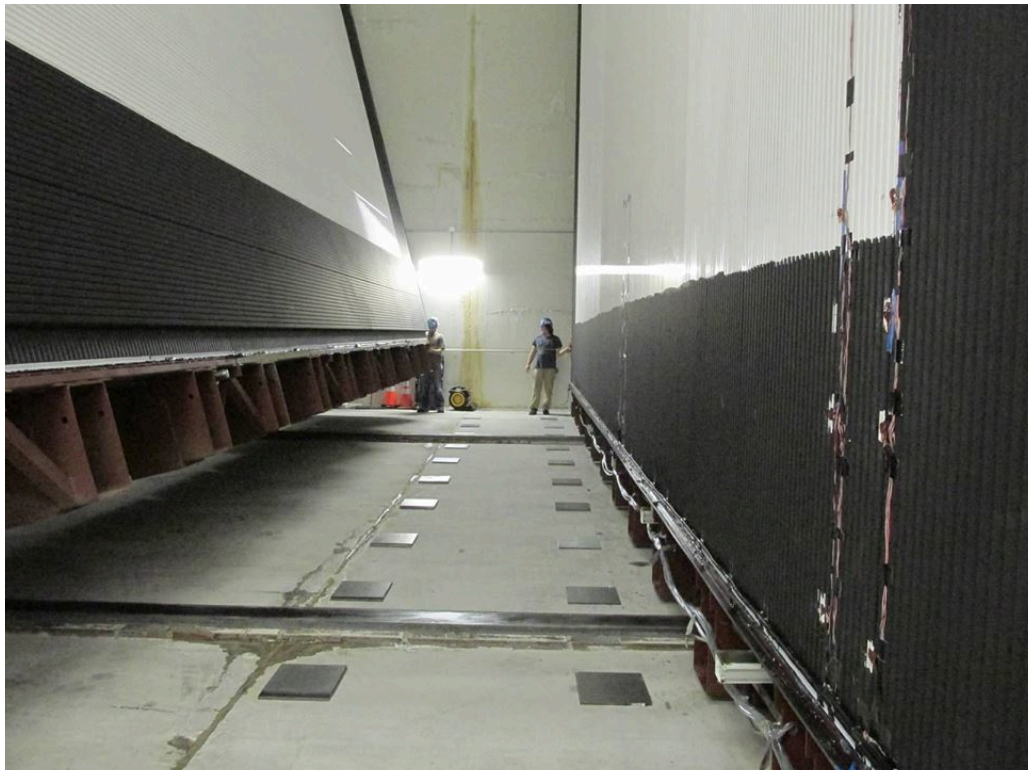


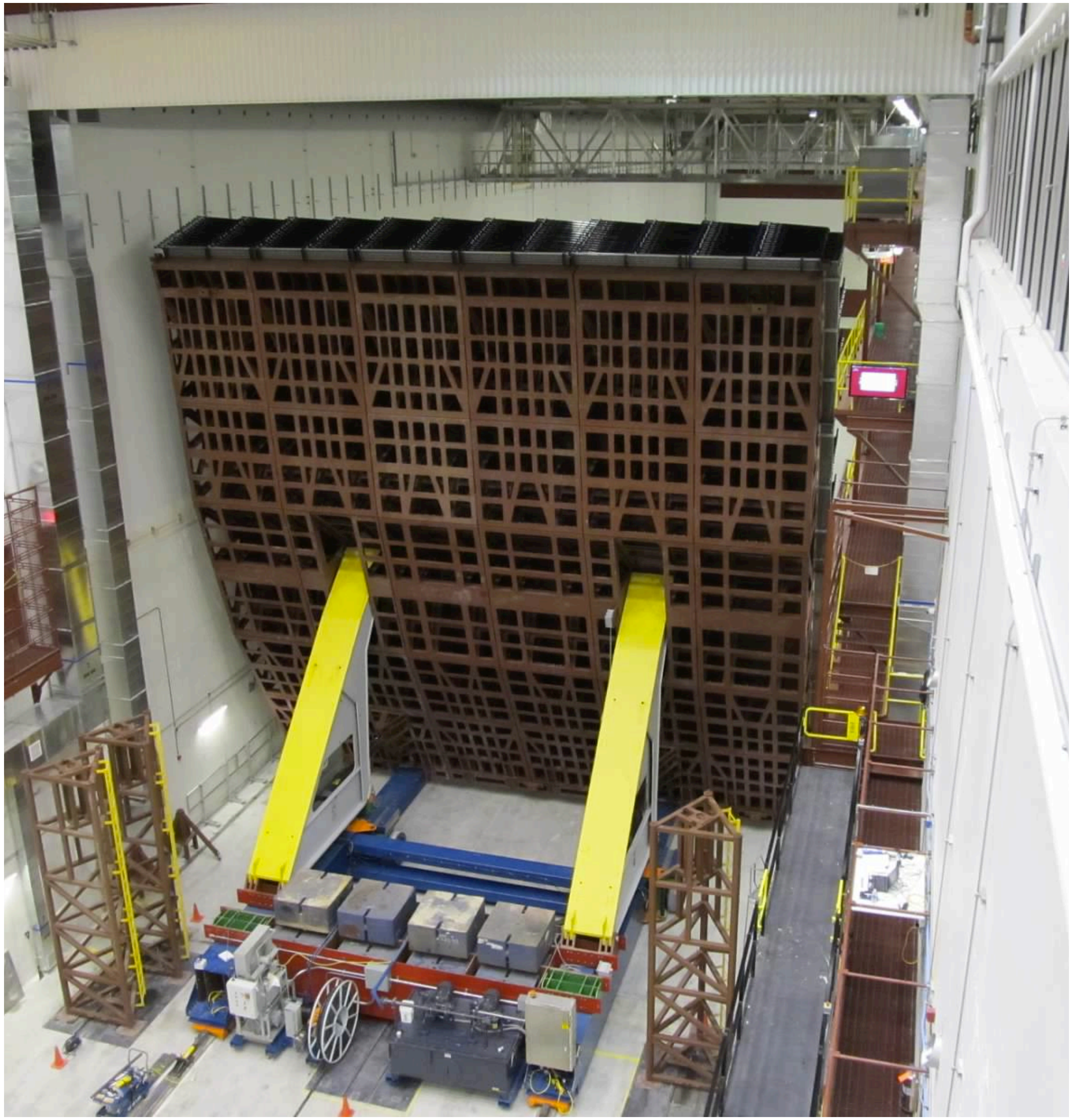
NuMI Medium Energy Target

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

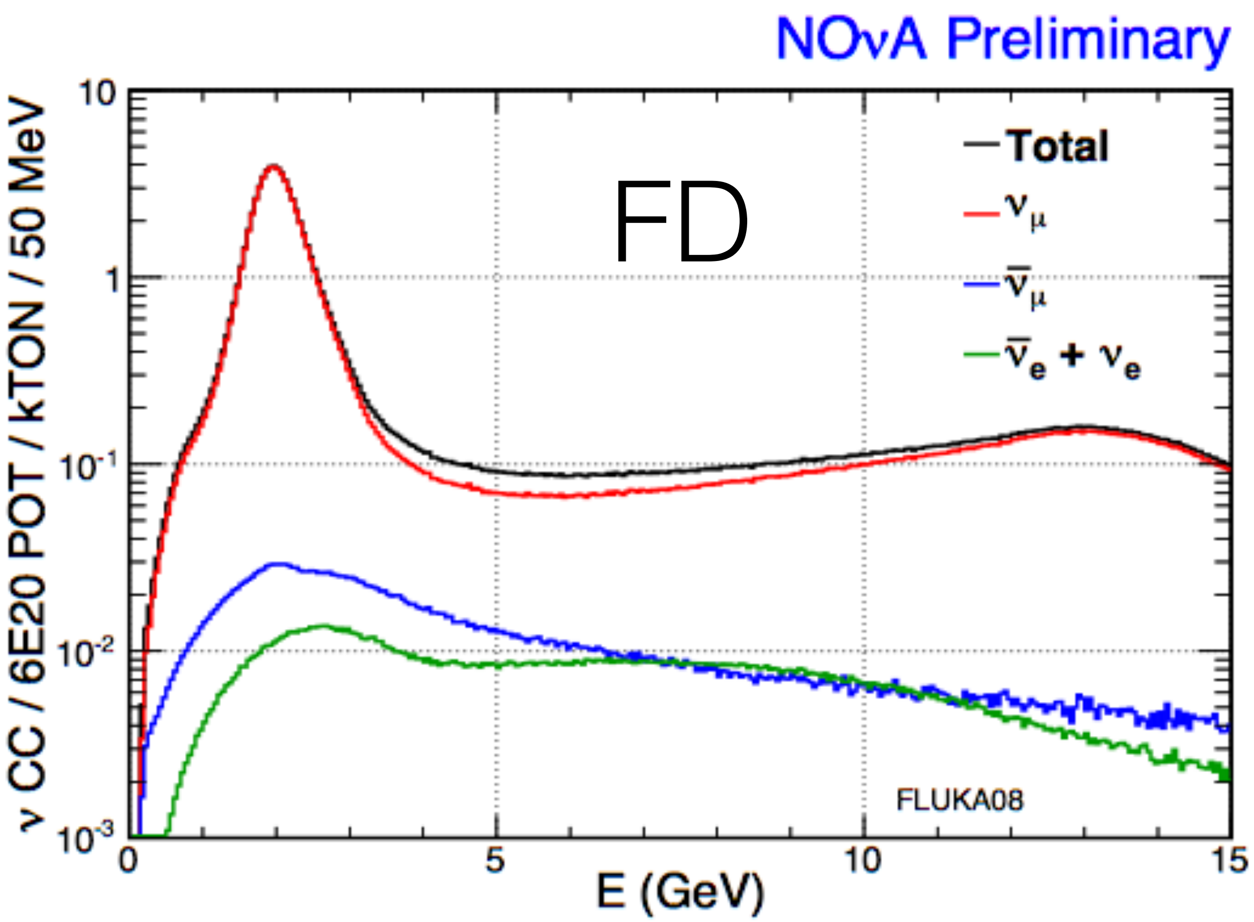


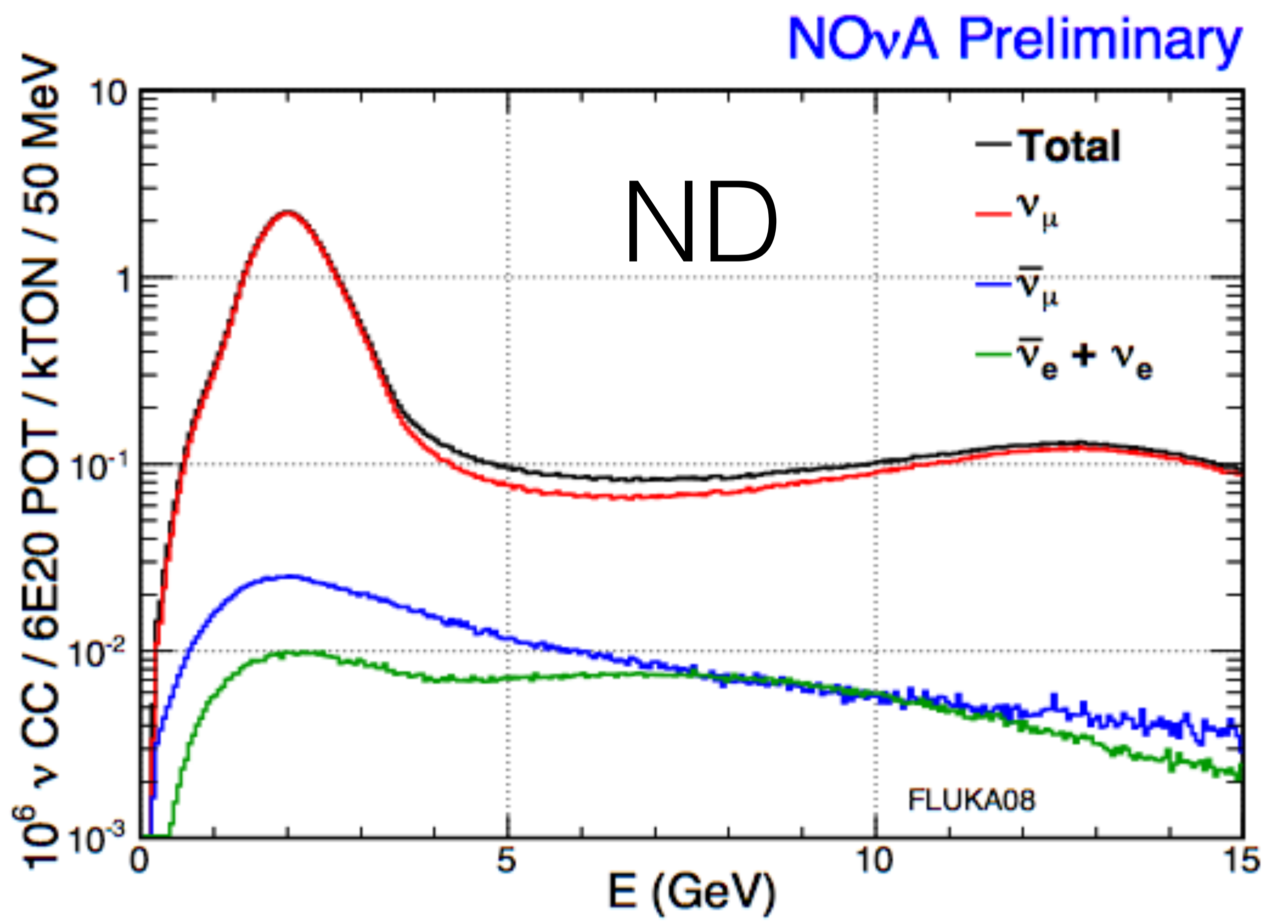
NOvA Far Detector Construction





Forward Horn Current Mode





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

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

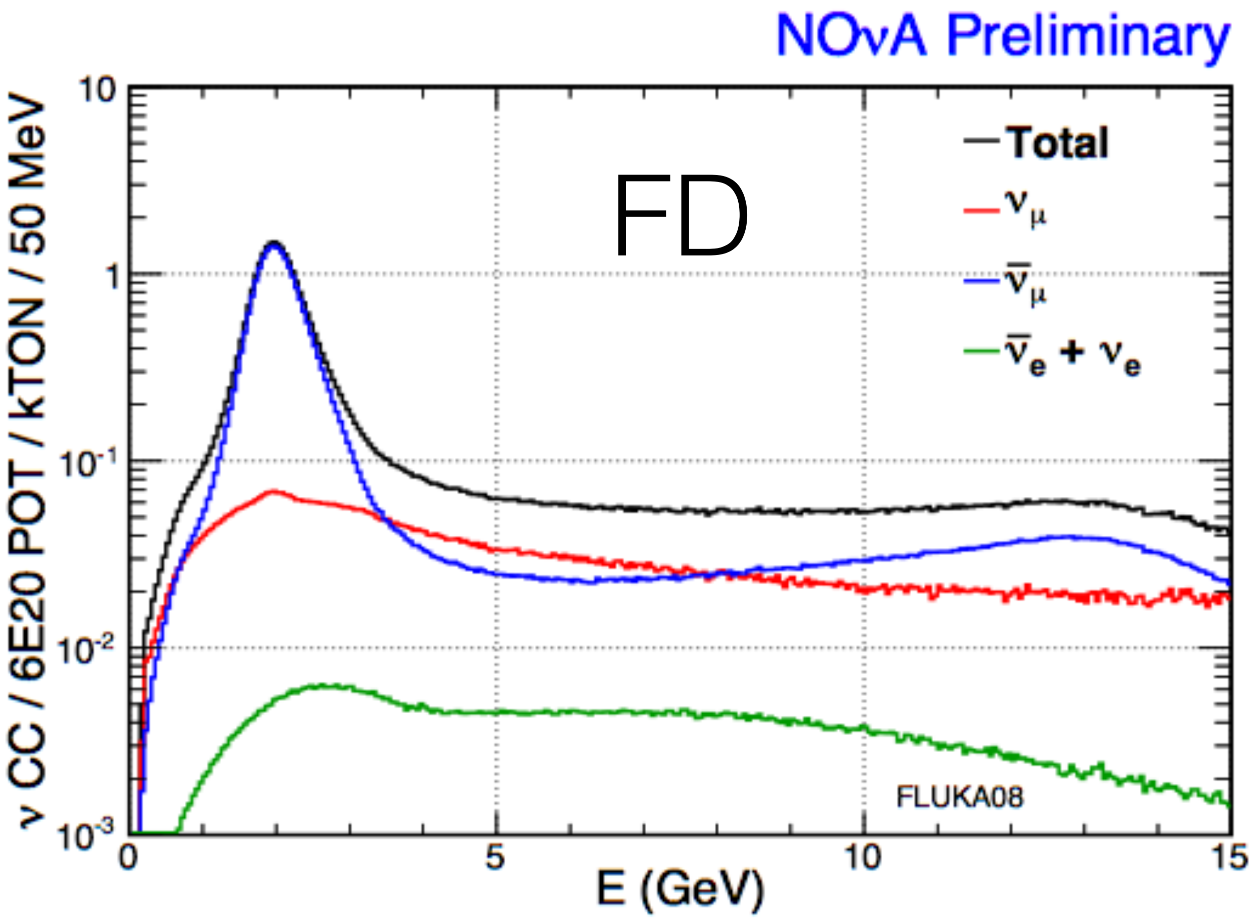
[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 0.6%

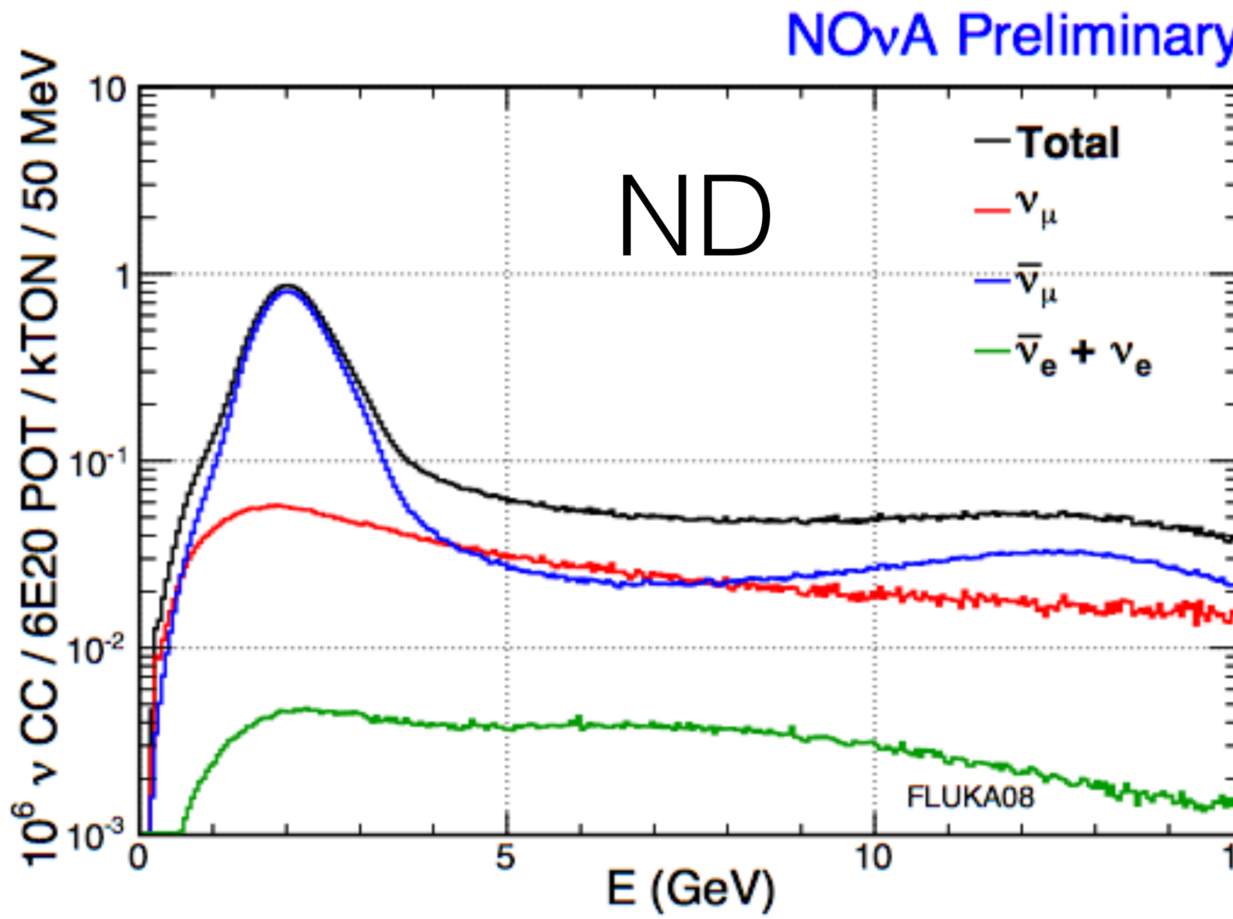
x10	[1,3]GeV	[0,120]Gev
Total	53.9	95
Numu	52.6	89.5
Anti-Numu	0.9	3.5
Nue+Anti-Nue	0.4	2

[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%

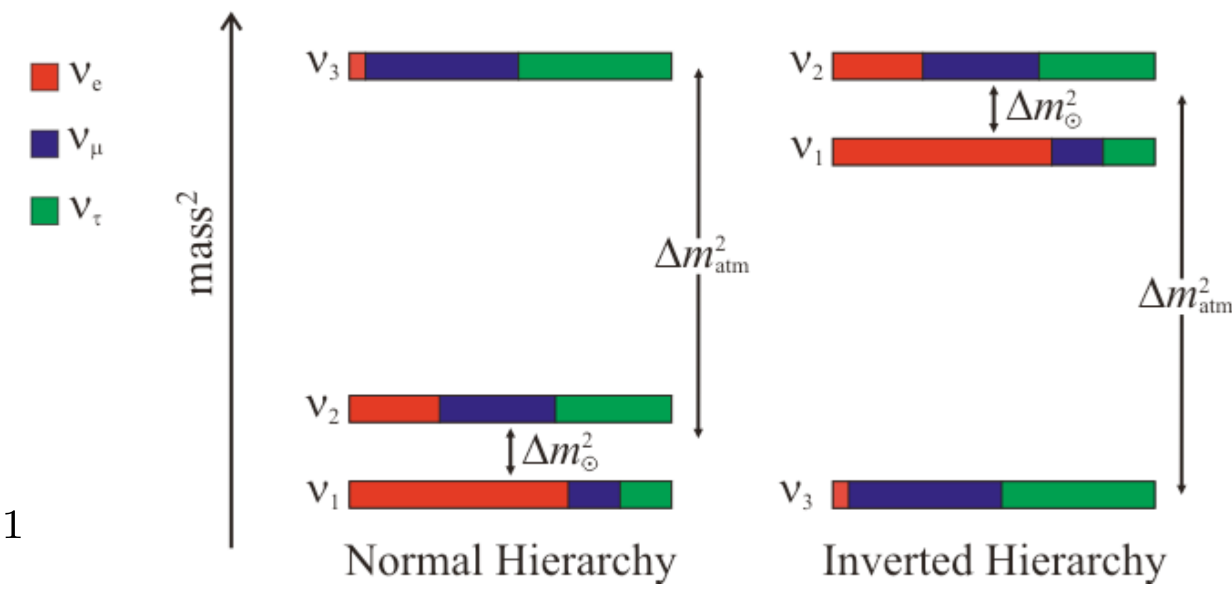
[1,3]GeV: $(\nu_e + \bar{\nu}_e)/\nu_\mu$ = 0.8%

x10	[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%

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



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

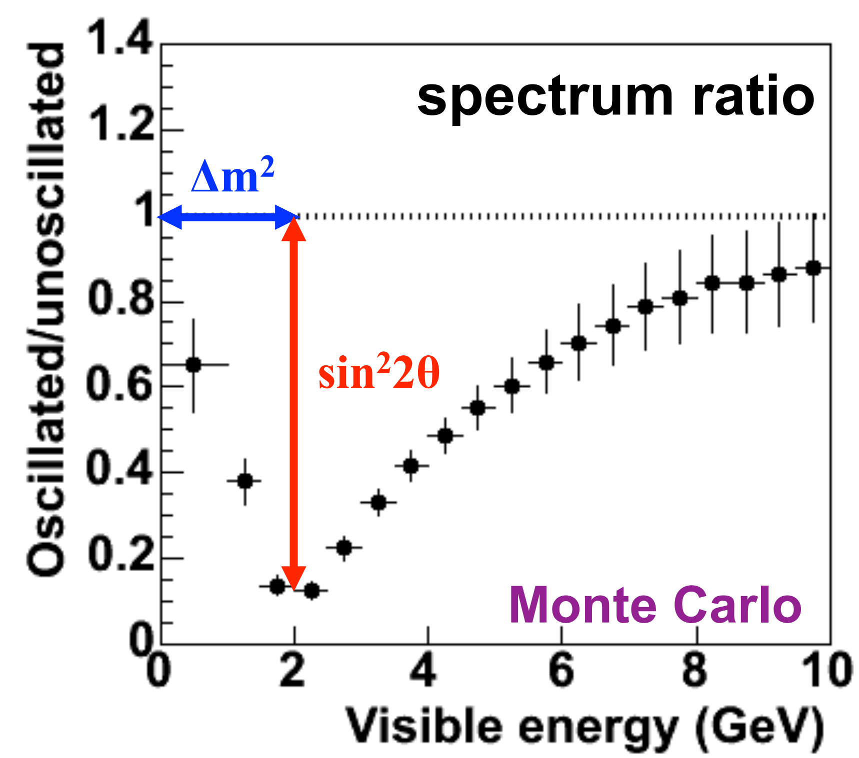
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$\alpha \sin 2\theta_{13} \cos\delta \frac{\sin(aL)}{(aL)} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \cos\Delta_{32} -$$
$$\alpha \sin 2\theta_{13} \sin\delta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

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

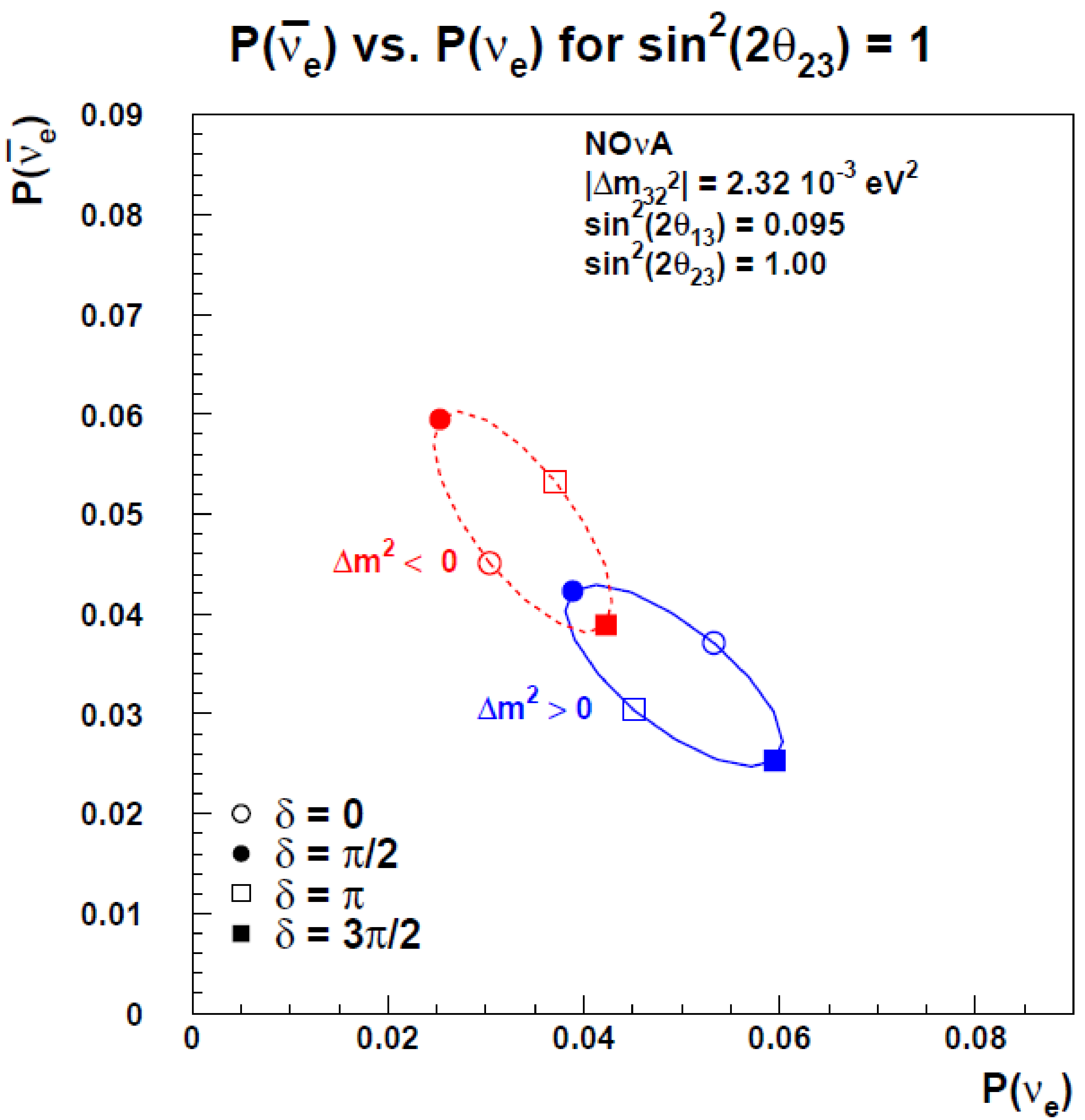
$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$ eg, in NOvA: $aL \simeq 0.23$

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

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

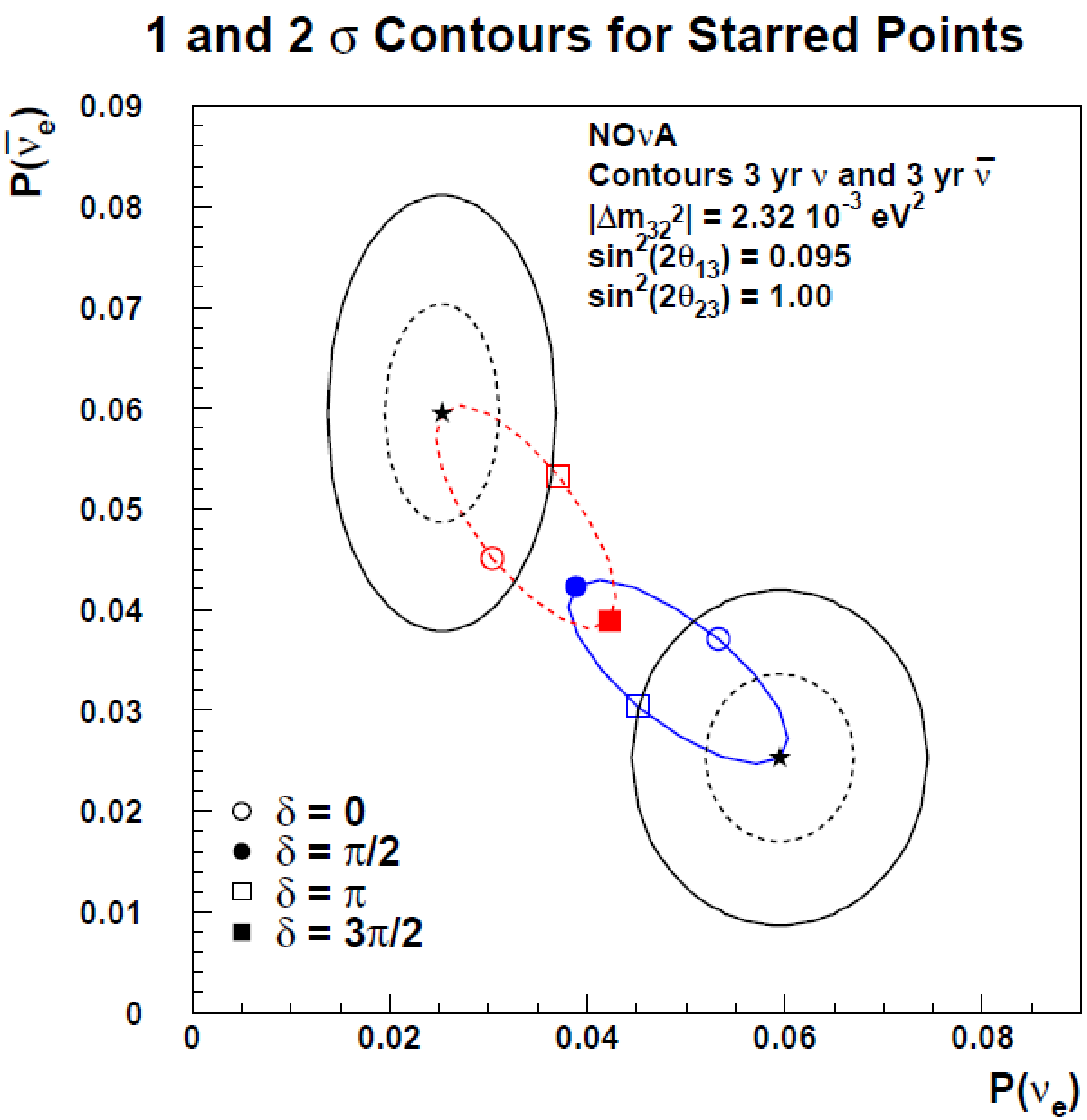


NOvA Measurements



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

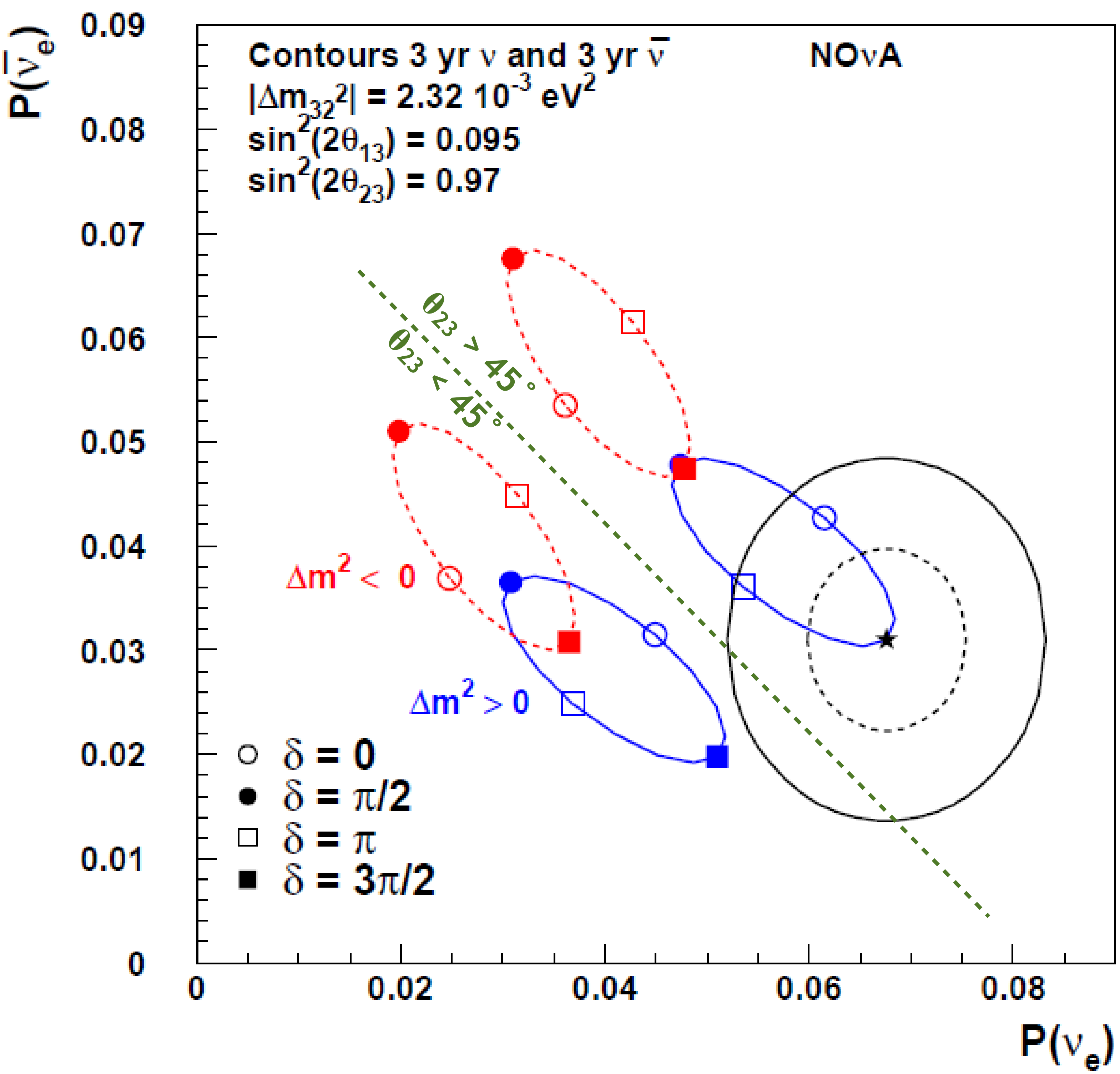
NOvA Measurements



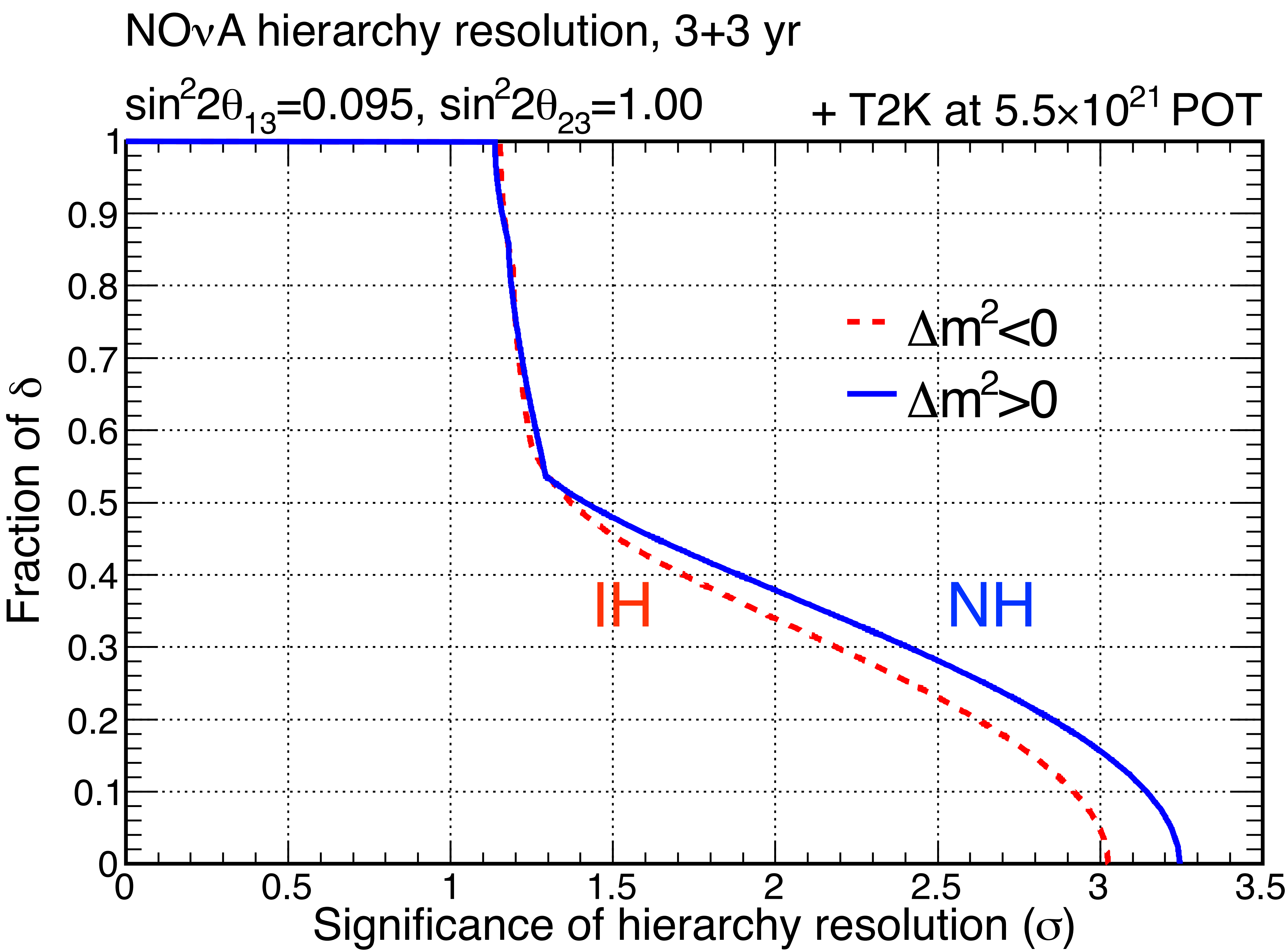
- The strategy in NOνA is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
- These cases represent best-case scenarios for determining the mass hierarchy after 3 years of running each mode each. Contours are 1- and 2-sigma measurements.

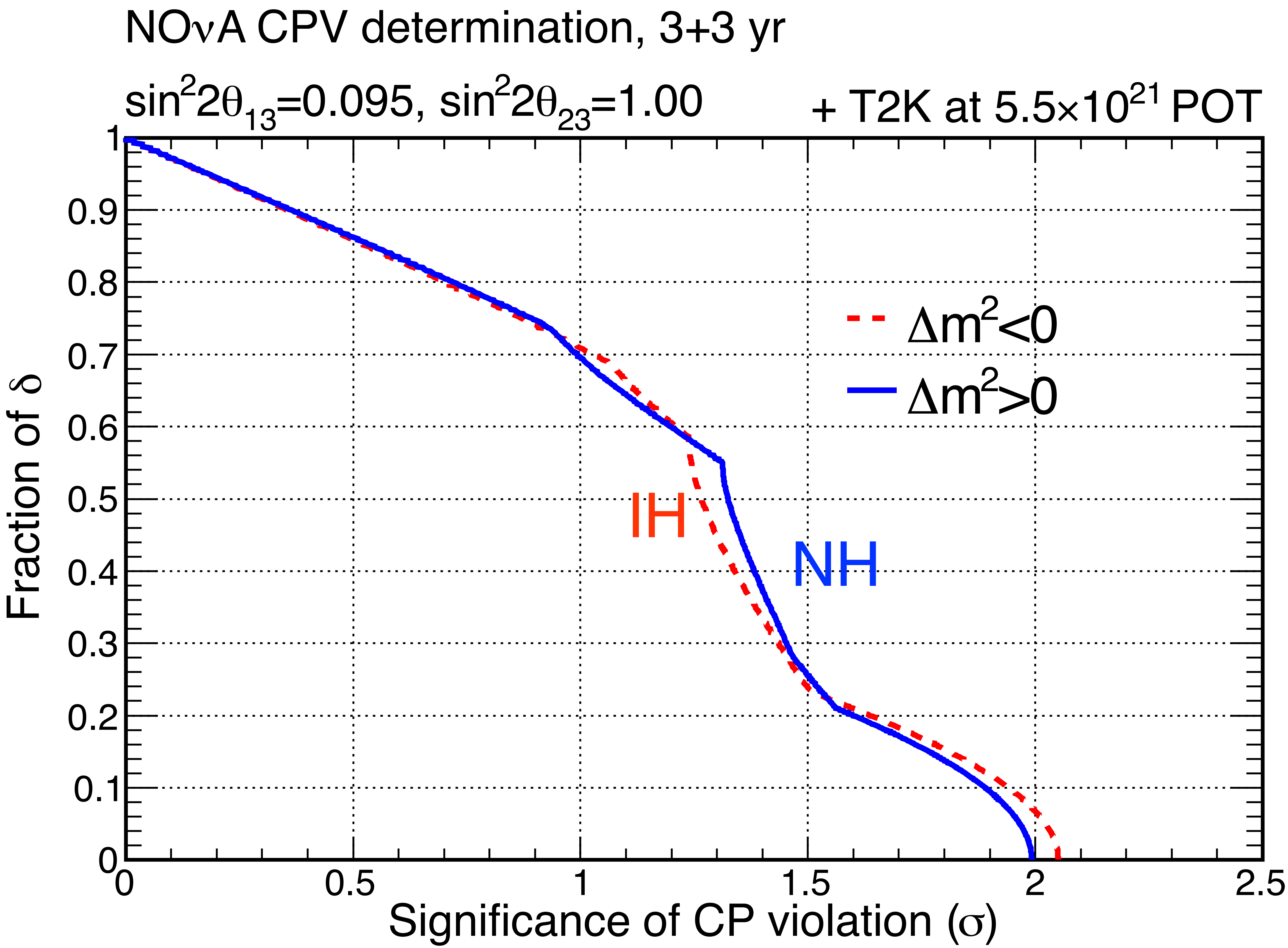
NOvA Measurements

1 and 2 σ Contours for Starred Point



- The strategy in NOνA is to compare the oscillation probability of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to extract mass hierarchy and first information on δ_{CP}
- Precision measurement of $\sin^2(2\theta_{23})$ from $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
- 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.


NOνA hierarchy resolution, 3+3 yr
sin²2θ13=0.095, sin²2θ23=1.00
+ T2K at 5.5×10²¹ POT
Fraction of δ
Significance of hierarchy resolution (σ)
Δm²<0
Δm²>0
IH
NH
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
3
3.5


NOνA CPV determination, 3+3 yr
sin²2θ₁₃=0.095, sin²2θ₂₃=1.00
+ T2K at 5.5×10²¹ POT
Fraction of δ
Significance of CP violation (σ)
Δm²<0
Δm²>0
IH
NH
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

Other Physics in the NOvA Far Detector