The NOνA Experiment

Martin Frank
University of Virginia
on behalf of the NOνA Collaboration

NuInt 2014
May 22nd, 2014

INTRODUCTION

- NOνA:
  - NuMI: Neutrinos at the Main Injector (ν_μ)
  - Off-Axis: narrow band beam (2 GeV)
  - ν_e Appearance

$$P(\nu_\mu \rightarrow \nu_e) = f(\theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \text{mass hierarchy}, \ldots)$$

- Overview and Status of the Experiment
- First Neutrino Candidates
- Survey Some Physics Goals:
  - Oscillation Physics
  - Neutrino Cross Sections
  - Magnetic Monopoles

Physics Goals

- θ_{13}
- θ_{23} Octant
- CP-violating Phase Angle δ_{CP}
- Neutrino Mass Hierarchy
- Neutrino Cross Sections
- Neutrino Magnetic Moment
- Sterile Neutrinos
- Dark Matter
- WISPs
- Magnetic Monopoles
- Supernova
- WIMPs
- And More!

INTRODUCTION

- NOνA:
  - NuMI: Neutrinos at the Main Injector (ν_μ)
  - Off-Axis: narrow band beam (2 GeV)
  - ν_e Appearance

$$P(\nu_\mu \to \nu_e) \\ = f(\theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \text{mass hierarchy}, \ldots)$$

- Overview and Status of the Experiment
- First Neutrino Candidates
- Survey Some Physics Goals:
  - Oscillation Physics
  - Neutrino Cross Sections
  - Magnetic Monopoles

Physics Goals

- θ_{13}
- θ_{23} Octant
- CP-violating Phase Angle δ_{CP}
- Neutrino Mass Hierarchy
- Neutrino Cross Sections
- Neutrino Magnetic Moment
- Sterile Neutrinos
- Dark Matter
- WISPs
- Magnetic Monopoles
- Supernova
- WIMPs
- And More!

INTRODUCTION

- NOνA:
  - NuMI: Neutrinos at the Main Injector (ν_μ)
  - Off-Axis: narrow band beam (2 GeV)
  - ν_e Appearance

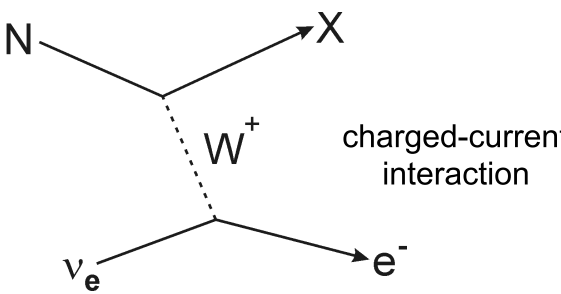
$$P(\nu_\mu \rightarrow \nu_e) \\ = f(\theta_{13}, \theta_{23}, \delta_{\mathrm{CP}}, \text{mass hierarchy}, \ldots)$$

- Overview and Status of the Experiment
- First Neutrino Candidates
- Survey Some Physics Goals:
  - Oscillation Physics
  - Neutrino Cross Sections
  - Magnetic Monopoles

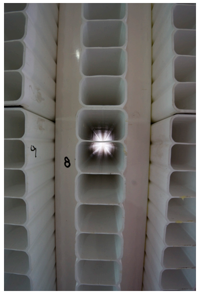
Physics Goals

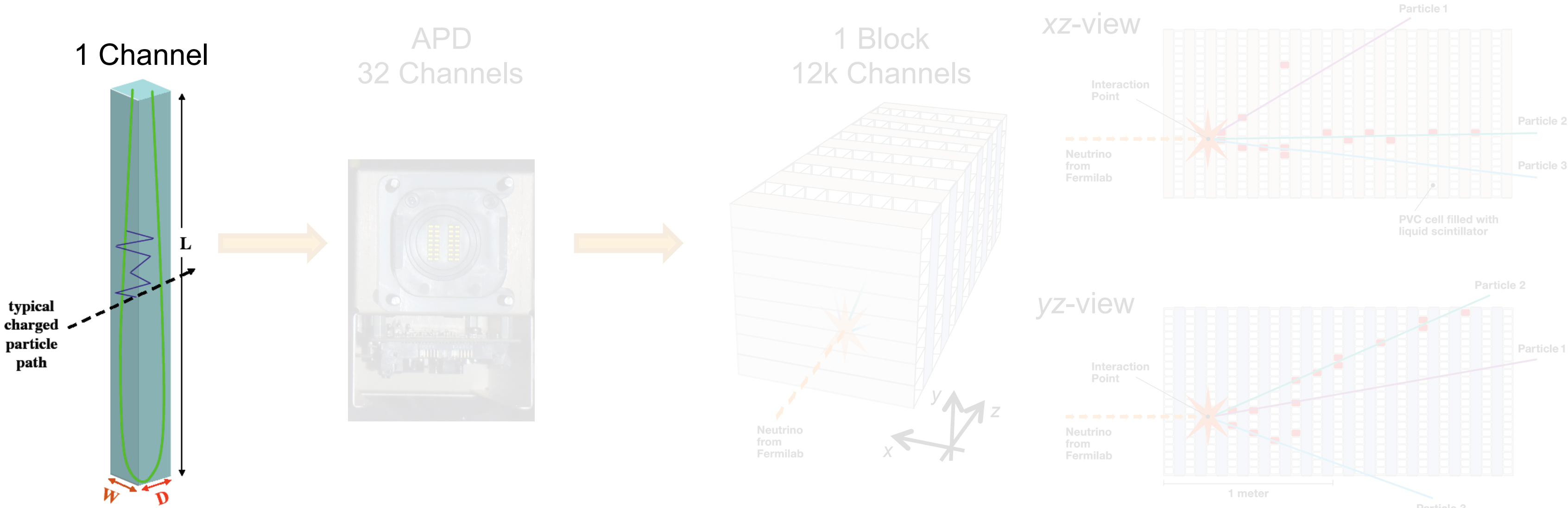
- θ_{13}
- θ_{23} Octant
- CP-violating Phase Angle δ_{CP}
- Neutrino Mass Hierarchy
- Neutrino Cross Sections
- Neutrino Magnetic Moment
- Sterile Neutrinos
- Dark Matter
- WISPs
- Magnetic Monopoles
- Supernova
- WIMPs
- And More!

NEUTRINO DETECTION

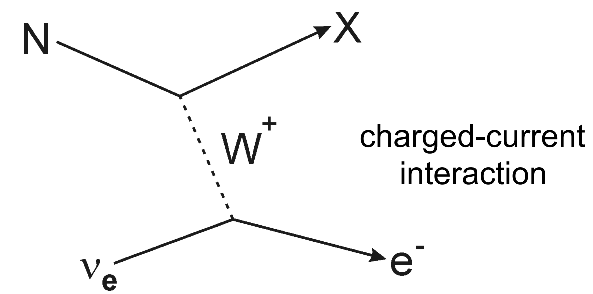


- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- Solution: “Fully” Active Detector
  - use low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides many samples per radiation length (differentiate e^- and π^0)
  - each extrusion contains one wavelength-shifting fiber
  - ends of fiber read out by avalanche photo-diode (APD)

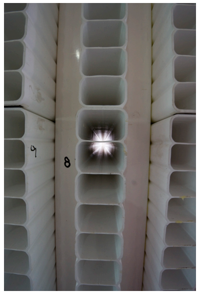


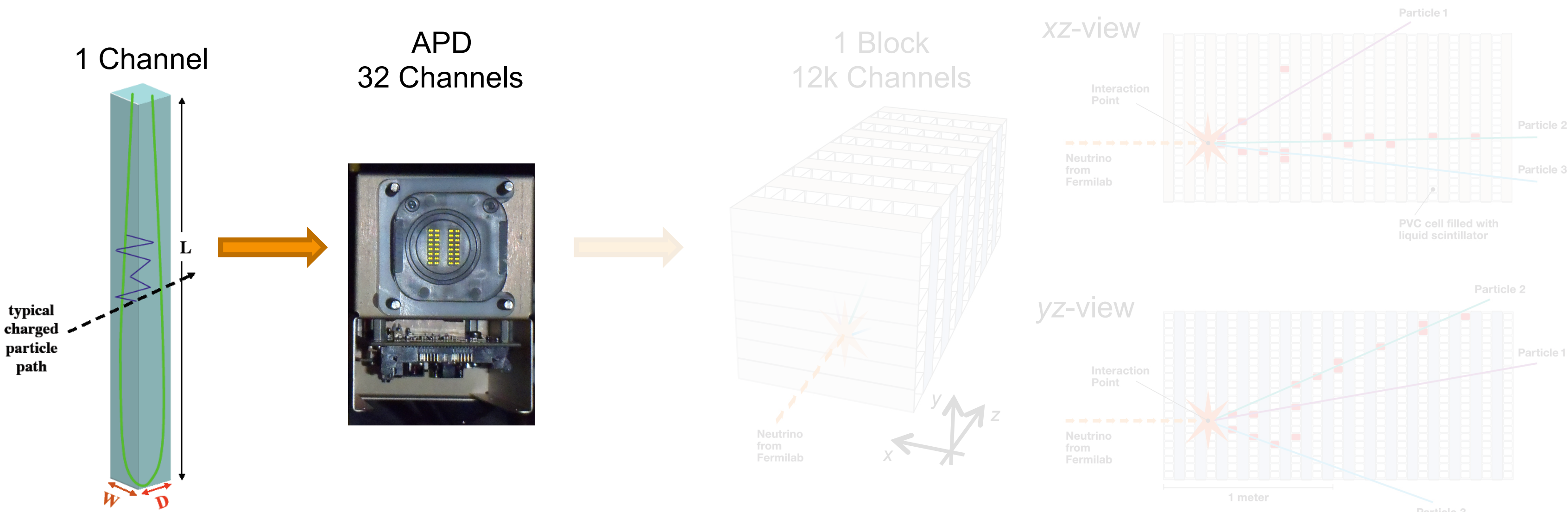


NEUTRINO DETECTION

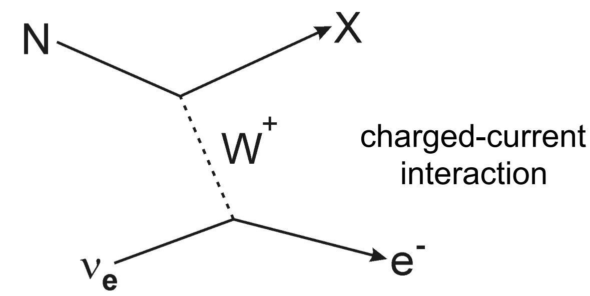


- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- Solution: "Fully" Active Detector
  - use low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides many samples per radiation length (differentiate e^- and π^0)
  - each extrusion contains one wavelength-shifting fiber
  - ends of fiber read out by avalanche photo-diode (APD)

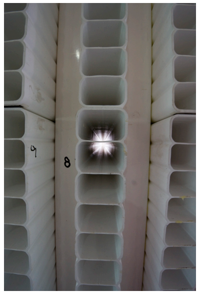


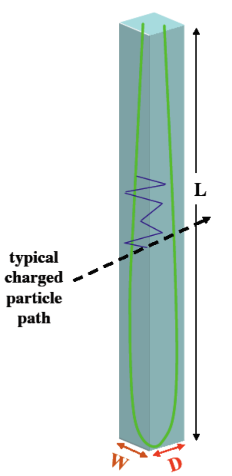


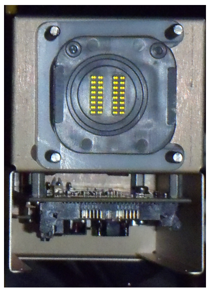
Neutrino Detection

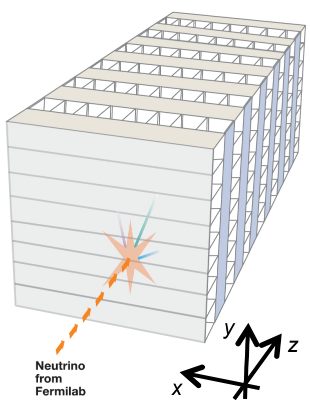


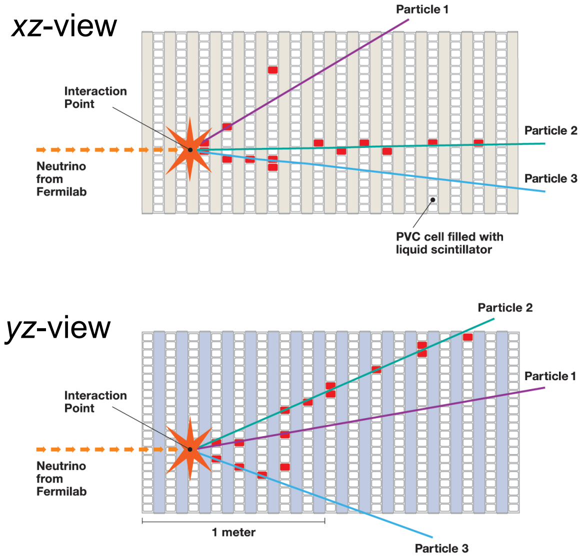
- We want to detect electron neutrinos (ν_e):
  - This requires a large detector mass and good electron identification.
- Solution: "Fully" Active Detector
  - use low Z materials: PVC extrusions filled with liquid scintillator
    - radiation length ~ 40 cm, Molière radius ~ 11 cm
    - provides many samples per radiation length (differentiate e^- and π^0)
  - each extrusion contains one wavelength-shifting fiber
  - ends of fiber read out by avalanche photo-diode (APD)

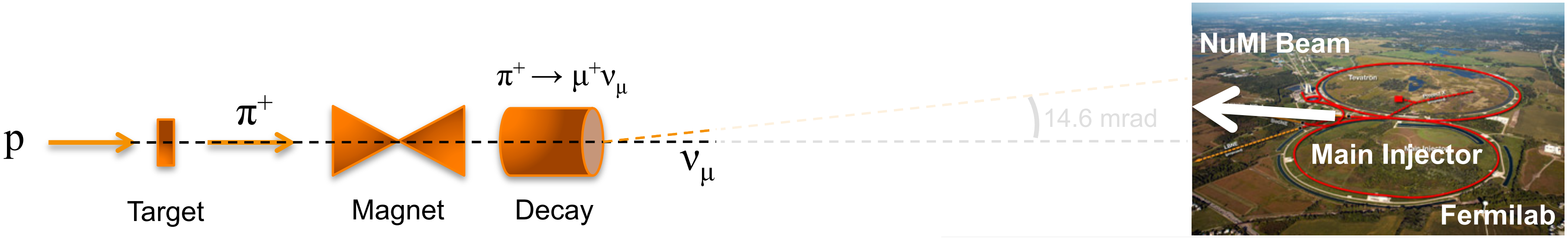






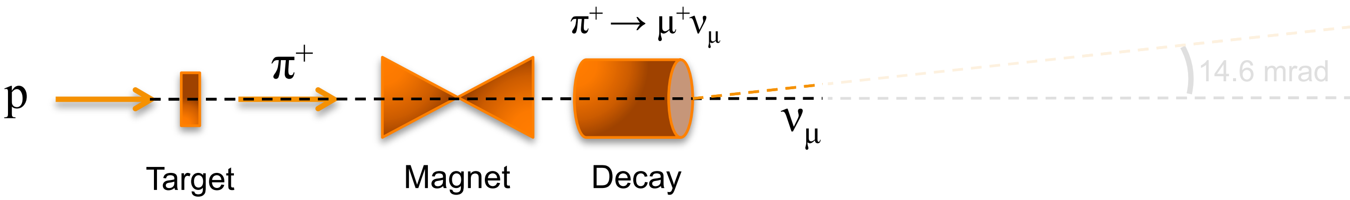


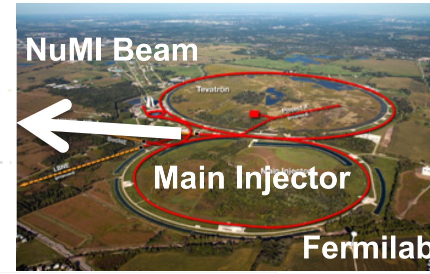




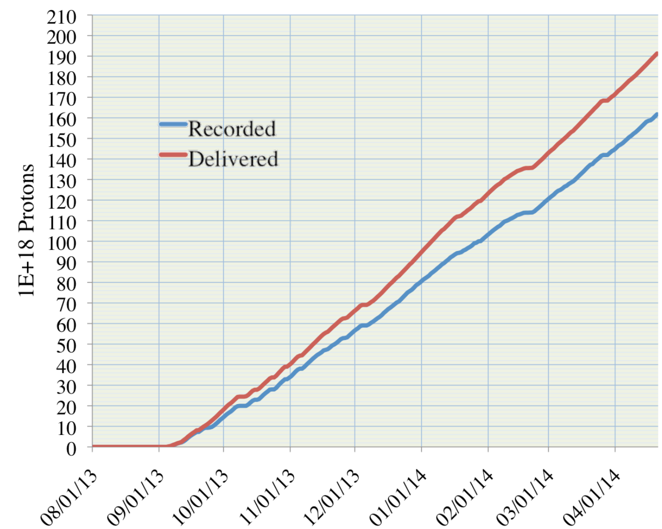
NEUTRINO PRODUCTION

- NuMI: Neutrinos at the Main Injector
- Beam Power:
  - currently at 300 kW
  - ramping to 500 kW (end of year)
  - 700 kW after Booster improvements (next year)
- Running stably since last summer.
- We can achieve a narrowly distributed neutrino energy by placing the detectors 14.6 mrad off the beam axis.
- This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.

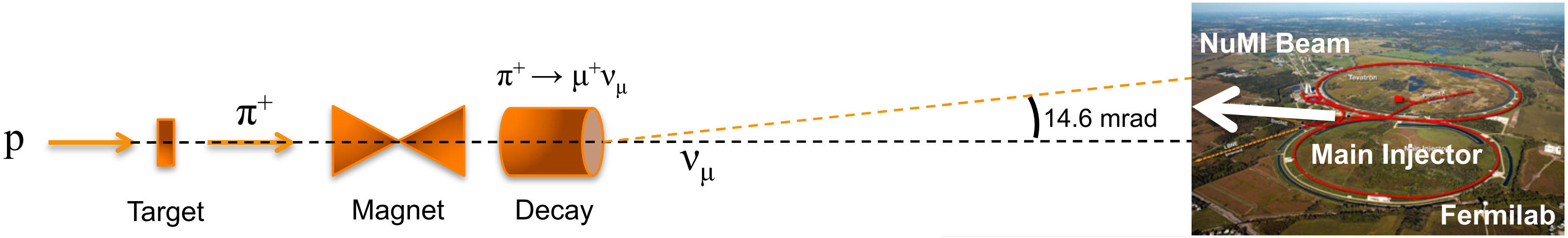




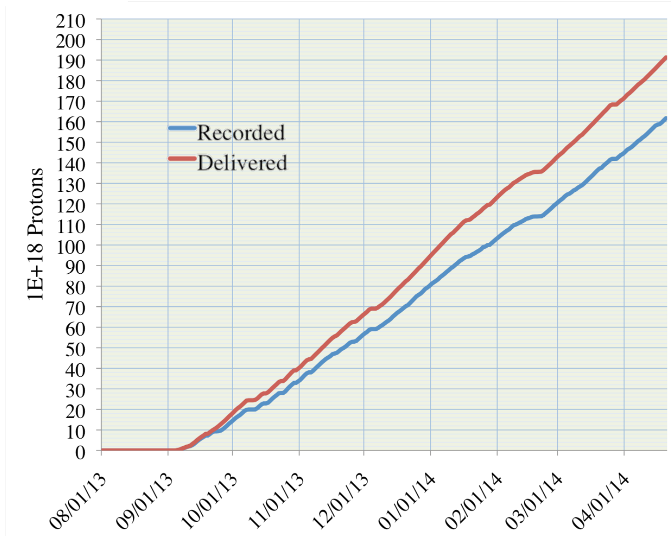
Neutrino Production



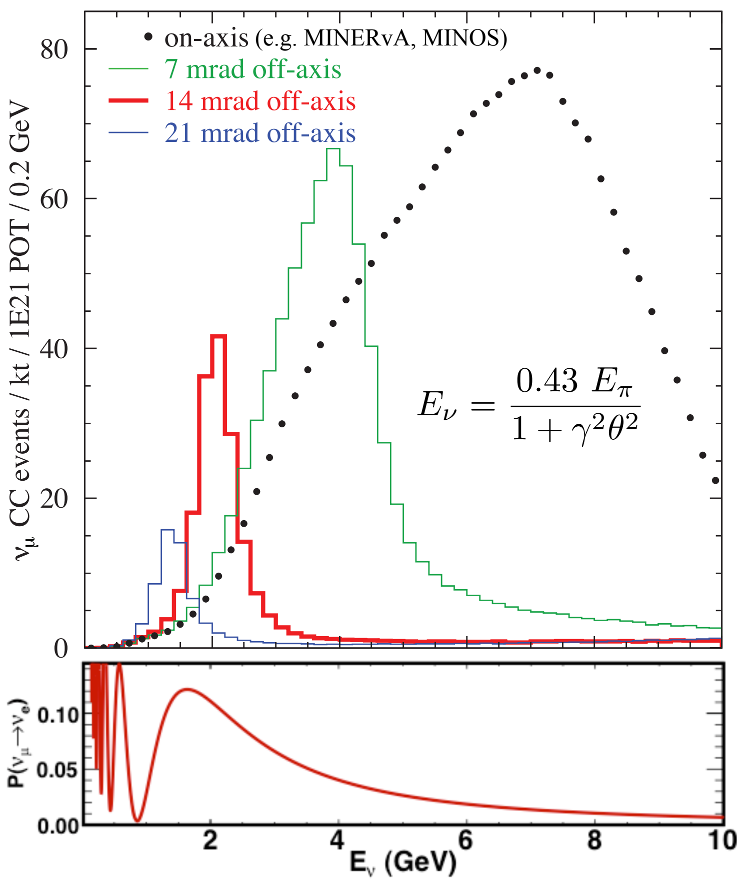
- NuMI: Neutrinos at the Main Injector
- Beam Power:
  - currently at 300 kW
  - ramping to 500 kW (end of year)
  - 700 kW after Booster improvements (next year)
- Running stably since last summer.
- We can achieve a narrowly distributed neutrino energy by placing the detectors 14.6 mrad off the beam axis.
- This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.



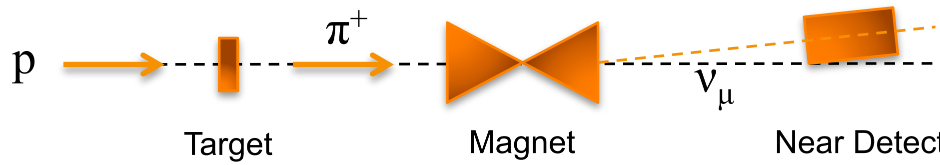
NEUTRINO PRODUCTION

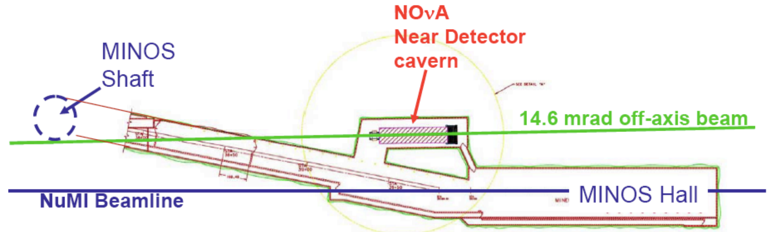


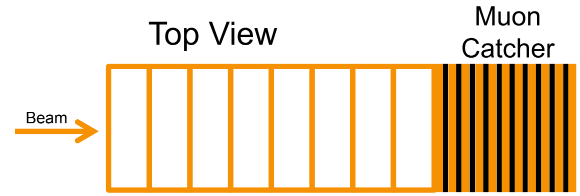
NuMI Medium Energy Tune



- NuMI: Neutrinos at the Main Injector
- Beam Power:
  - currently at 300 kW
  - ramping to 500 kW (end of year)
  - 700 kW after Booster improvements (next year)
- Running stably since last summer.
- We can achieve a narrowly distributed neutrino energy by placing the detectors 14.6 mrad off the beam axis.
- This is also the $\nu_\mu \rightarrow \nu_e$ oscillation peak.

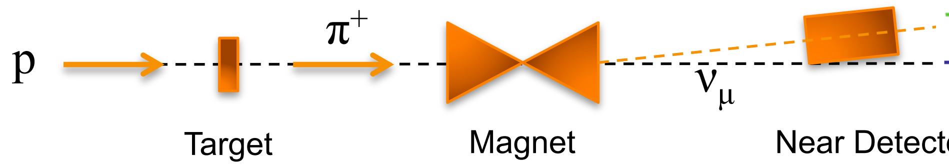


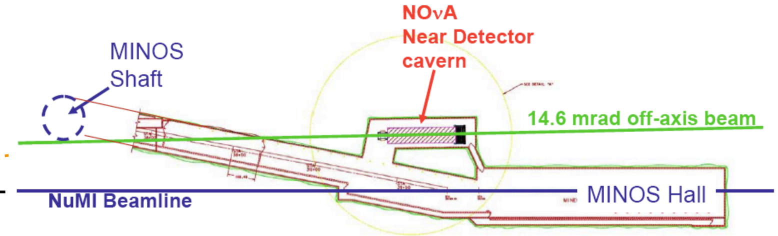




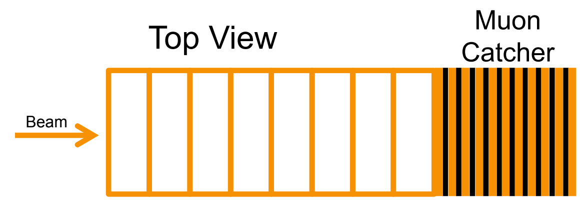
NEAR DETECTOR AT FERMILAB

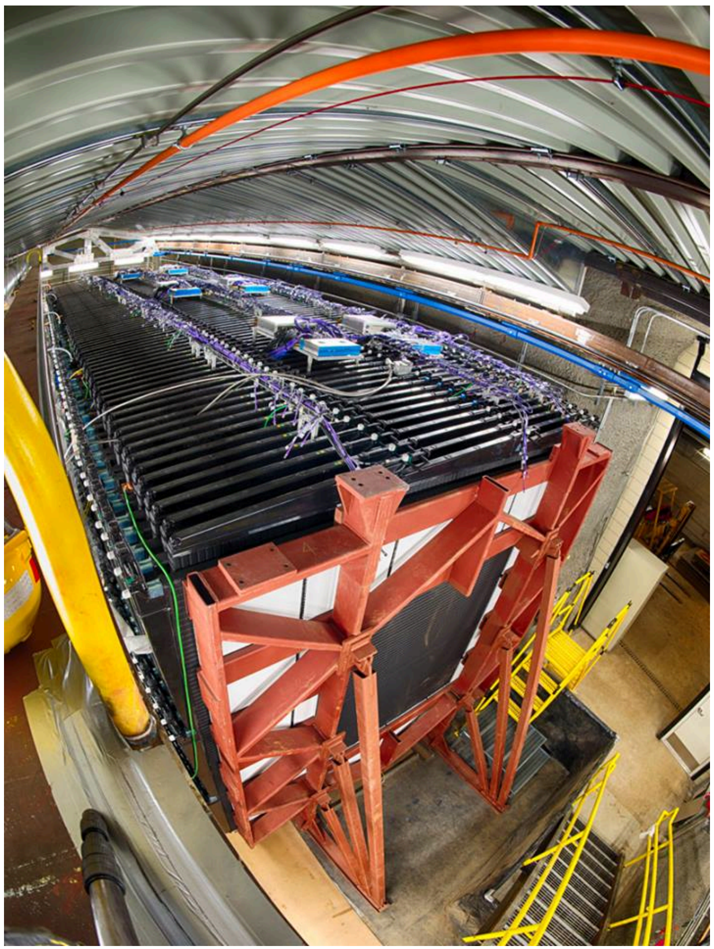
- 1 km downstream from NuMI target
- 105 m underground
- 300 tons
- 4 m × 4 m × 15 m
- Muon Catcher:
  - 10 alternating planes of detector and 4 inch steel plates
- Instrumented with 20k channels.
- We also have a prototype detector on the surface (NDOS).
  - See J. Nowak's talk for more NDOS details.



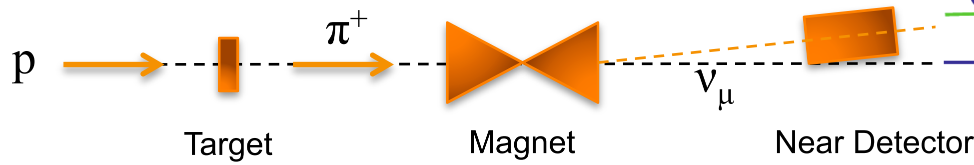


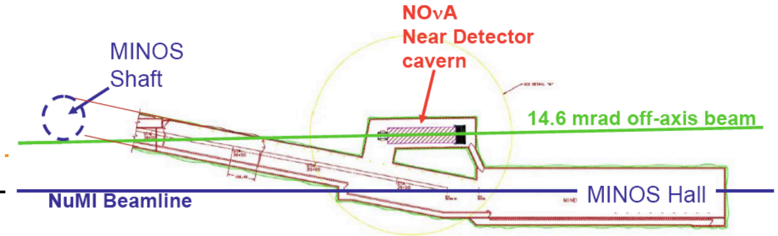
NEAR DETECTOR AT FERMILAB

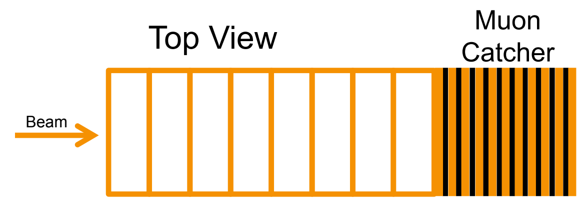




- 1 km downstream from NuMI target
- 105 m underground
- 300 tons
- 4 m × 4 m × 15 m
- Muon Catcher:
  - 10 alternating planes of detector and 4 inch steel plates
- Instrumented with 20k channels.
- We also have a prototype detector on the surface (NDOS).
  - See J. Nowak's talk for more NDOS details.

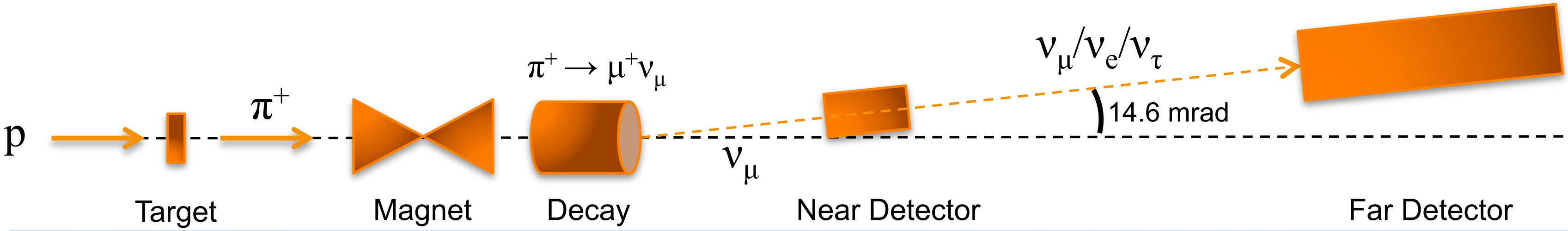




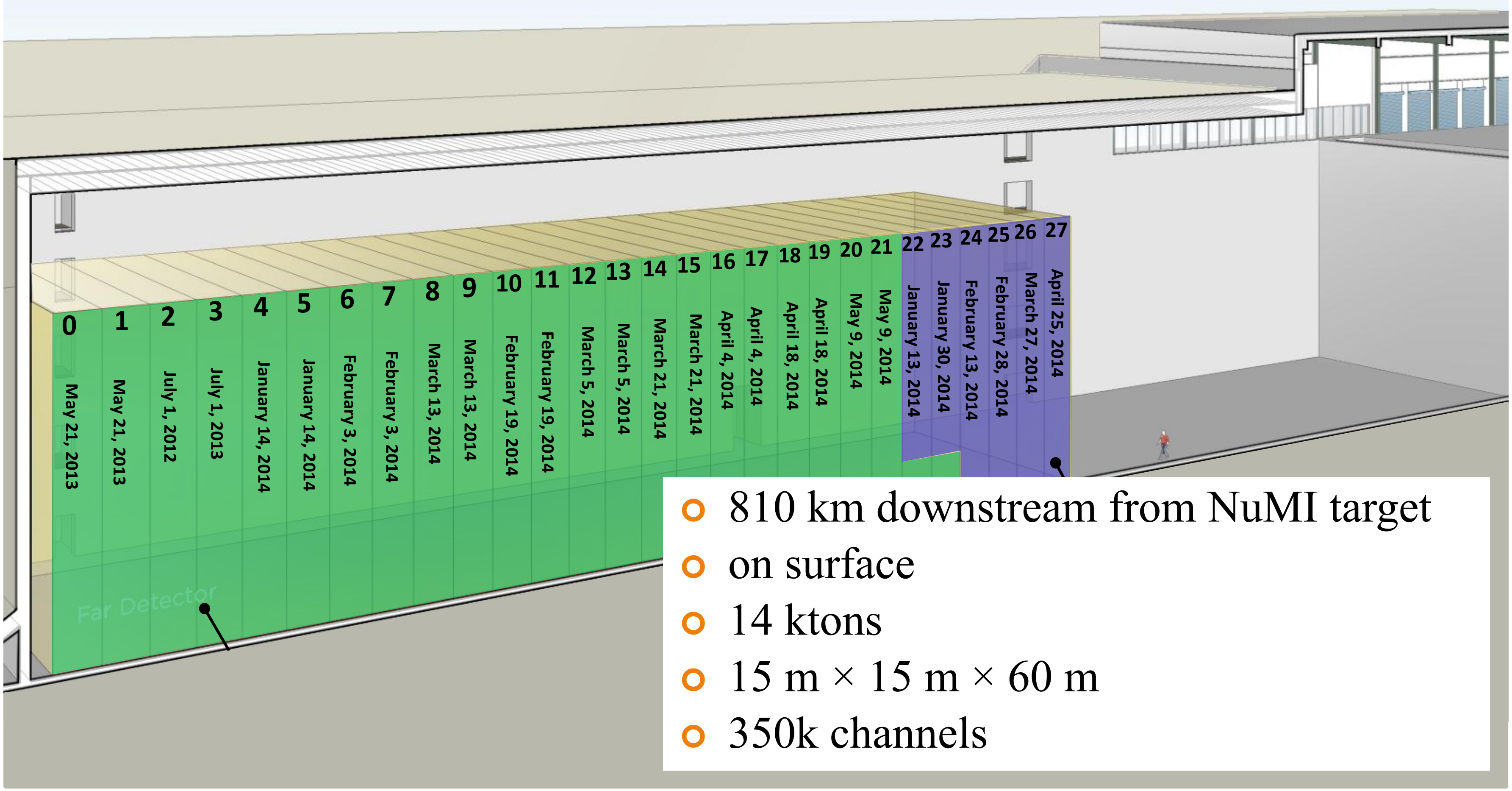


NEAR DETECTOR AT FERMILAB

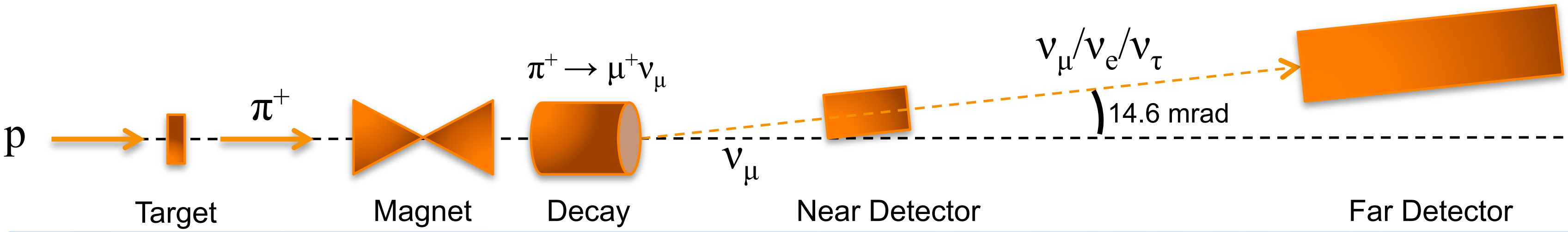
- 1 km downstream from NuMI target
- 105 m underground
- 300 tons
- 4 m × 4 m × 15 m
- Muon Catcher:
  - 10 alternating planes of detector and 4 inch steel plates
- Instrumented with 20k channels.
- We also have a prototype detector on the surface (NDOS).
  - See J. Nowak's talk for more NDOS details.



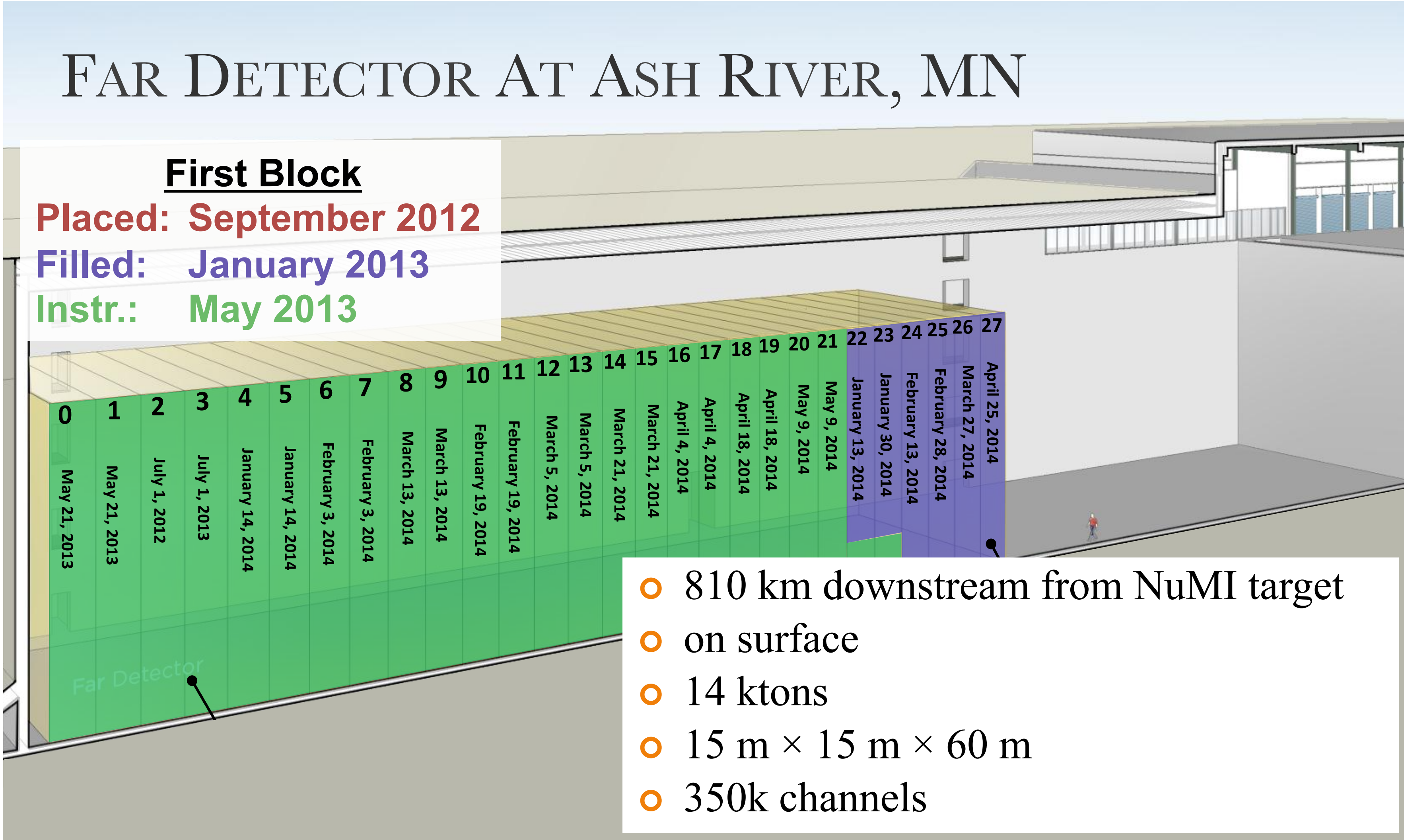
Far Detector At Ash River, MN



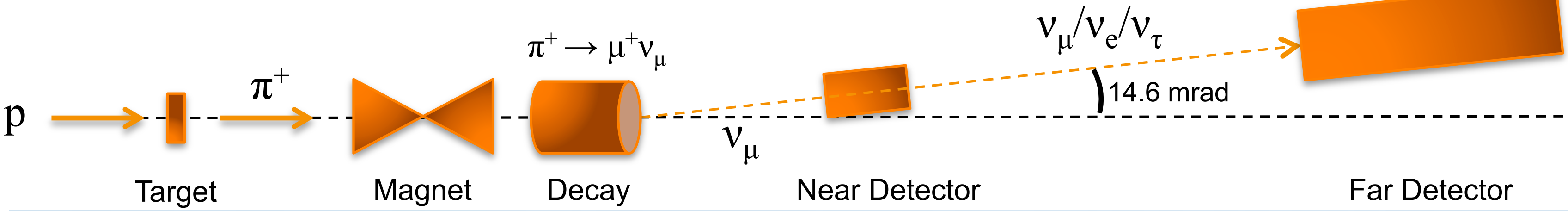
- 810 km downstream from NuMI target
- on surface
- 14 ktons
- 15 m × 15 m × 60 m
- 350k channels



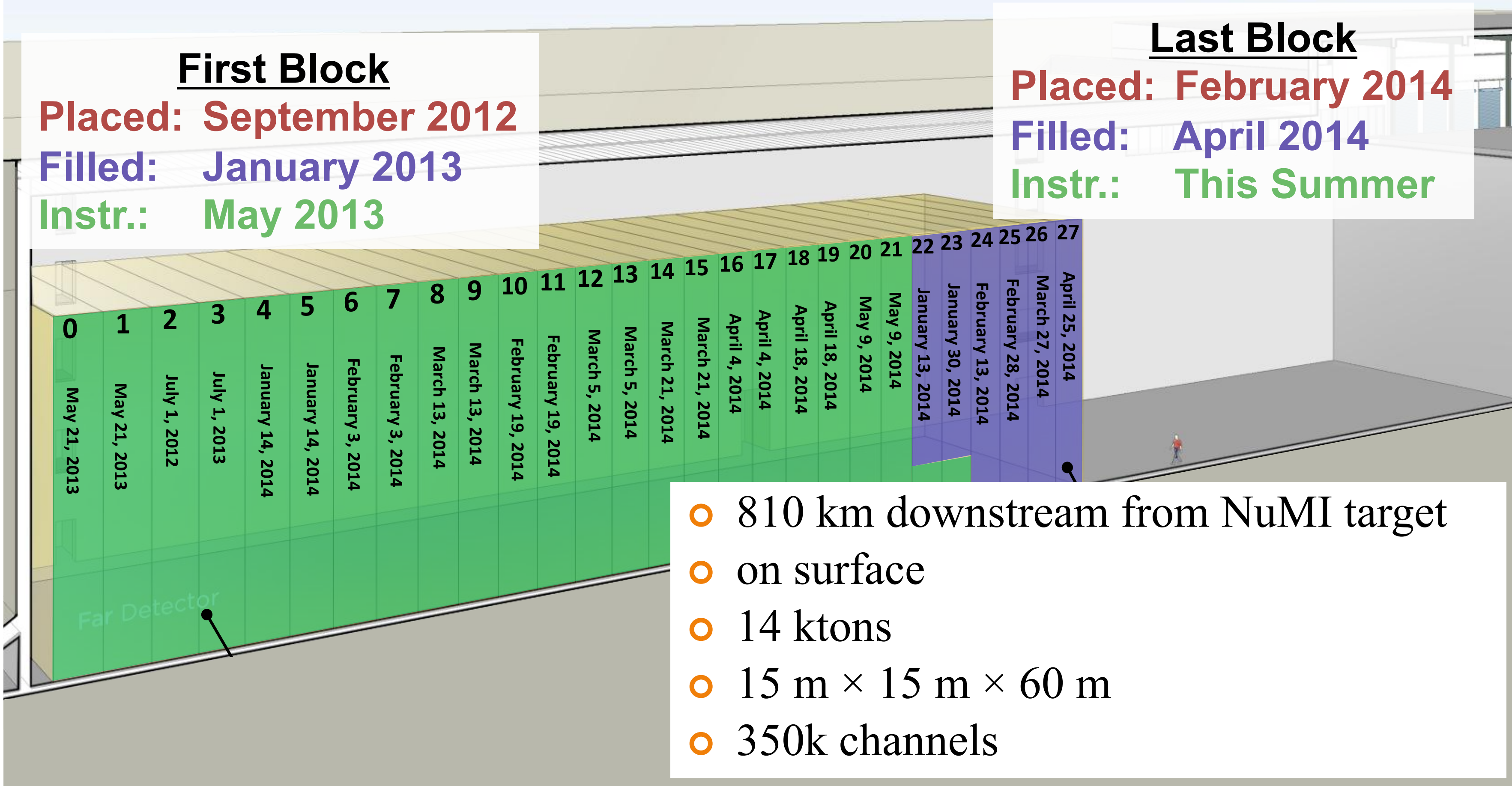
FAR DETECTOR AT ASH RIVER, MN



- 810 km downstream from NuMI target
- on surface
- 14 ktons
- 15 m × 15 m × 60 m
- 350k channels



FAR DETECTOR AT ASH RIVER, MN



First Block

Placed: September 2012
Filled: January 2013
Instr.: May 2013

Last Block

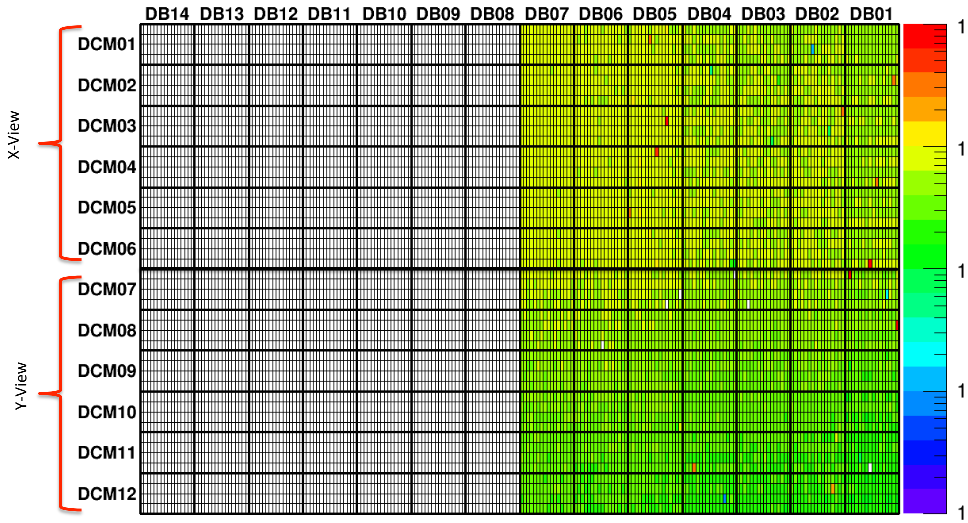
Placed: February 2014
Filled: April 2014
Instr.: This Summer

- 810 km downstream from NuMI target
- on surface
- 14 ktons
- 15 m × 15 m × 60 m
- 350k channels

ELECTRONICS PROGRESS

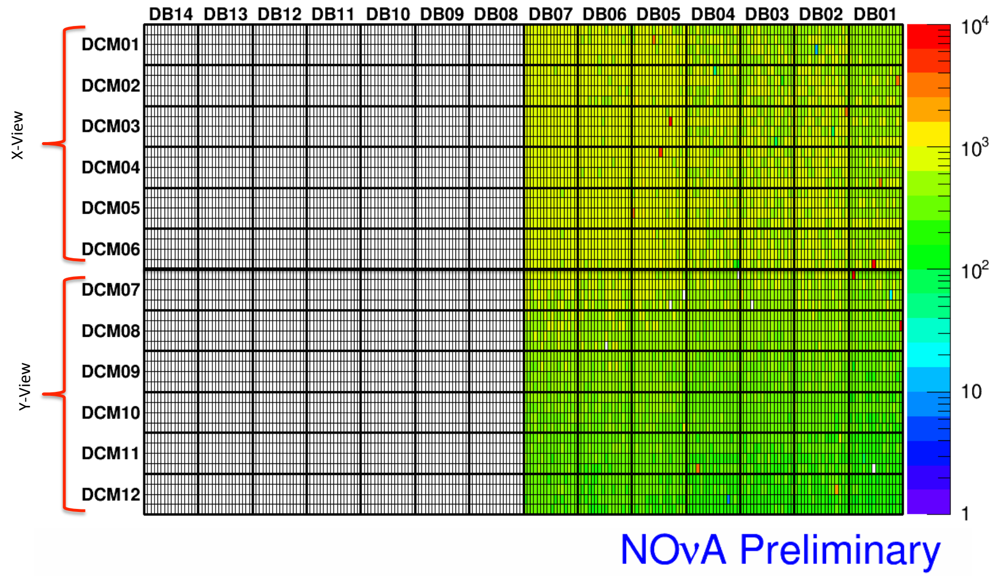
And It Works!

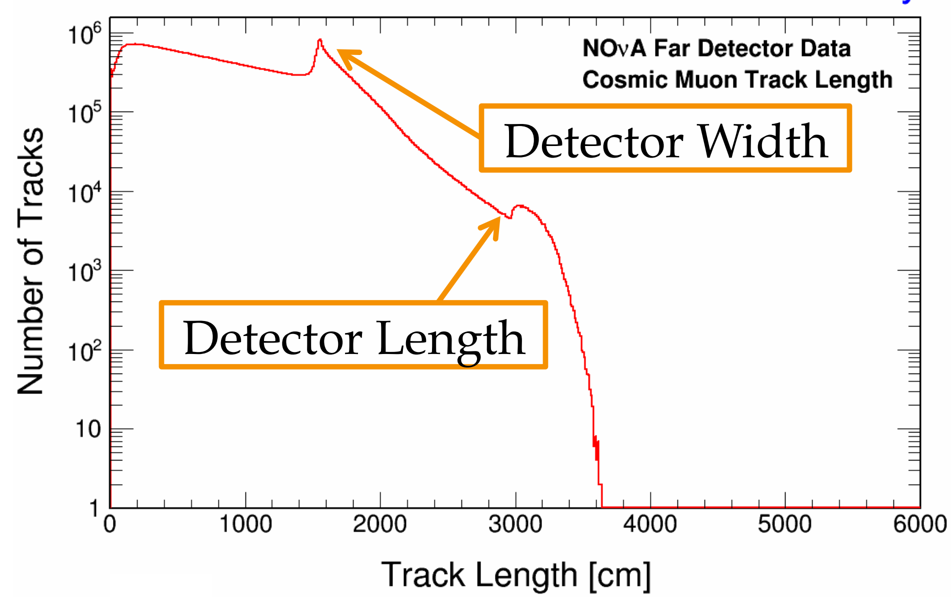
- An excerpt from our data quality monitoring from April.
- Collected physics data with 50% of the full detector then.
  - Currently using 70%.
- Hit Rate (top)
  - “physics” hits per second
  - each bin = 1 APD = 32 channels
  - 170k total channels
  - >99% of channels working!
- Muon Track Length (bottom)
  - number of tracks / 10^3 s
  - cosmic ray rate ~ 10^5 Hz
  - We can reconstruct the incoming cosmic rays!



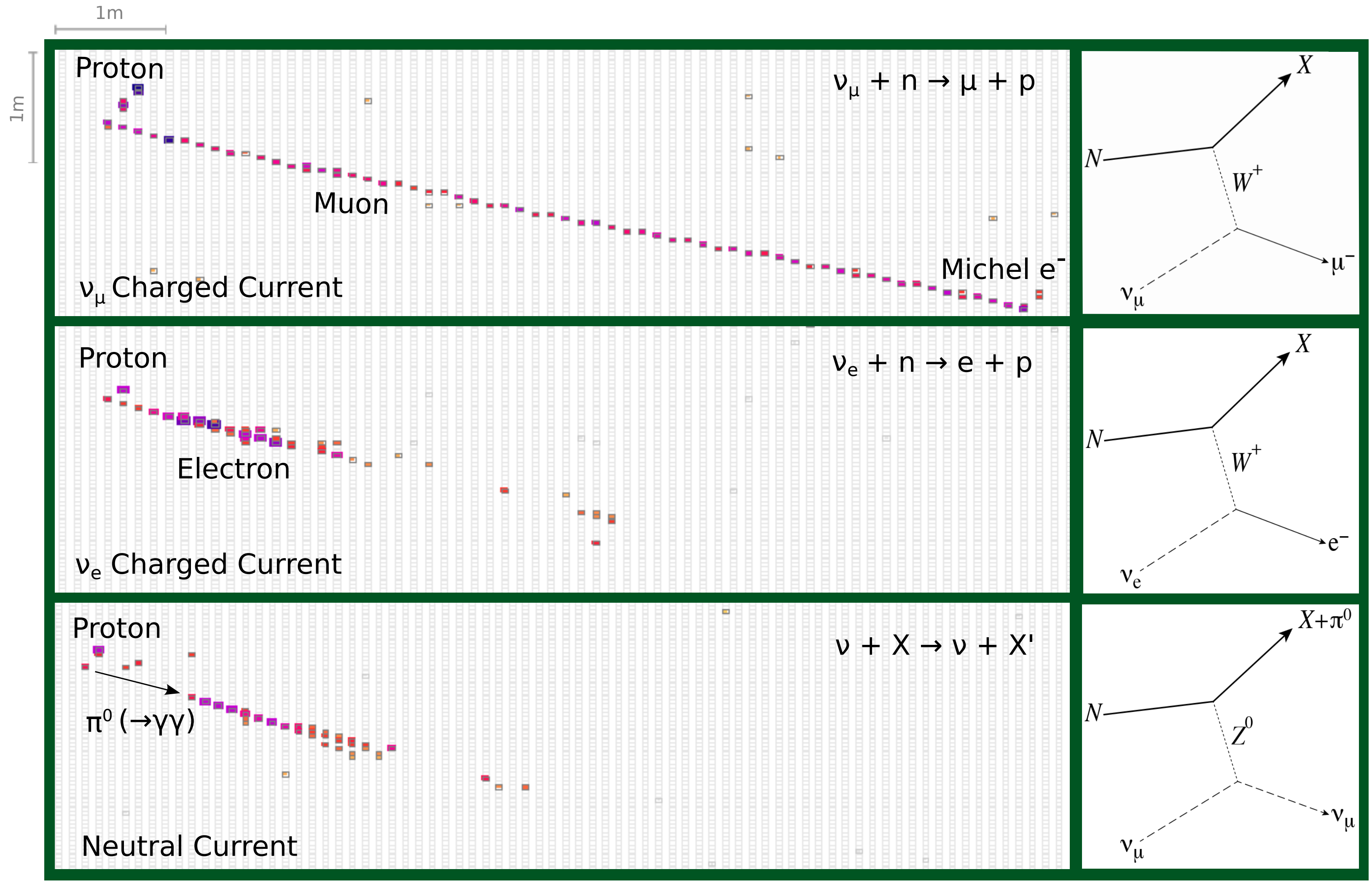
And It Works!

- An excerpt from our data quality monitoring from April.
- Collected physics data with 50% of the full detector then.
  - Currently using 70%.
- Hit Rate (top)
  - "physics" hits per second
  - each bin = 1 APD = 32 channels
  - 170k total channels
  - >99% of channels working!
- Muon Track Length (bottom)
  - number of tracks / 10^3 s
  - cosmic ray rate ~ 10^5 Hz
  - We can reconstruct the incoming cosmic rays!



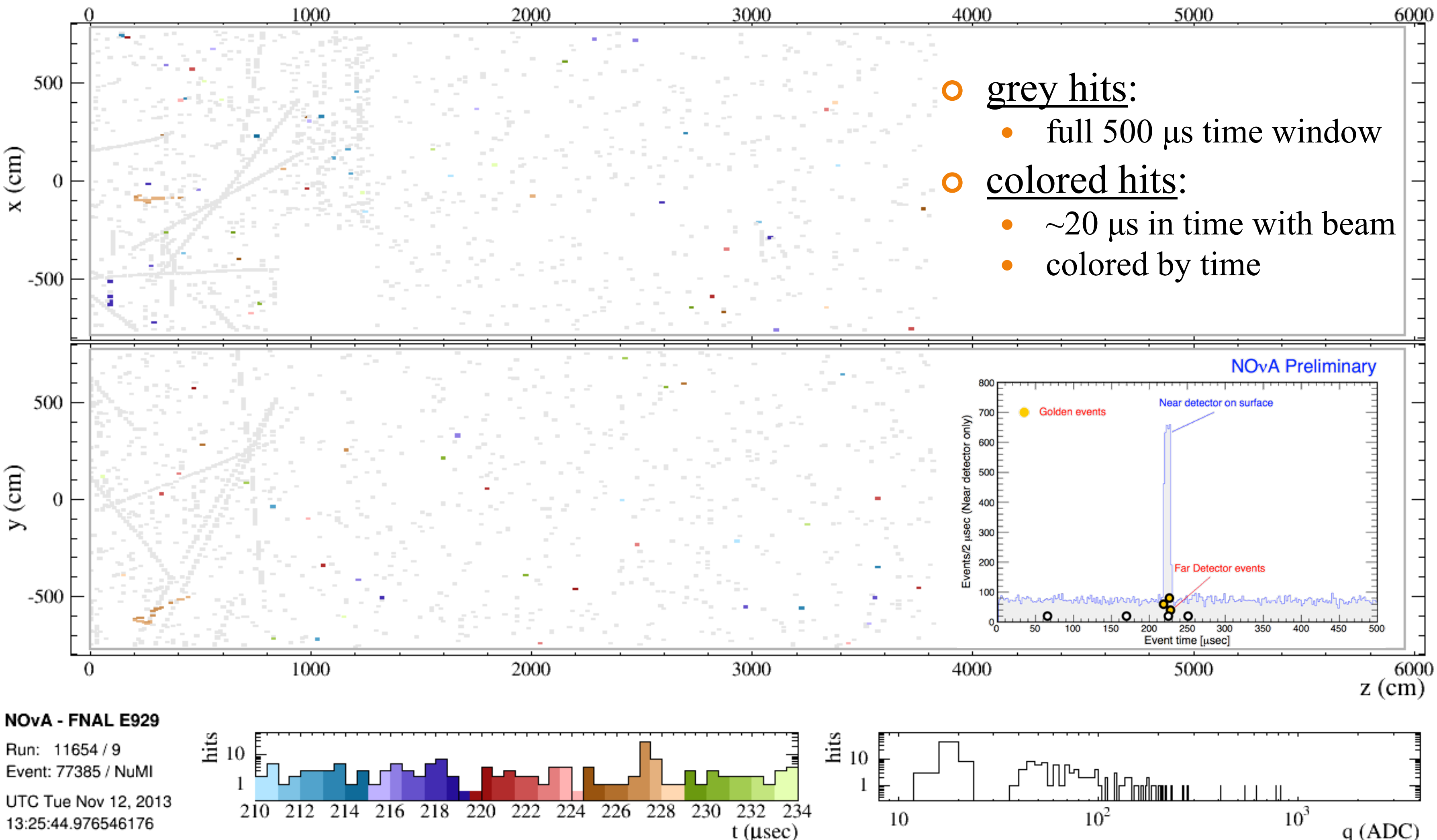


Simulated Event Display



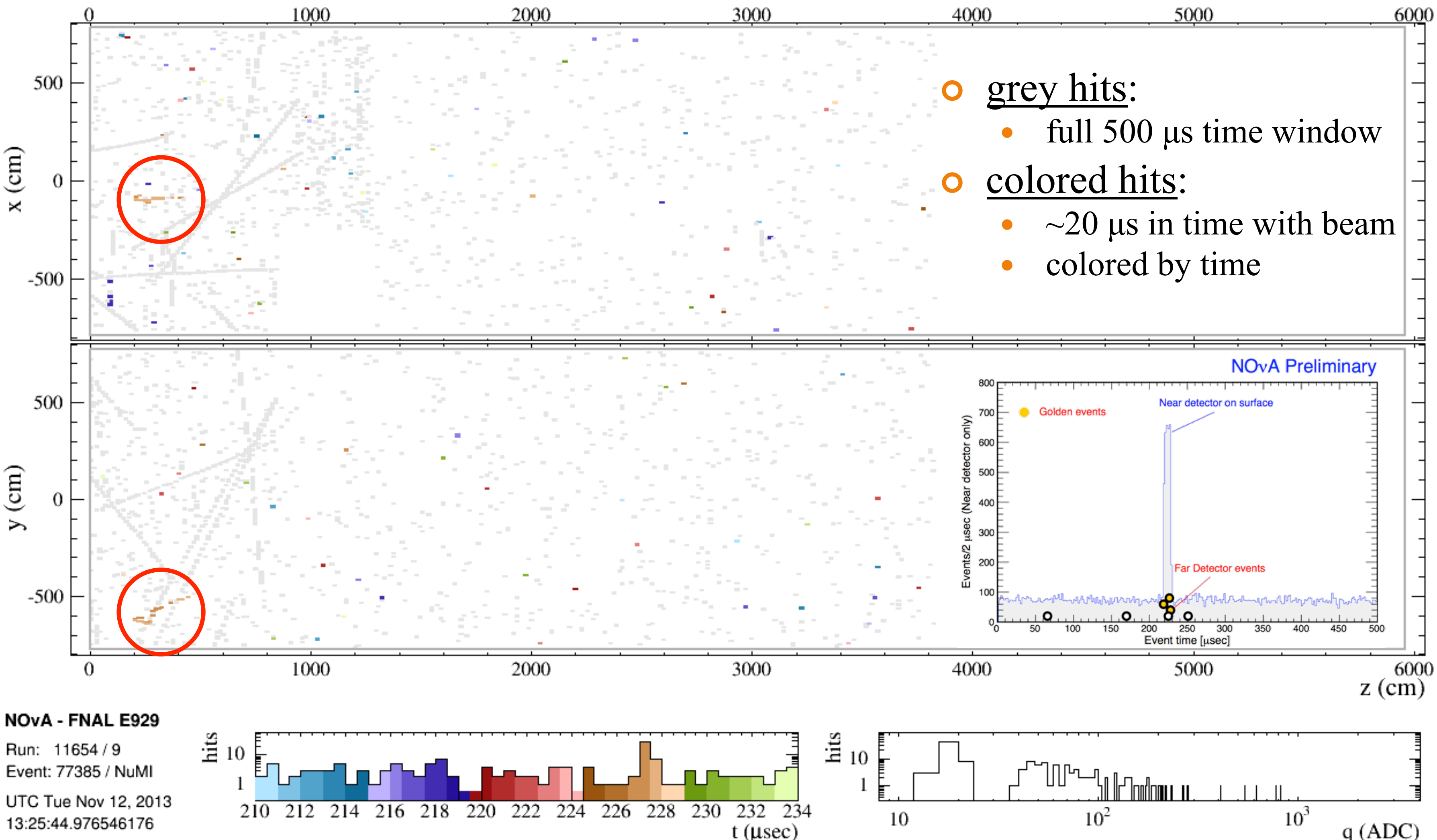
Real Event Display

- grey hits:
  - full 500 μs time window
- colored hits:
  - ~20 μs in time with beam
  - colored by time



Time **Energy**

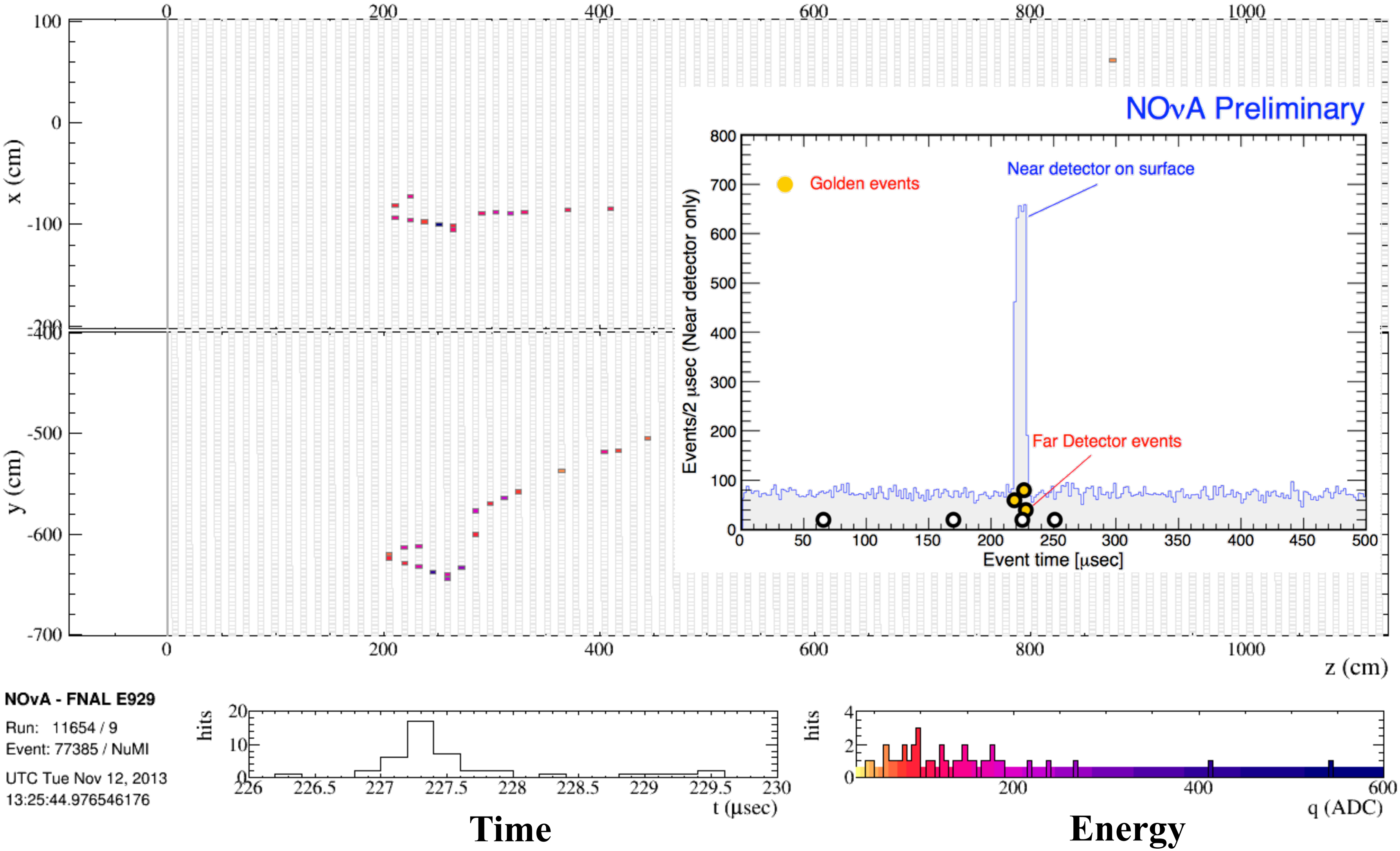
Real Event Display



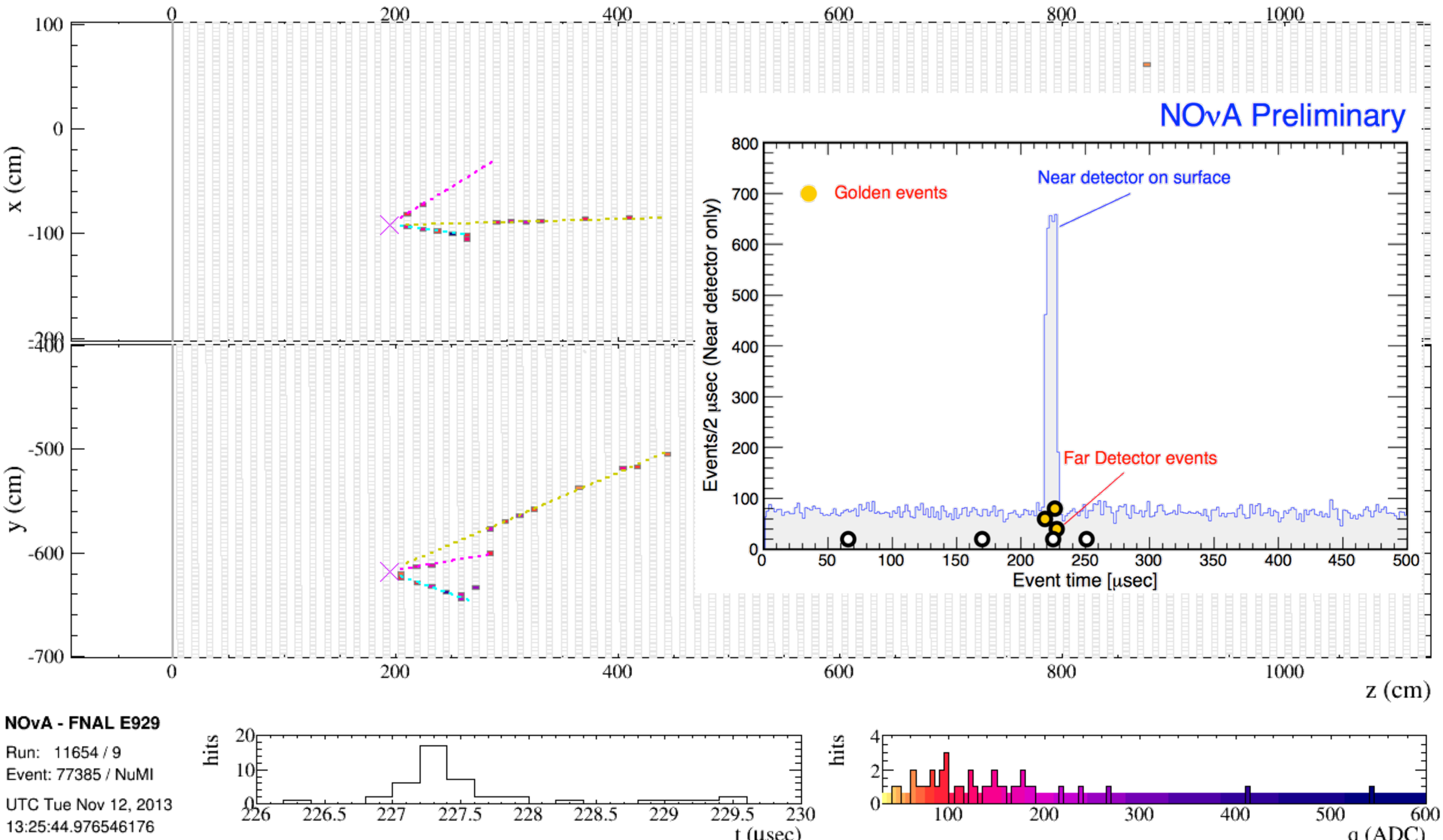
- **grey hits:**
  - full 500 μs time window
- **colored hits:**
  - ~20 μs in time with beam
  - colored by time

Time **Energy**

REAL EVENT DISPLAY (zoomed in)

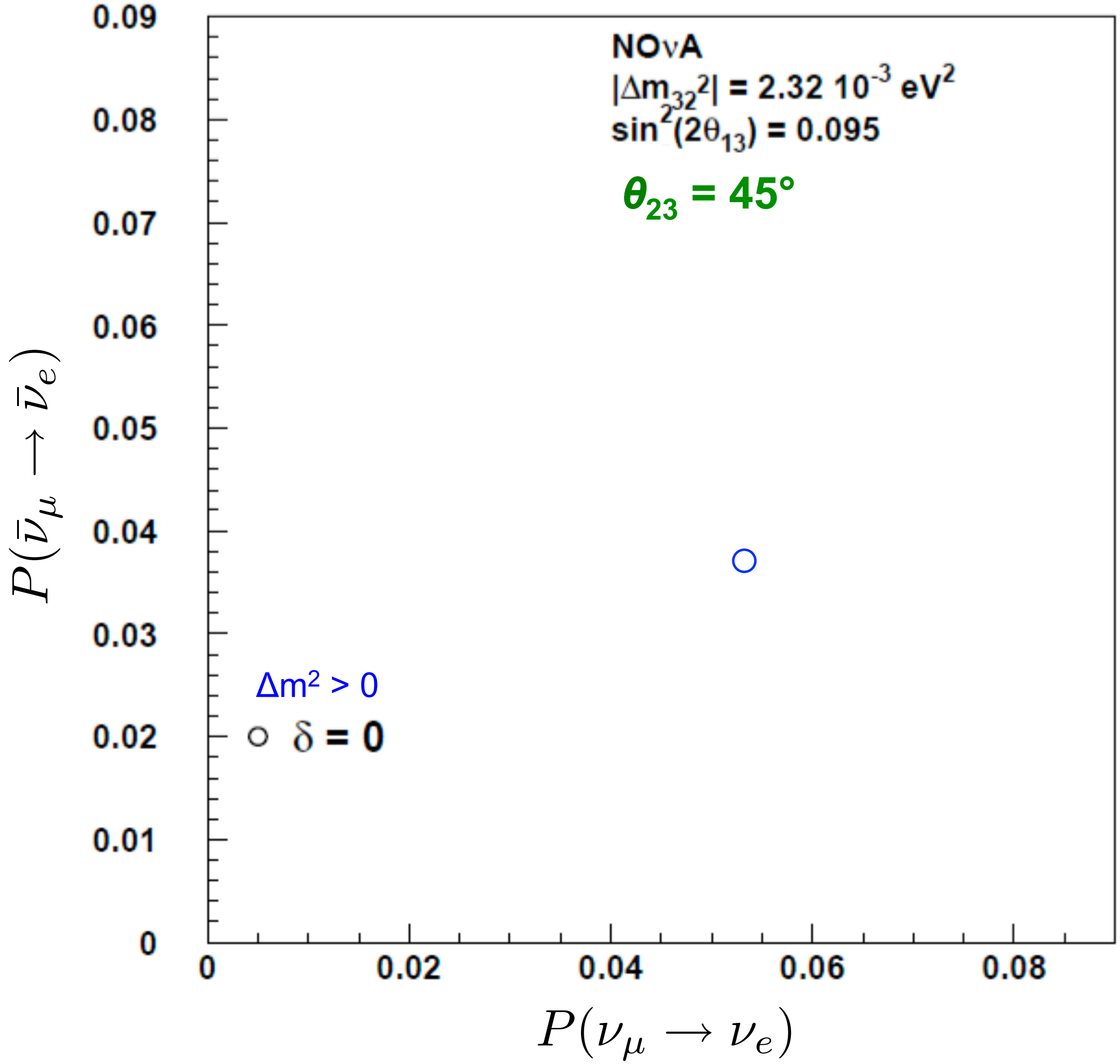


REAL EVENT DISPLAY (with reconstruction)



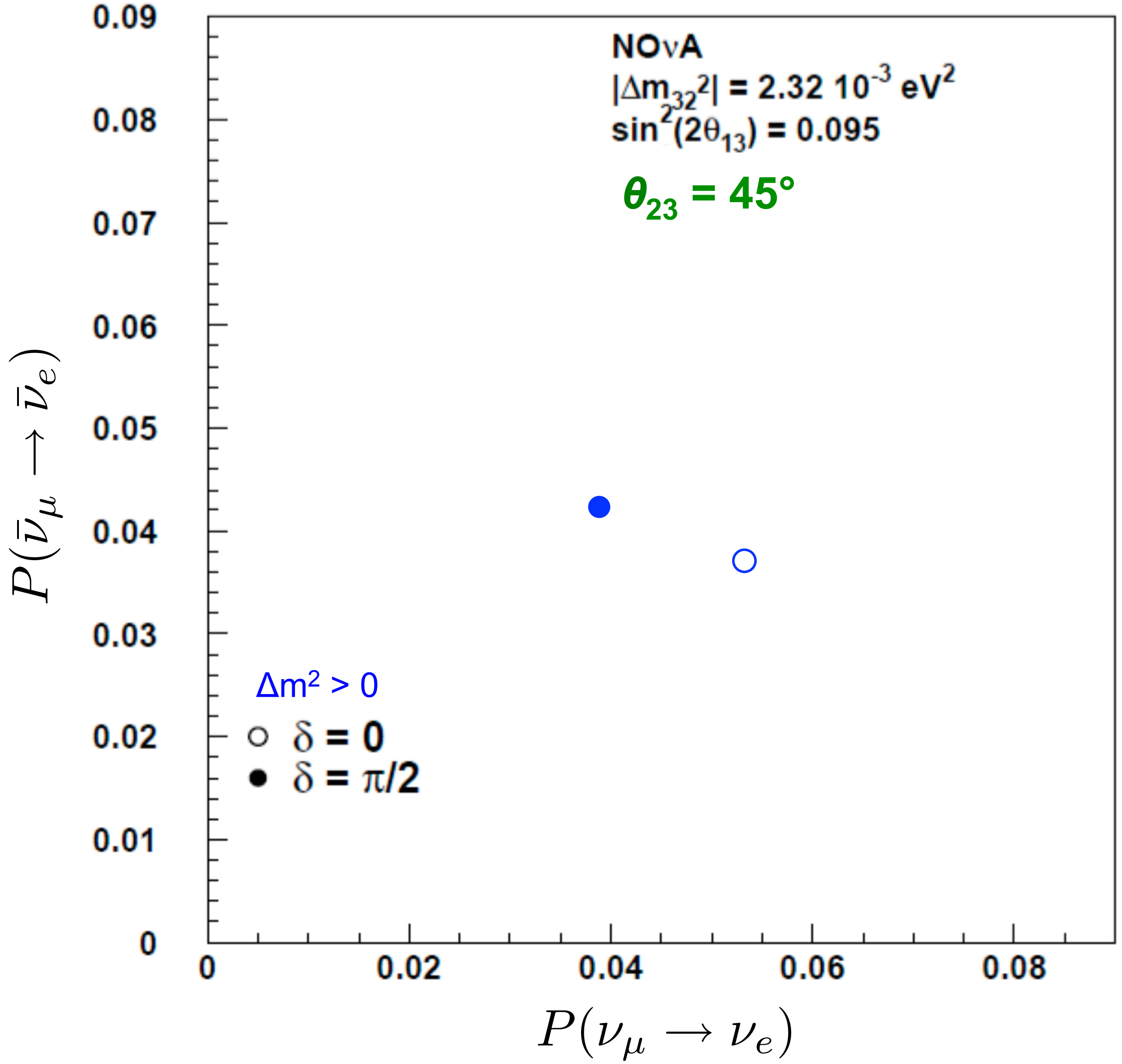
Time **Energy**

OSCILLATION PHYSICS REACH



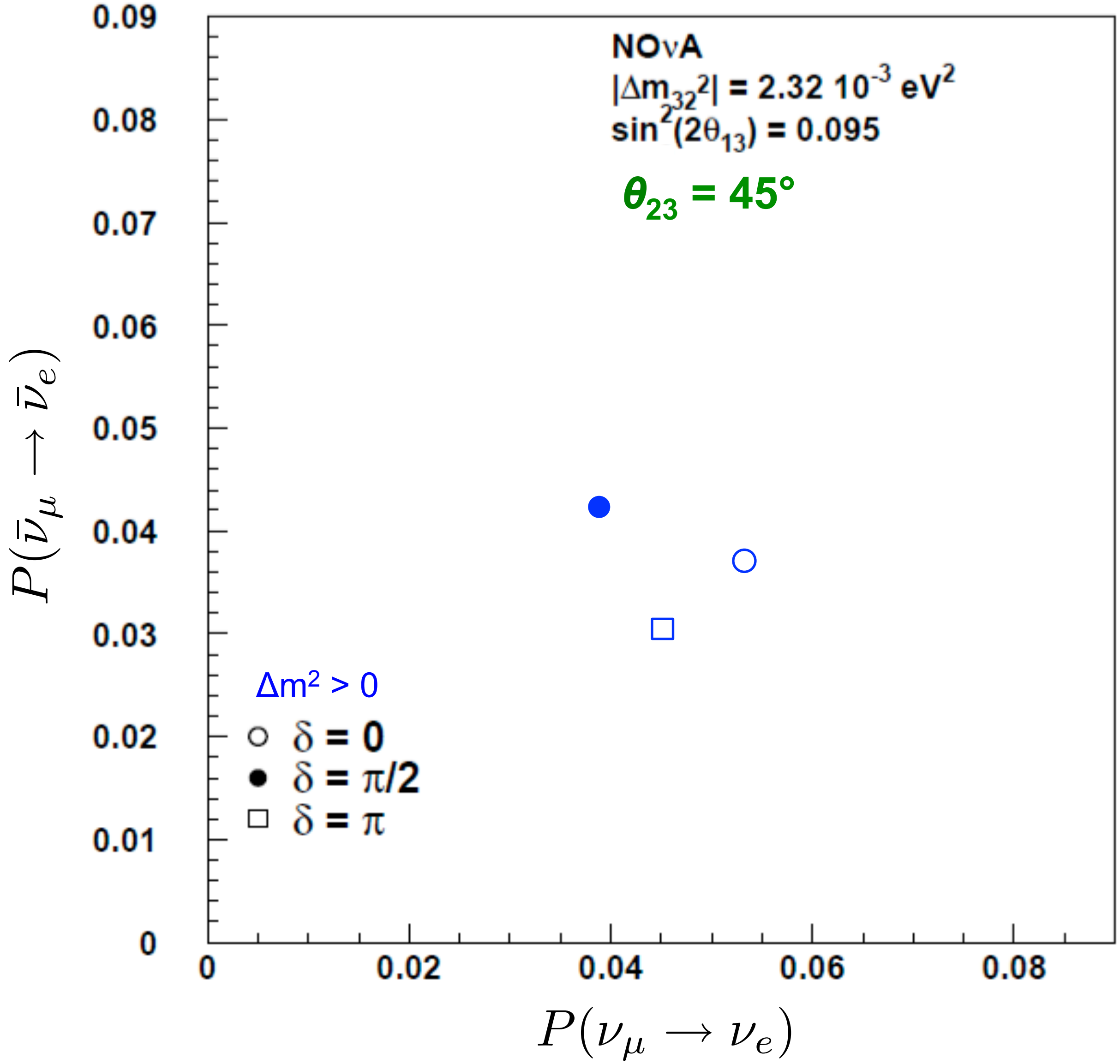
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

Oscillation Physics Reach



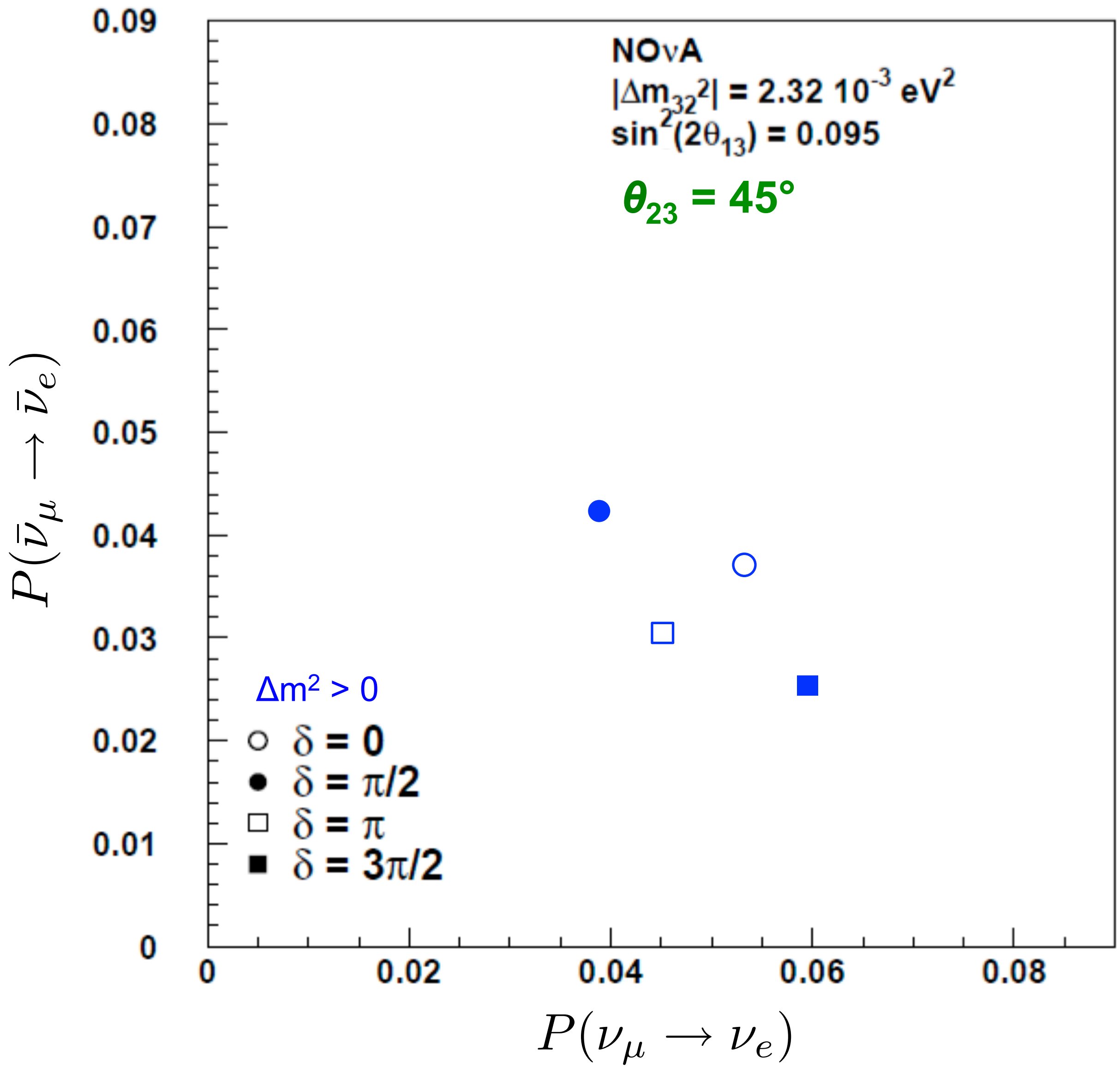
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

Oscillation Physics Reach



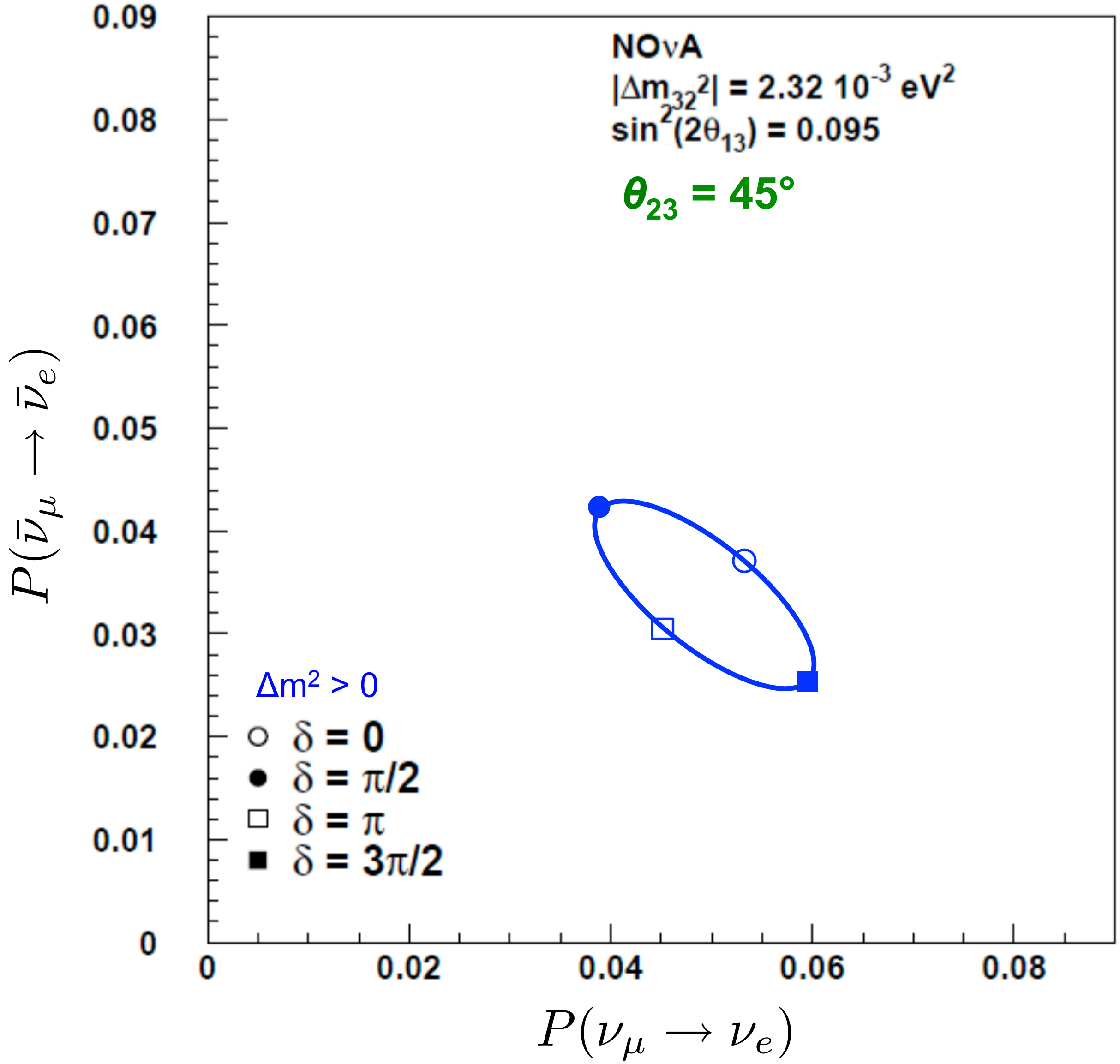
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

OSCILLATION PHYSICS REACH



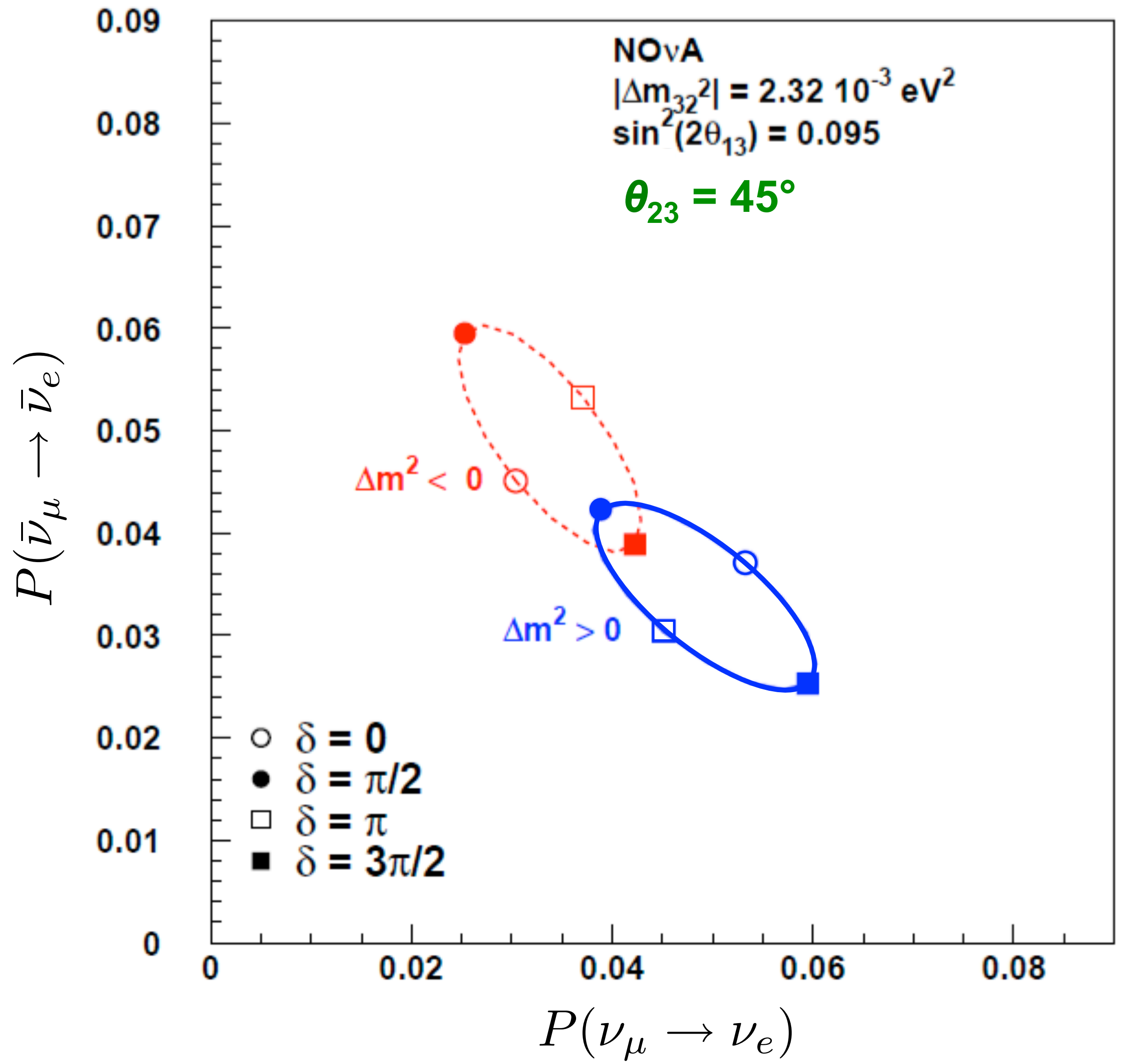
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

Oscillation Physics Reach



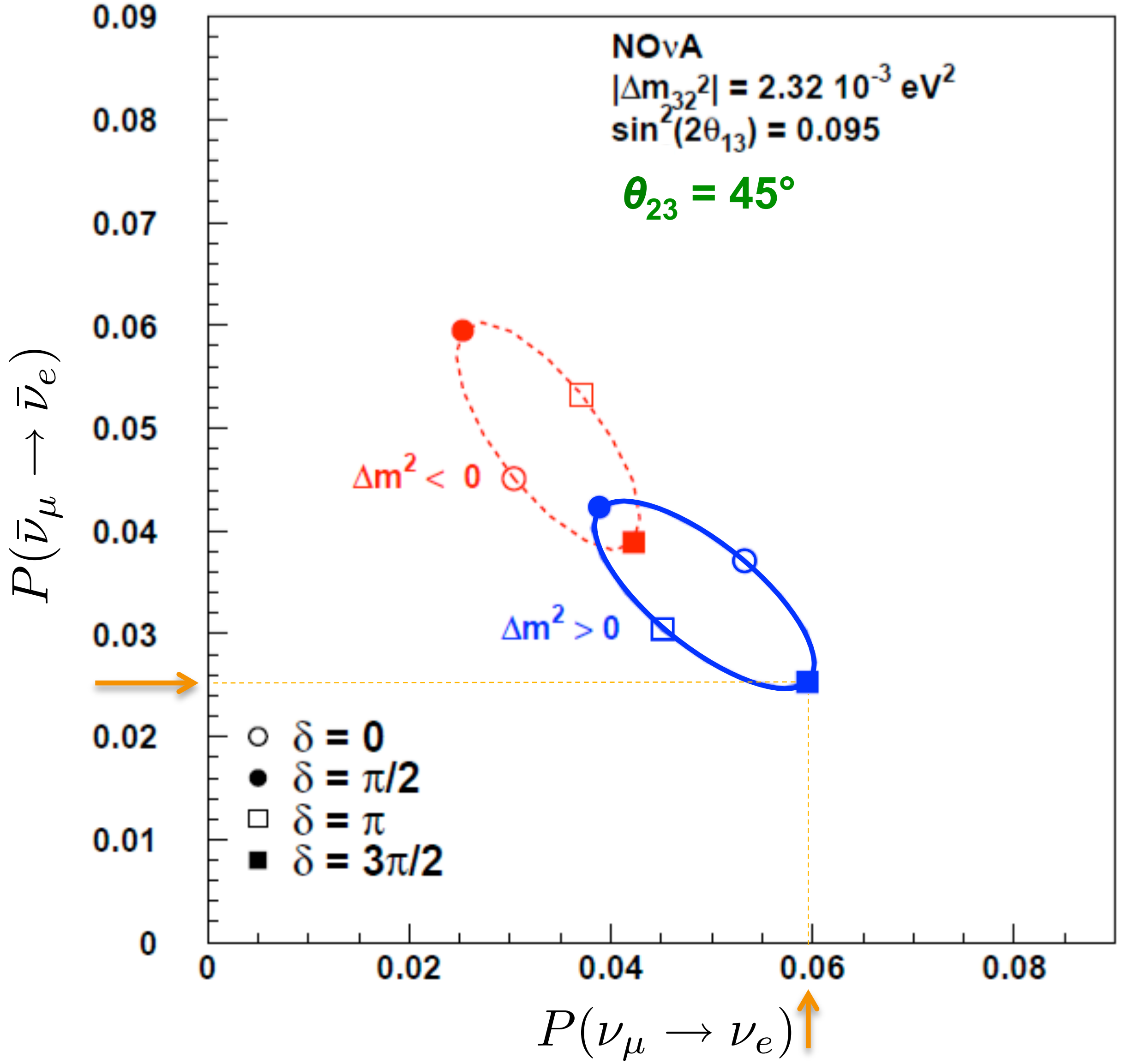
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

Oscillation Physics Reach



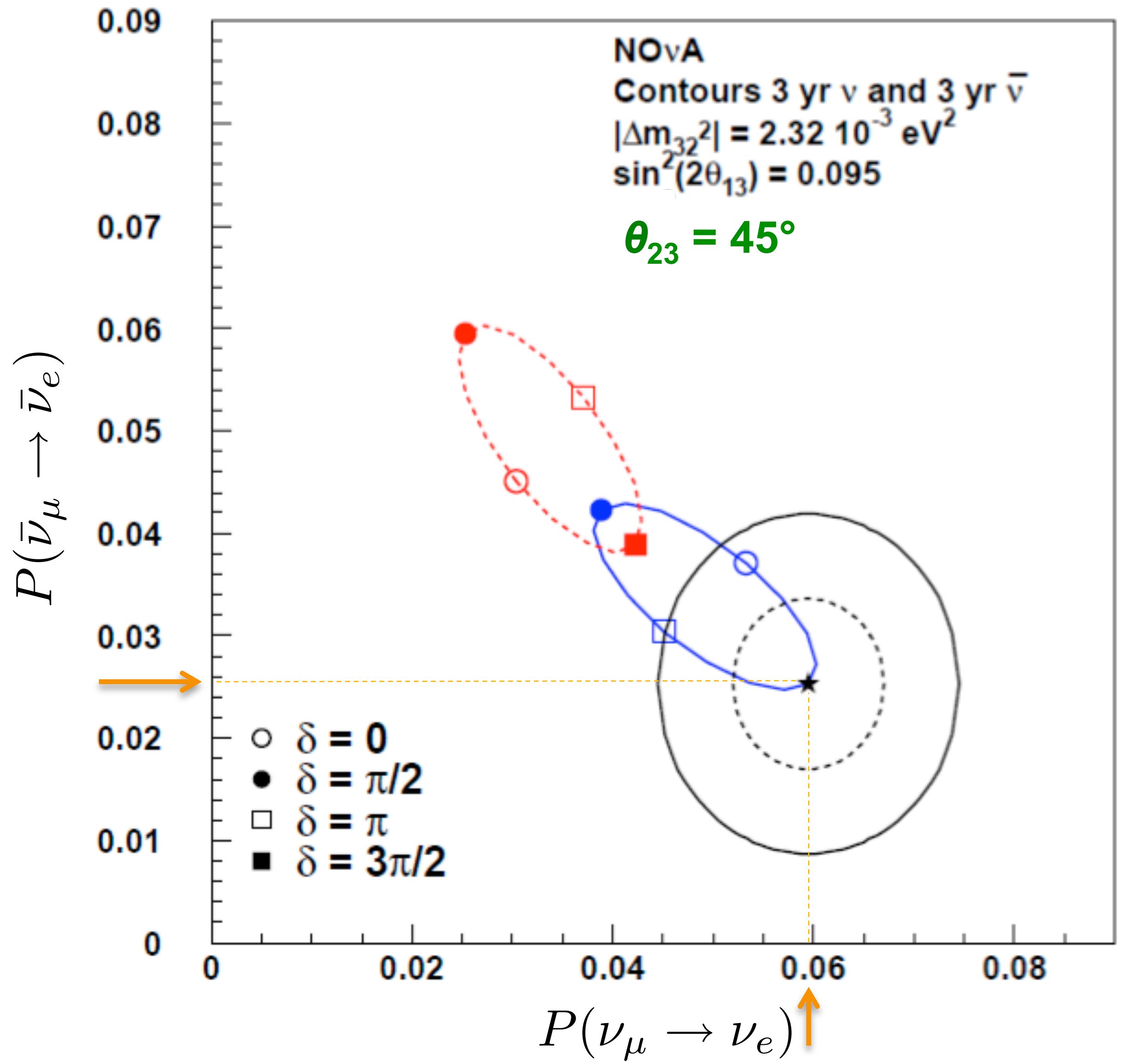
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

OSCILLATION PHYSICS REACH



- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

Oscillation Physics Reach

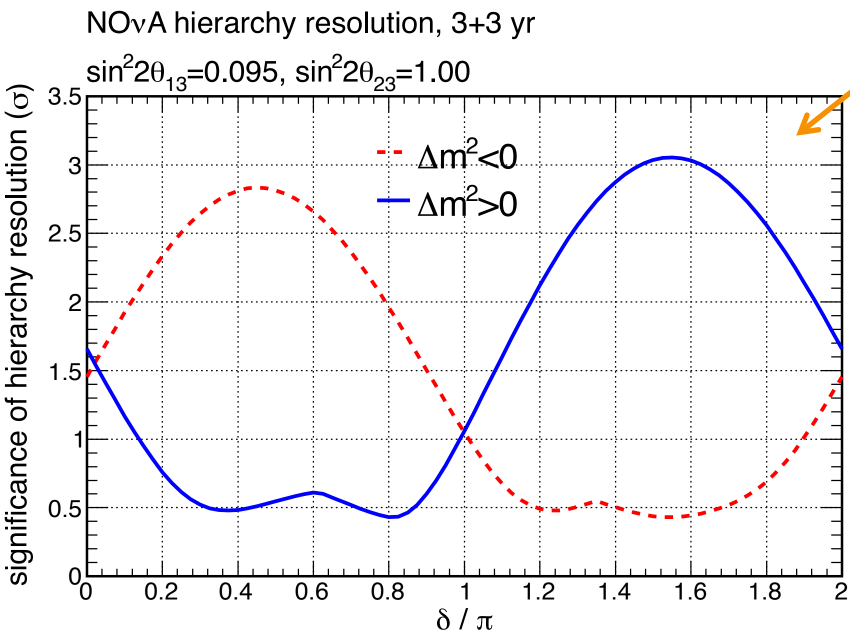


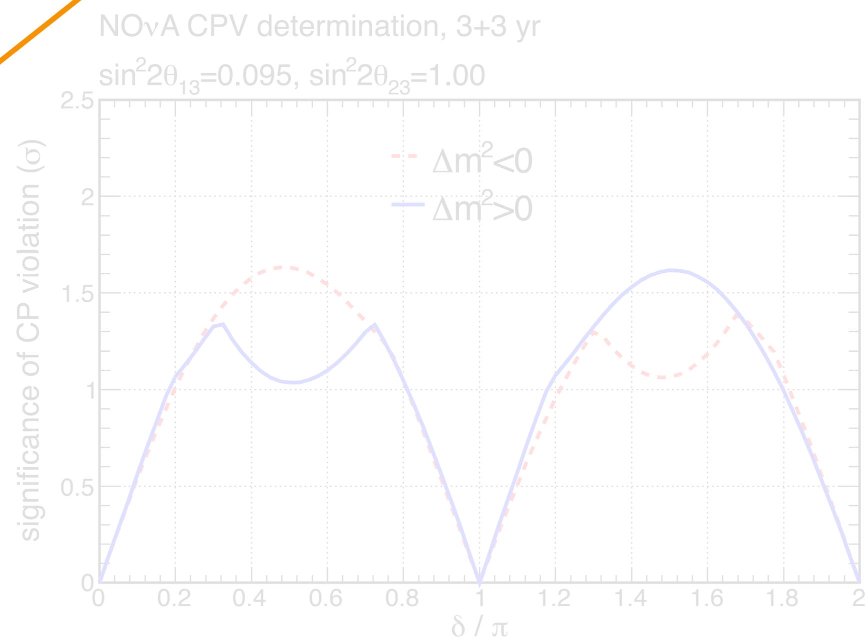
- Using the oscillation equations, we can calculate the neutrino and anti-neutrino appearance probabilities.
- Assume that NOνA would measure where the orange arrows point (best case scenario).
- The bold and dotted lines show the 1 and 2 σ contours that we could achieve with:
- 3 years neutrino running plus 3 years anti-neutrino running

Mass Hierarchy and δ_{CP} Sensitivity

- Given the plots from the previous slides and using our analysis framework, we can determine how sensitive we will be to resolve the:
  - Mass Hierarchy (even better with T2K)
  - CP-violating phase angle (δ_{CP})

Results from full simulation, reconstruction, and selection.

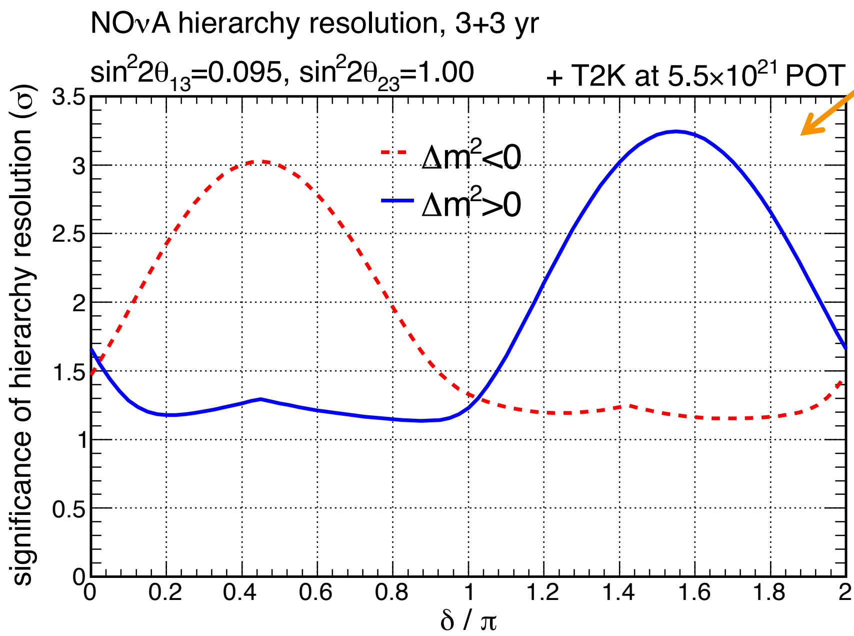


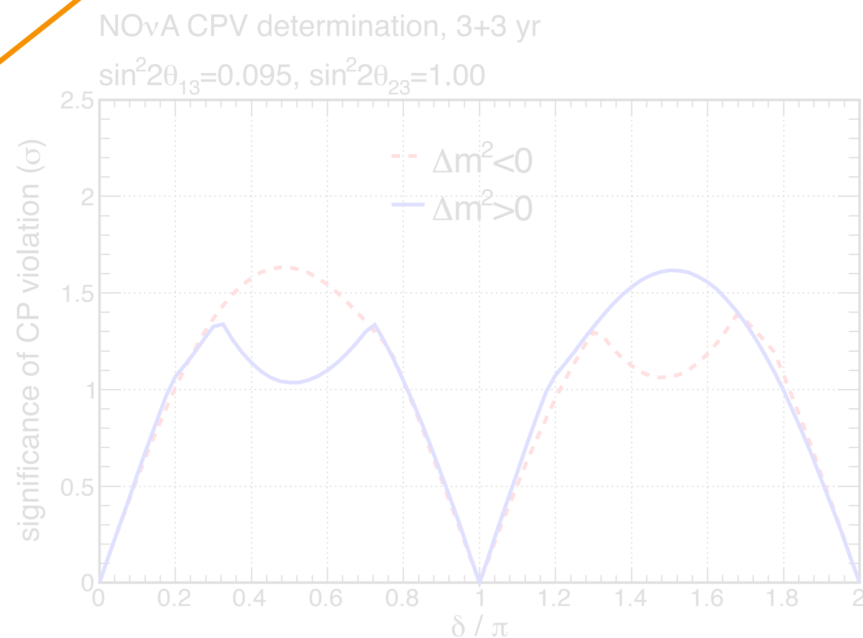


MASS HIERARCHY AND δ_{CP} SENSITIVITY

- Given the plots from the previous slides and using our analysis framework, we can determine how sensitive we will be to resolve the:
  - Mass Hierarchy (even better with T2K)
  - CP-violating phase angle (δ_{CP})

Results from full simulation, reconstruction, and selection.

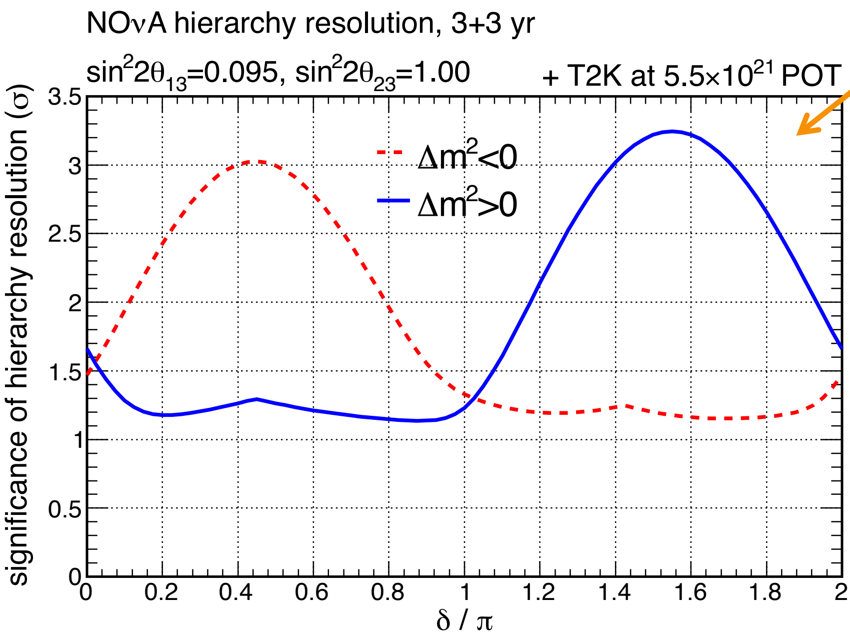


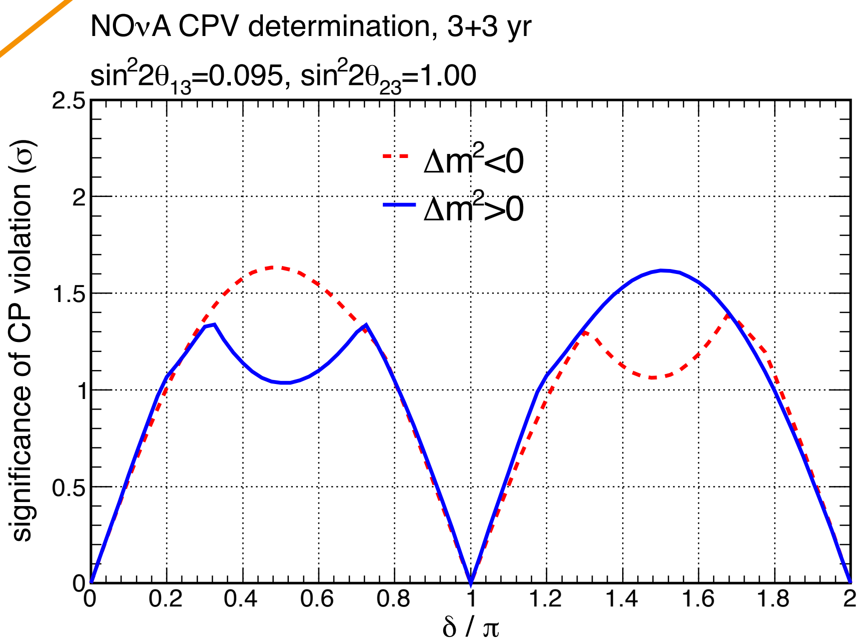


Mass Hierarchy and δ_{CP} Sensitivity

- Given the plots from the previous slides and using our analysis framework, we can determine how sensitive we will be to resolve the:
  - Mass Hierarchy (even better with T2K)
  - CP-violating phase angle (δ_{CP})

Results from full simulation, reconstruction, and selection.



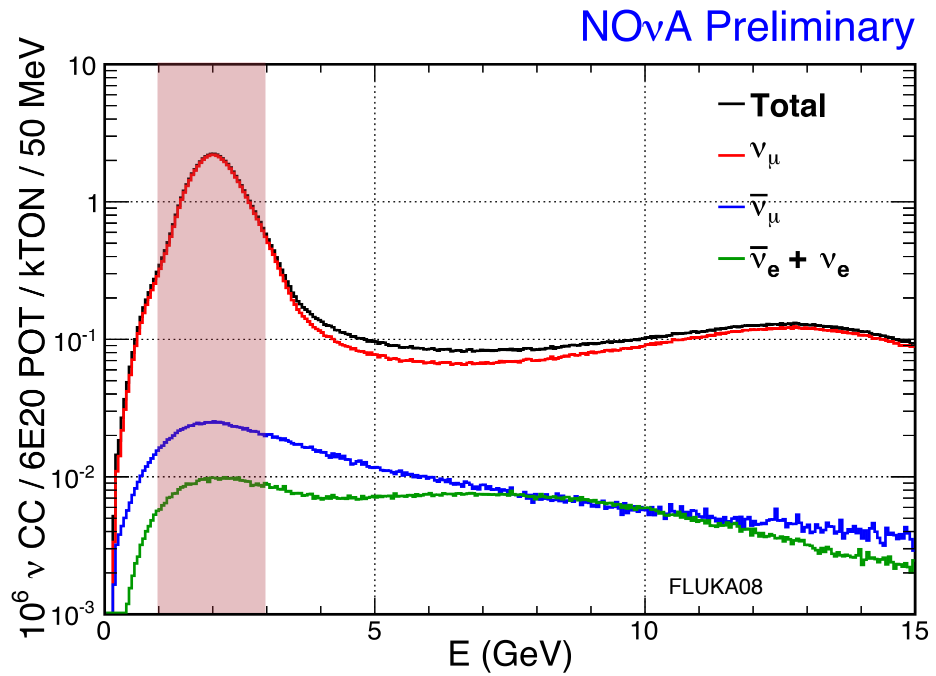


First glimpse at (δ_{CP})!

Neutrino Cross Sections

- Target = Near Detector:
  - 2.6×10^{31} nucleons
  - 47% CH_2 (from oil)
  - 40% C_2H_3Cl (from plastic)

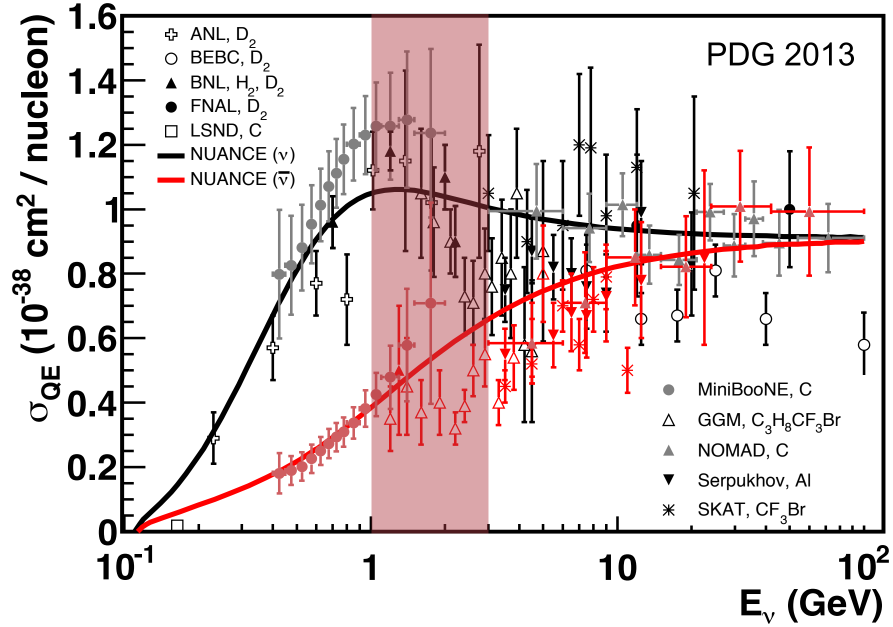
- Off-axis beam provides lots of neutrinos:
  - between 1 and 3 GeV
  - with 6×10^{20} POT per year
  - 1.62×10^7 neutrino interactions per year
    - 1.58×10^7 muon neutrinos
    - 2.7×10^6 electron neutrinos



$\times 10^6$	[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

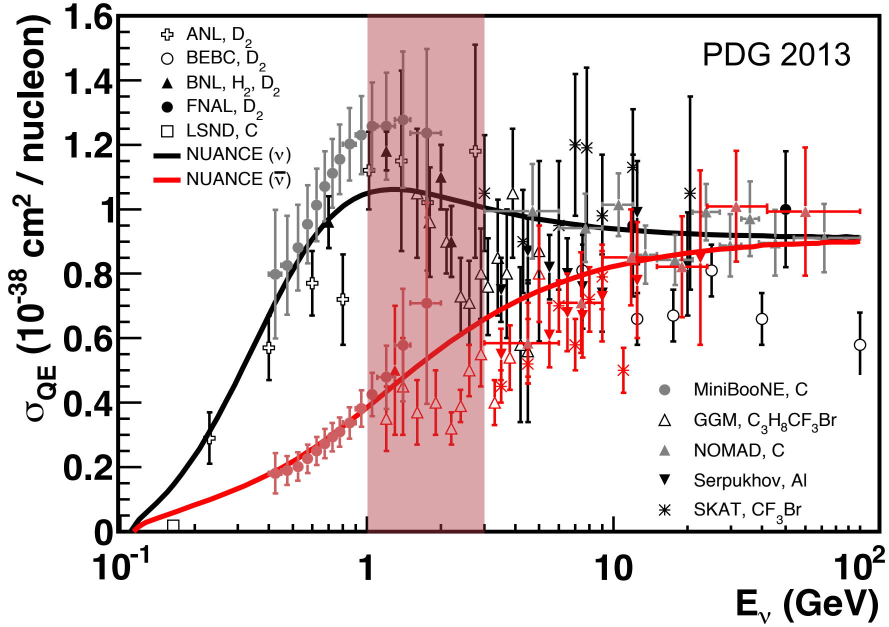
Muon Neutrino Cross Sections

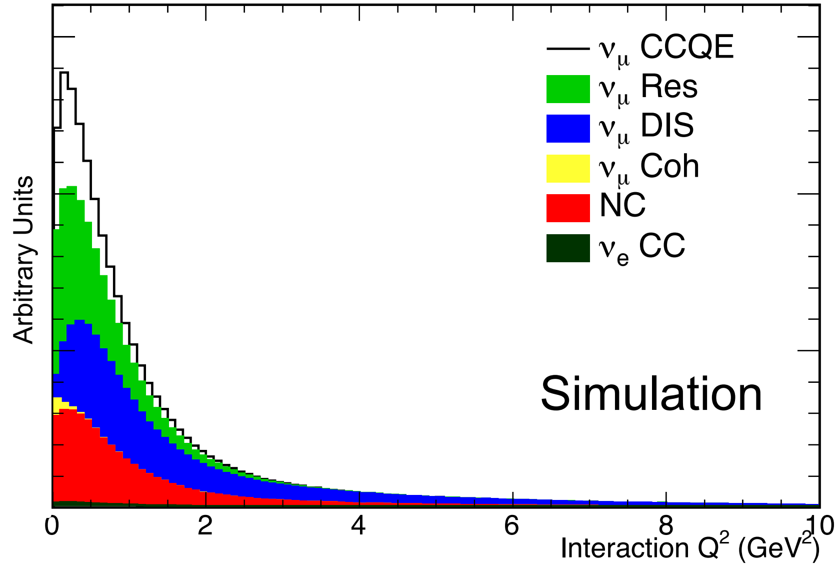
- Excellent muon identification.
- Muon catcher designed to contain horizontal 2 GeV muons.
- With 2 GeV neutrino energy, the cross sections almost split evenly between CC channels:
  - Quasi-Elastic (CCQE)
  - Resonance (Res)
  - Deep Inelastic Scattering (DIS)
- CCQE analysis already done once with NDOS:
  - See J. Nowak's talk for more CCQE details.



Muon Neutrino Cross Sections

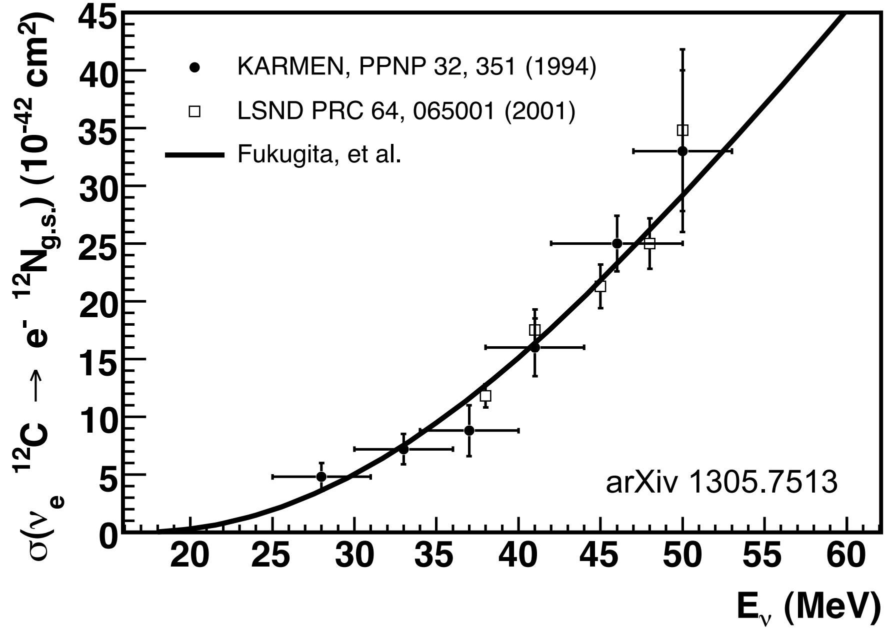
- Excellent muon identification.
- Muon catcher designed to contain horizontal 2 GeV muons.
- With 2 GeV neutrino energy, the cross sections almost split evenly between CC channels:
  - Quasi-Elastic (CCQE)
  - Resonance (Res)
  - Deep Inelastic Scattering (DIS)
- CCQE analysis already done once with NDOS:
  - See J. Nowak's talk for more CCQE details.





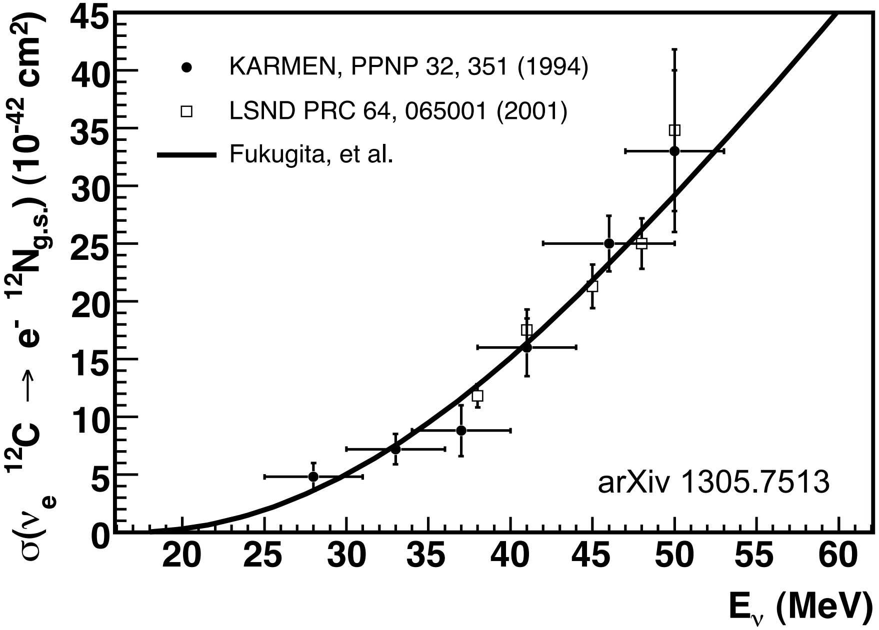
Electron Neutrino Cross Sections

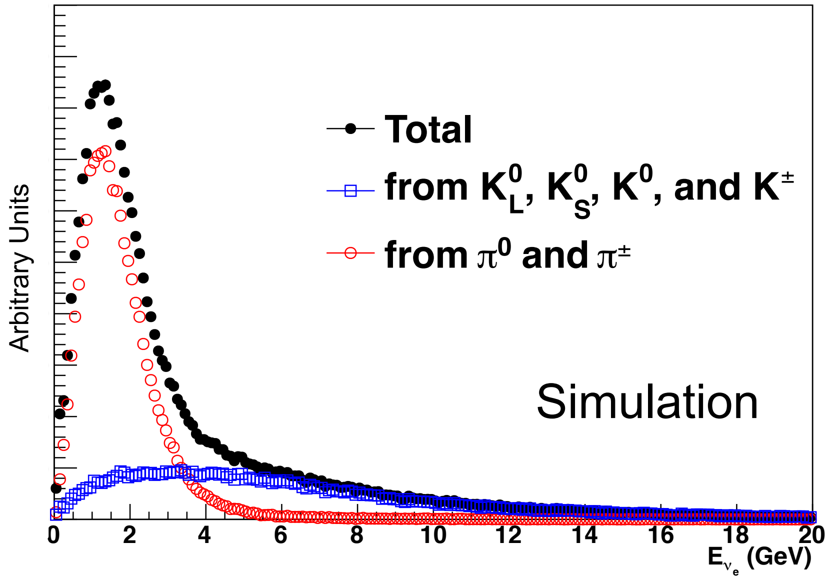
- Few electron neutrino cross section measurements, mostly below 55 MeV.
- Perhaps we can contribute at higher energies.
- NOνA designed to detect electrons!
- Muon neutrino background can easily be removed by vetoing on muon track.
- Challenges:
  - Large flux uncertainties due to Kaons at higher energies.
  - Beat down NC background.



Electron Neutrino Cross Sections

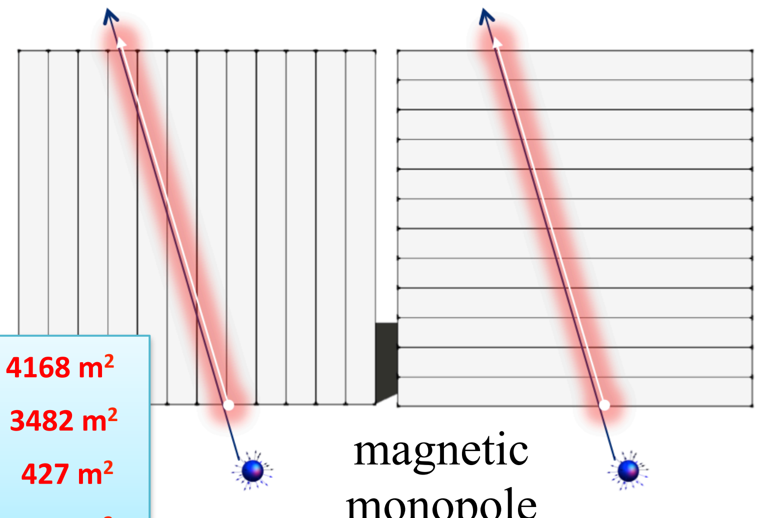
- Few electron neutrino cross section measurements, mostly below 55 MeV.
- Perhaps we can contribute at higher energies.
- NOνA designed to detect electrons!
- Muon neutrino background can easily be removed by vetoing on muon track.
- Challenges:
  - Large flux uncertainties due to Kaons at higher energies.
  - Beat down NC background.





Magnetic Monopoles

- Exciting analysis possibilities with the far detector because of its large surface area and surface location.
- Magnetic monopoles would be highly ionizing or slow moving particles.
- The plot on the right shows the monopole phase space we have access to.
- We have commissioned two triggers to search for possible monopole candidates:
  1. look for high energy deposition
  2. look for subluminal speed tracks

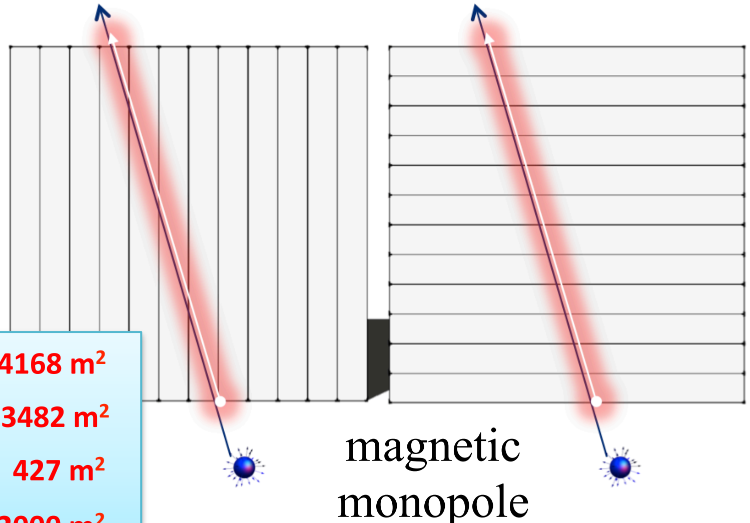


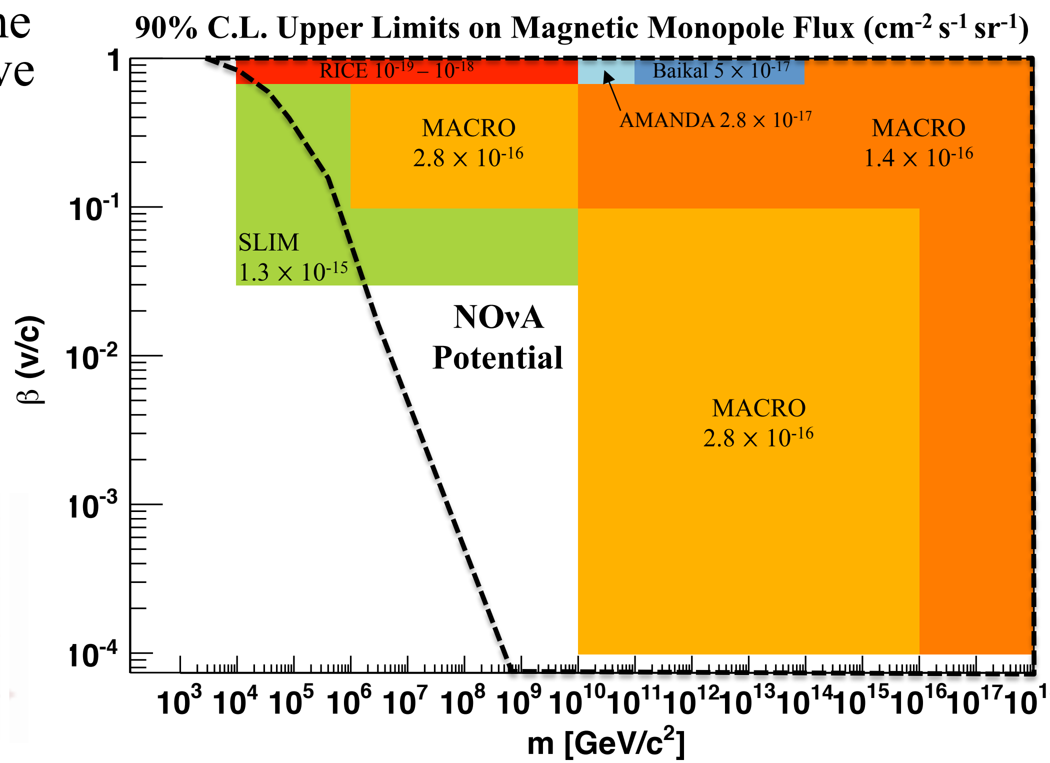
NOνA:	4168 m^2
MACRO:	3482 m^2
SLIM:	427 m^2
OHYA:	2000 m^2

Magnetic Monopoles

- Exciting analysis possibilities with the far detector because of its large surface area and surface location.
- Magnetic monopoles would be highly ionizing or slow moving particles.
- The plot on the right shows the monopole phase space we have access to.
- We have commissioned two triggers to search for possible monopole candidates:
  1. look for high energy deposition
  2. look for subluminal speed tracks

NOvA:	4168 m^2
MACRO:	3482 m^2
SLIM:	427 m^2
OHYA:	2000 m^2

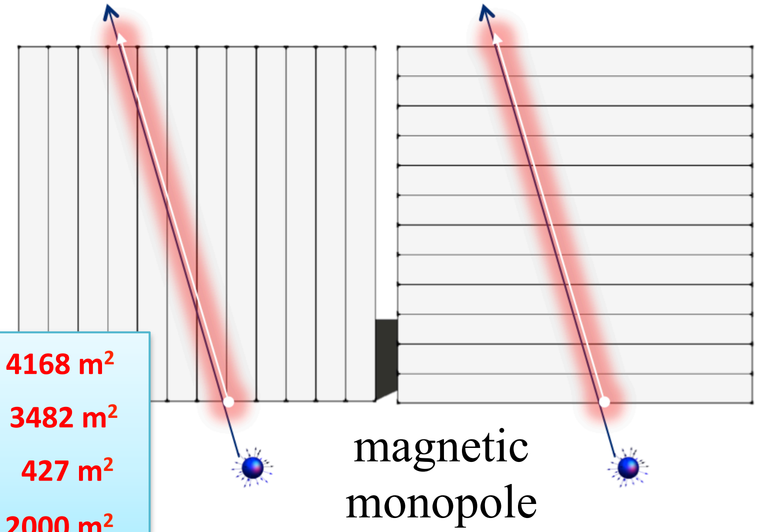


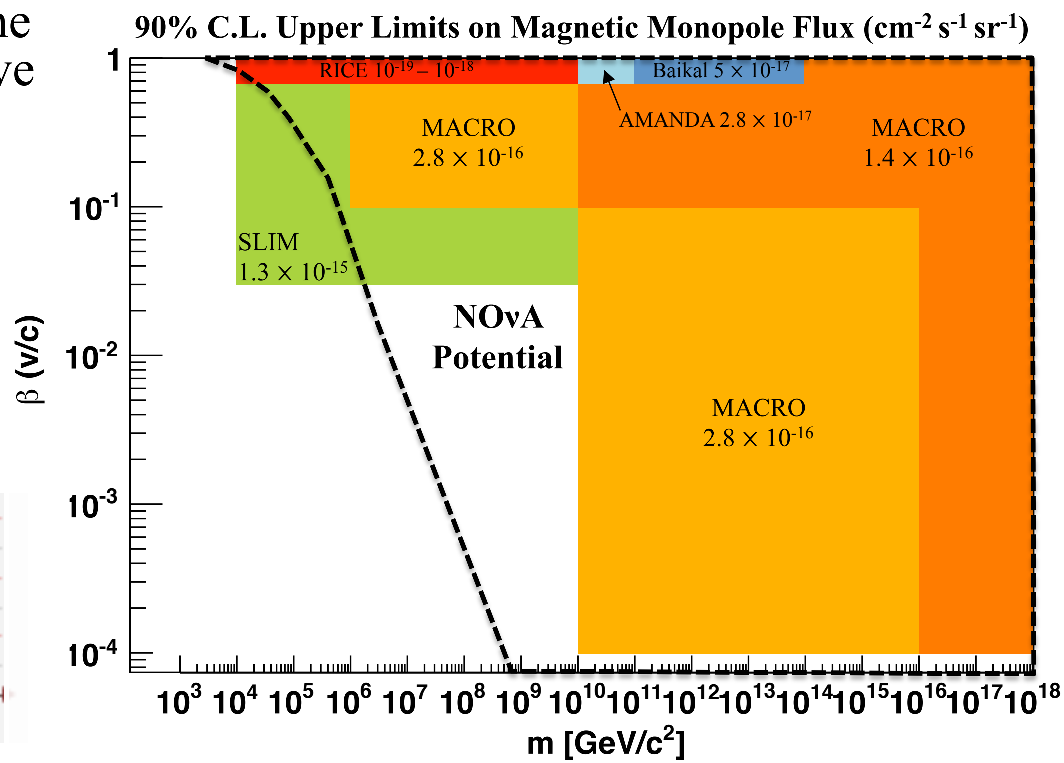


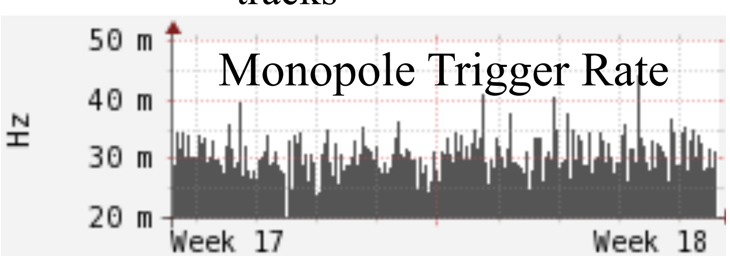
Magnetic Monopoles

- Exciting analysis possibilities with the far detector because of its large surface area and surface location.
- Magnetic monopoles would be highly ionizing or slow moving particles.
- The plot on the right shows the monopole phase space we have access to.
- We have commissioned two triggers to search for possible monopole candidates:
  1. look for high energy deposition
  2. look for subluminal speed tracks

NOνA:	4168 m^2
MACRO:	3482 m^2
SLIM:	427 m^2
OHYA:	2000 m^2





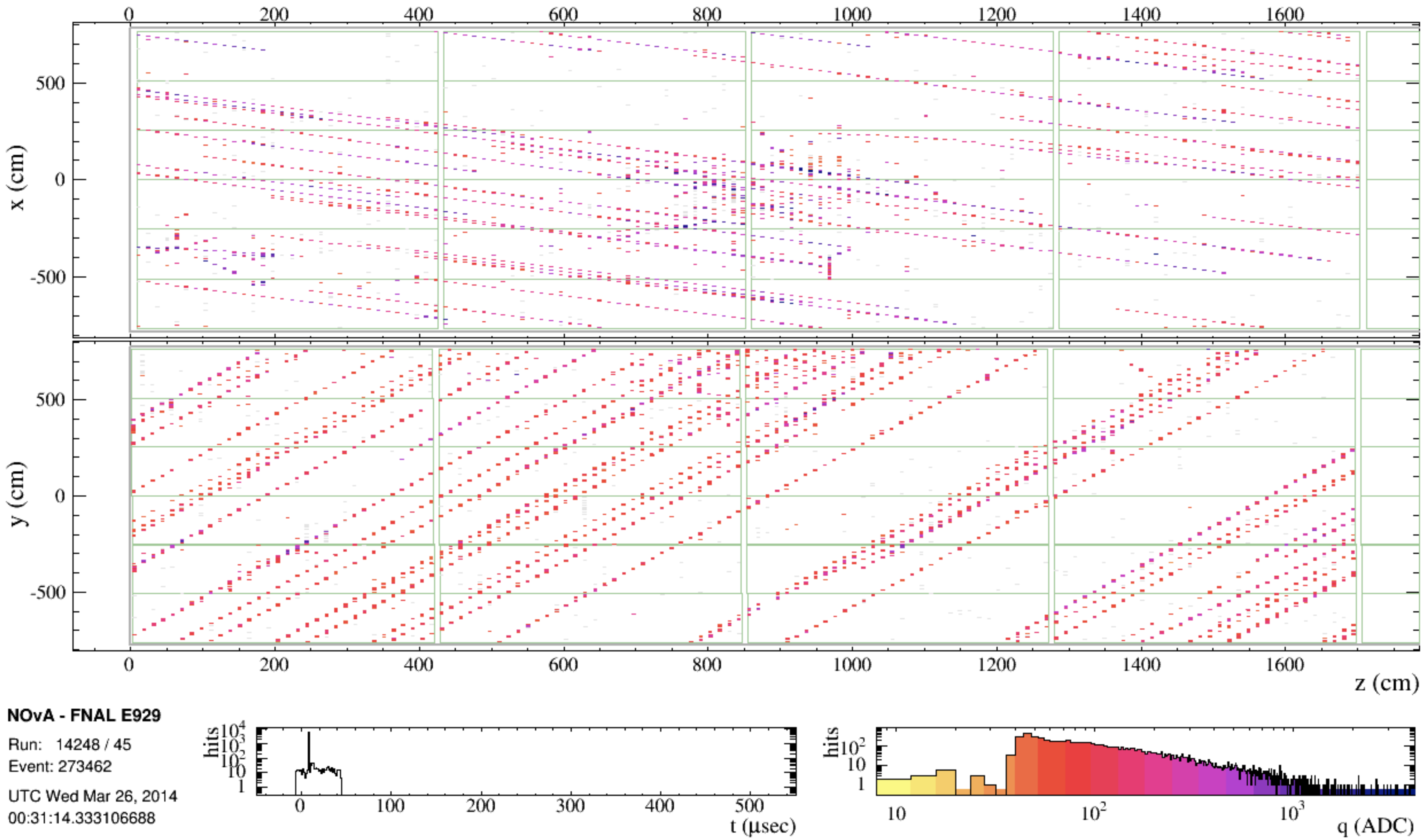


Summary

- Far and Near Detector construction is complete!
- Electronics installation and commissioning is in full swing and will finish this summer.
- NuMI beam is stable and power increasing!
- Collecting first data with partial detectors.
- Many analyses are ramping up as the data becomes available:
  - mass hierarchy, first glimpse at δ_{CP}
  - neutrino cross sections
  - magnetic monopoles
  - and many more!
- Stay tuned!

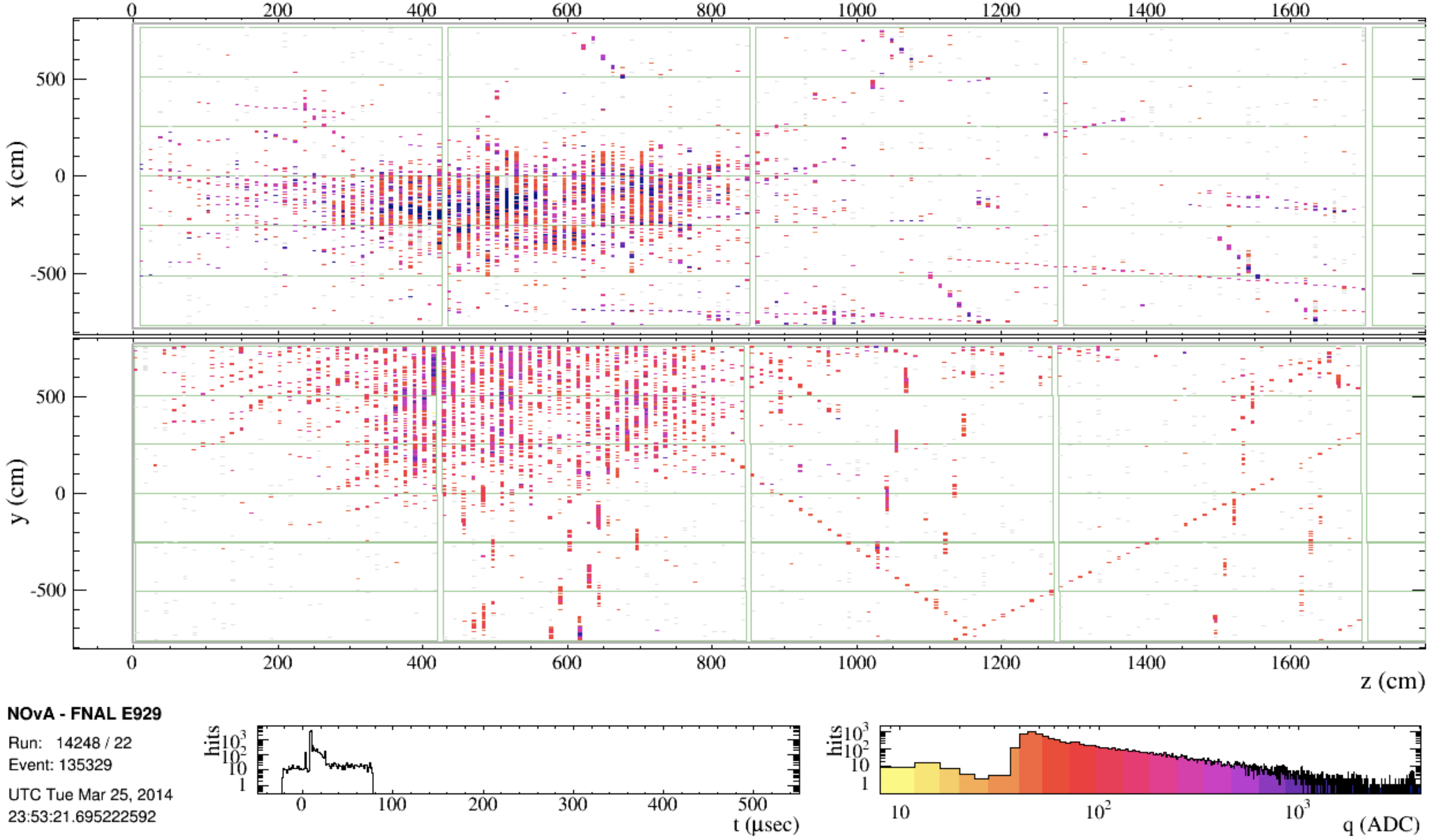
170+ scientists and engineers from 39 institutions from 7 countries

Just For Fun



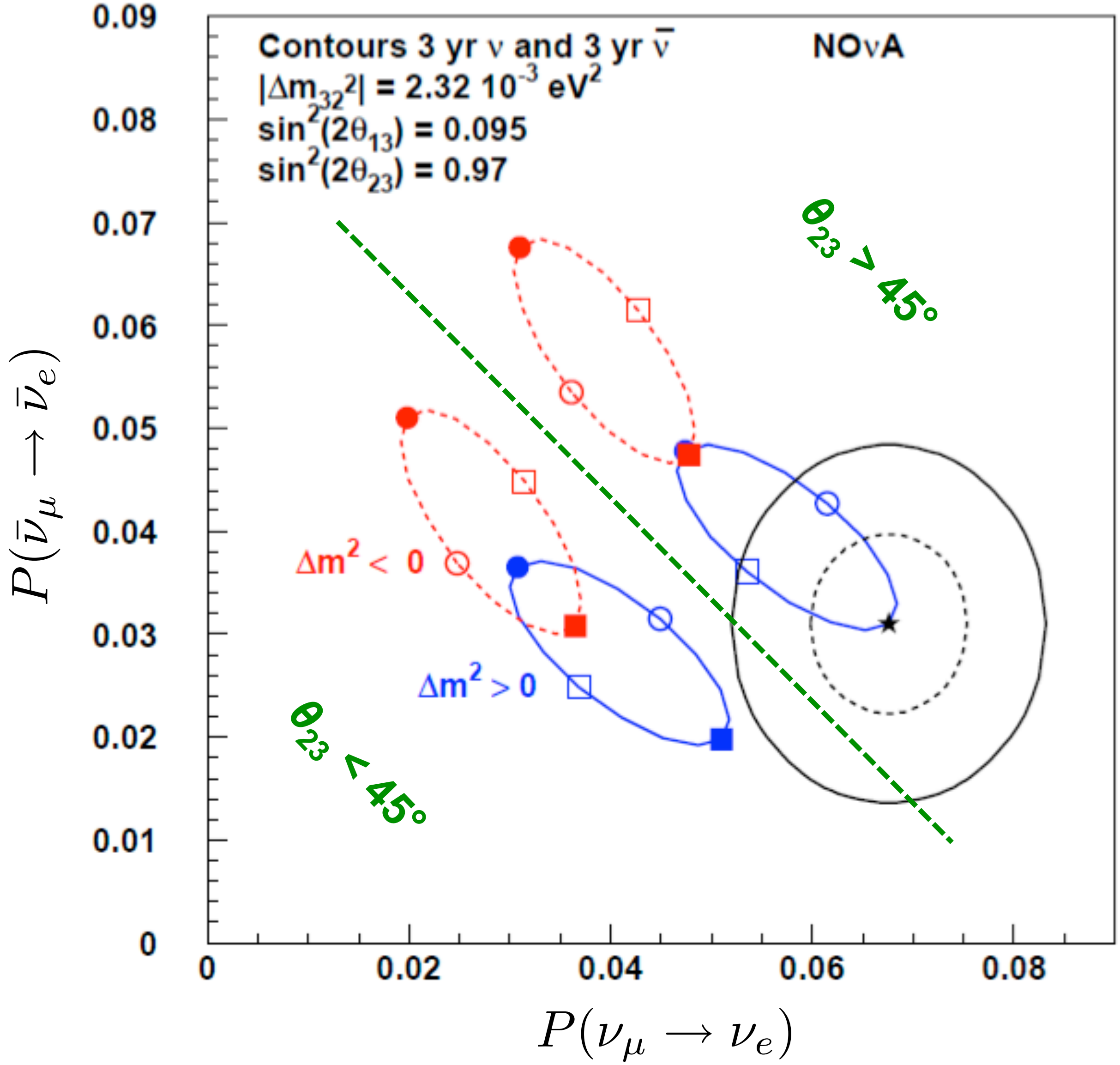
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 14248 / 45
Event: 273462
UTC Wed Mar 26, 2014
00:31:14.333106688
hits
t (μsec)
q (ADC)

Just For Fun


NOvA - FNAL E929
Run: 14248 / 22
Event: 135329
UTC Tue Mar 25, 2014
23:53:21.695222592
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

Back Up Slides

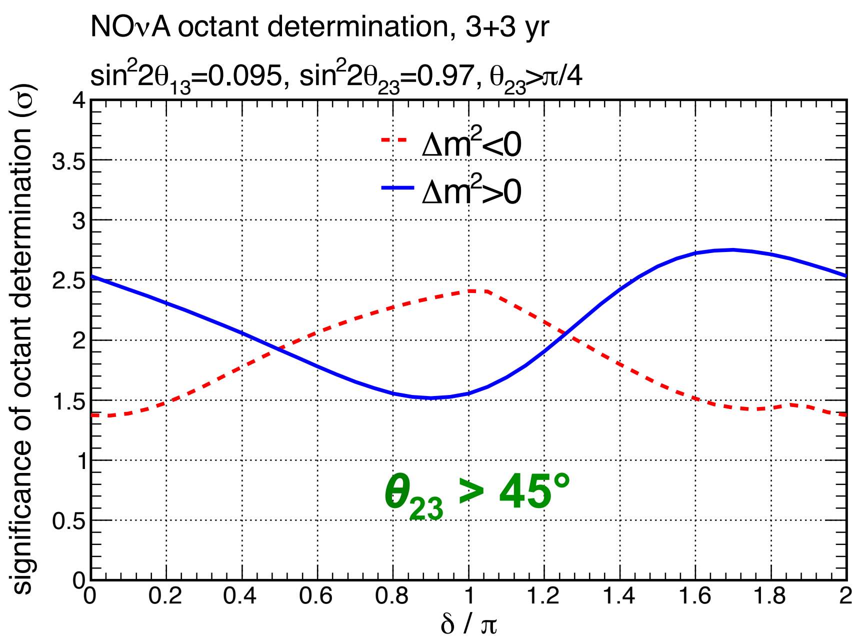
Physics Reach (θ_{23} Octant)

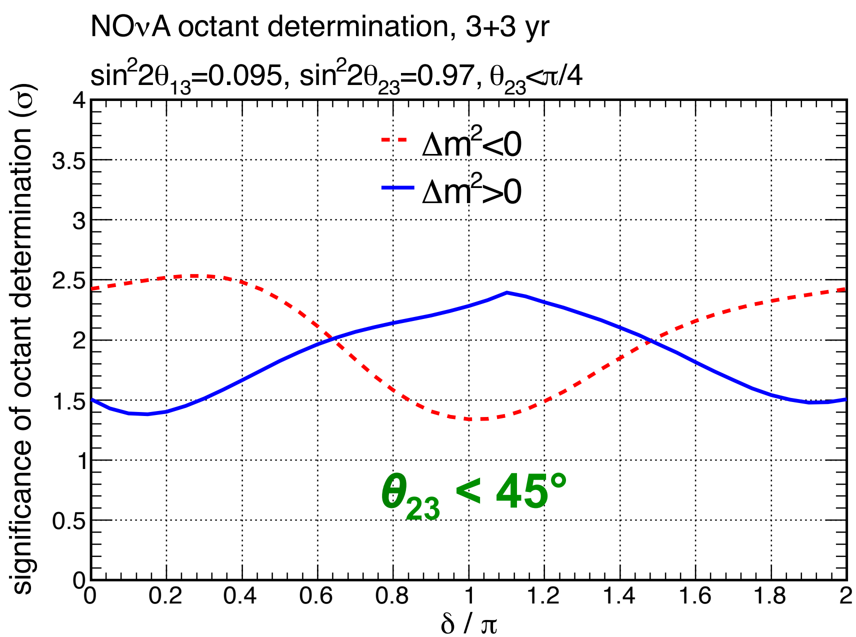


- We know that $\sin^2(2\theta_{23})$ is close to unity, but what octant does θ_{23} fall in?
  - $\theta_{23} > 45°$
  - $\theta_{23} < 45°$
- The probability ellipses are given for both scenarios separated by the green dotted line.

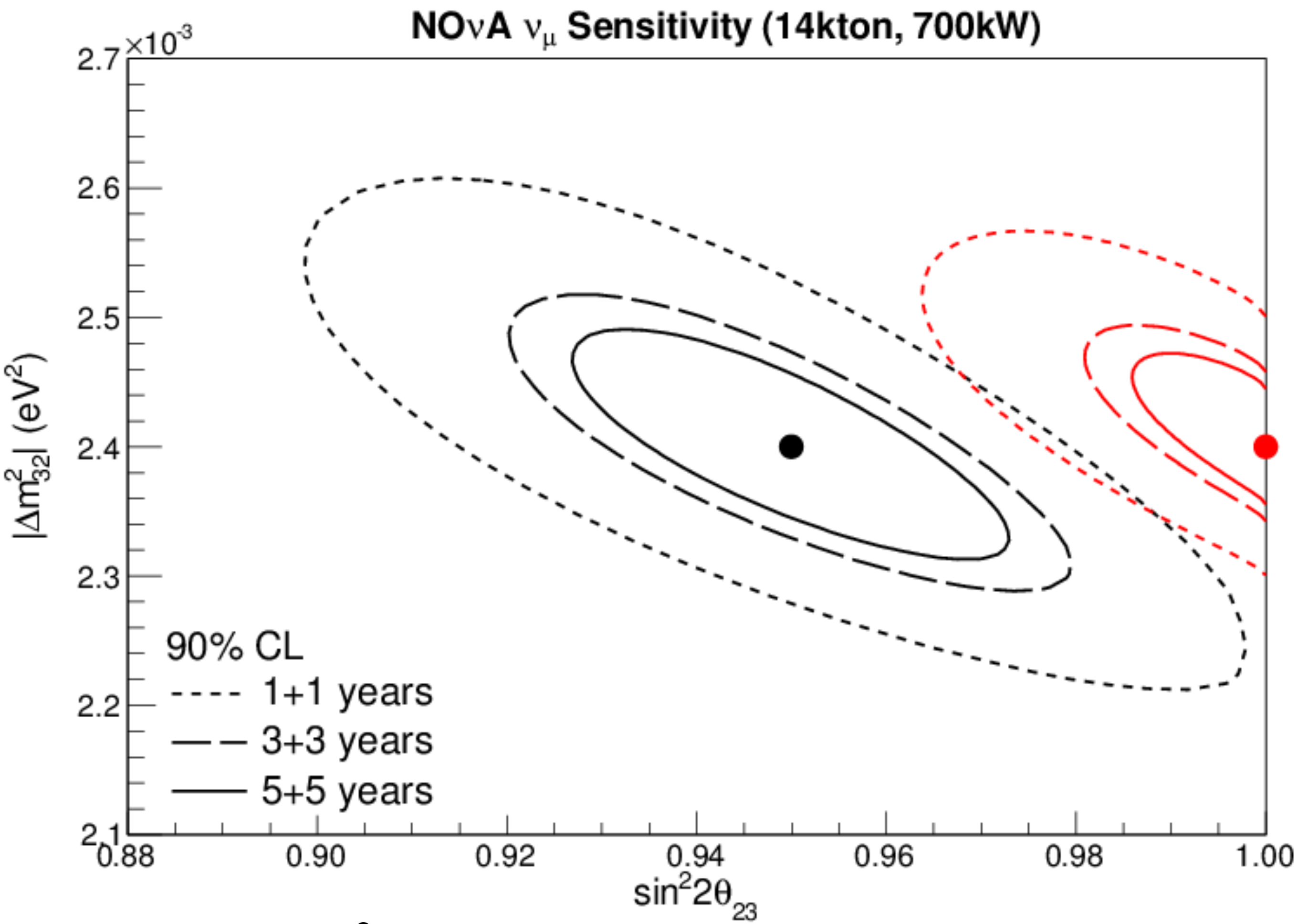
θ_{23} Octant Sensitivity

- Given the bi-probability plots, we can calculate how sensitive we will be to the θ_{23} octant:
  - $\theta_{23} > 45°$ (upper octant)
  - $\theta_{23} < 45°$ (lower octant)



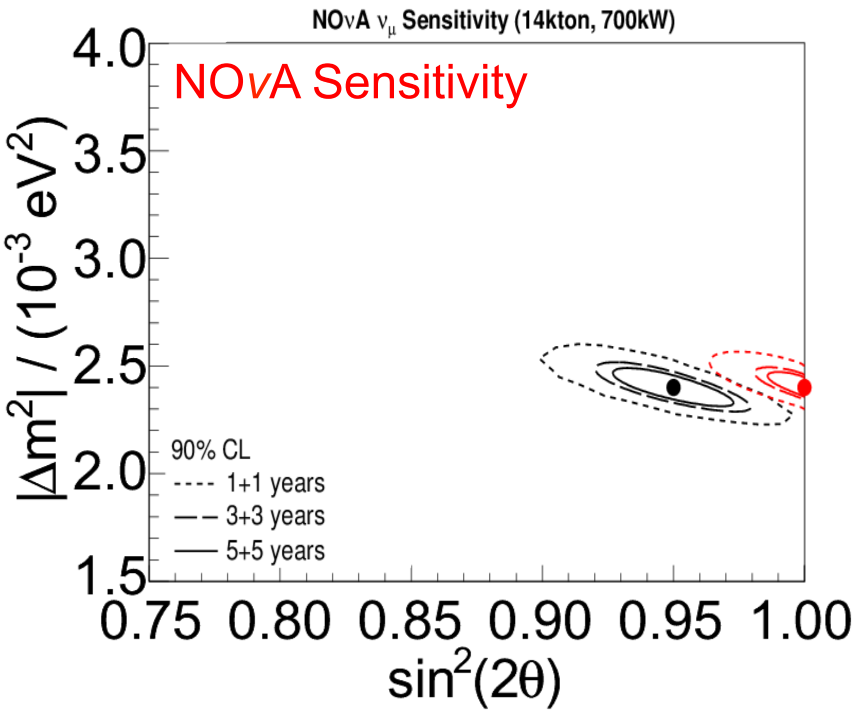


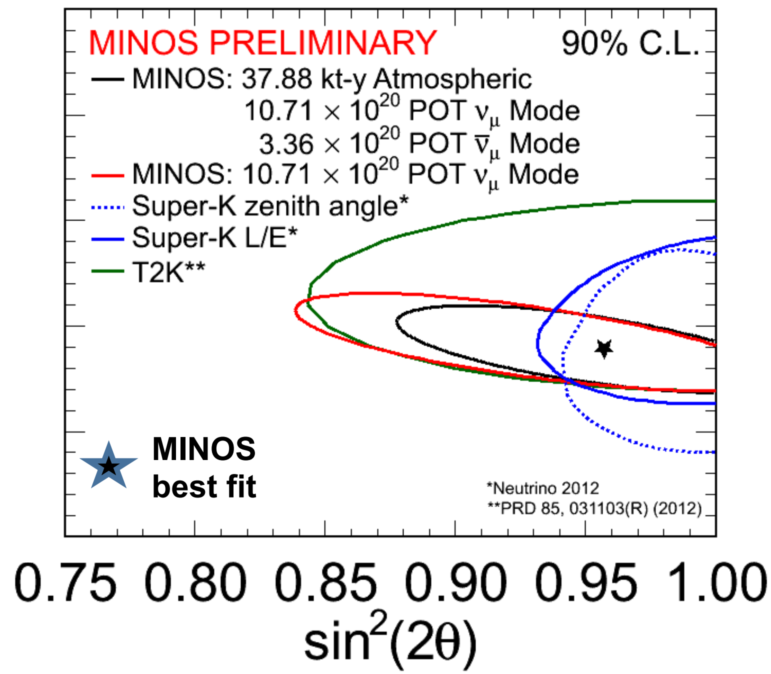
Precision Measurements



- Measure θ_{23}, Δm^2_{32} to the few percent level
- using ν_μ disappearance: $P(\nu_\mu \rightarrow \nu_\mu)$

Precision Measurements





- Measure θ_{23}, Δm^2_{32} to the few percent level
- using ν_μ disappearance: $P(\nu_\mu \rightarrow \nu_\mu)$