Gavin S. Davies

Iowa State University

for the NOvA Collaboration

nuTURN Workshop

Laboratori Nazionali del Gran Sasso, Italy

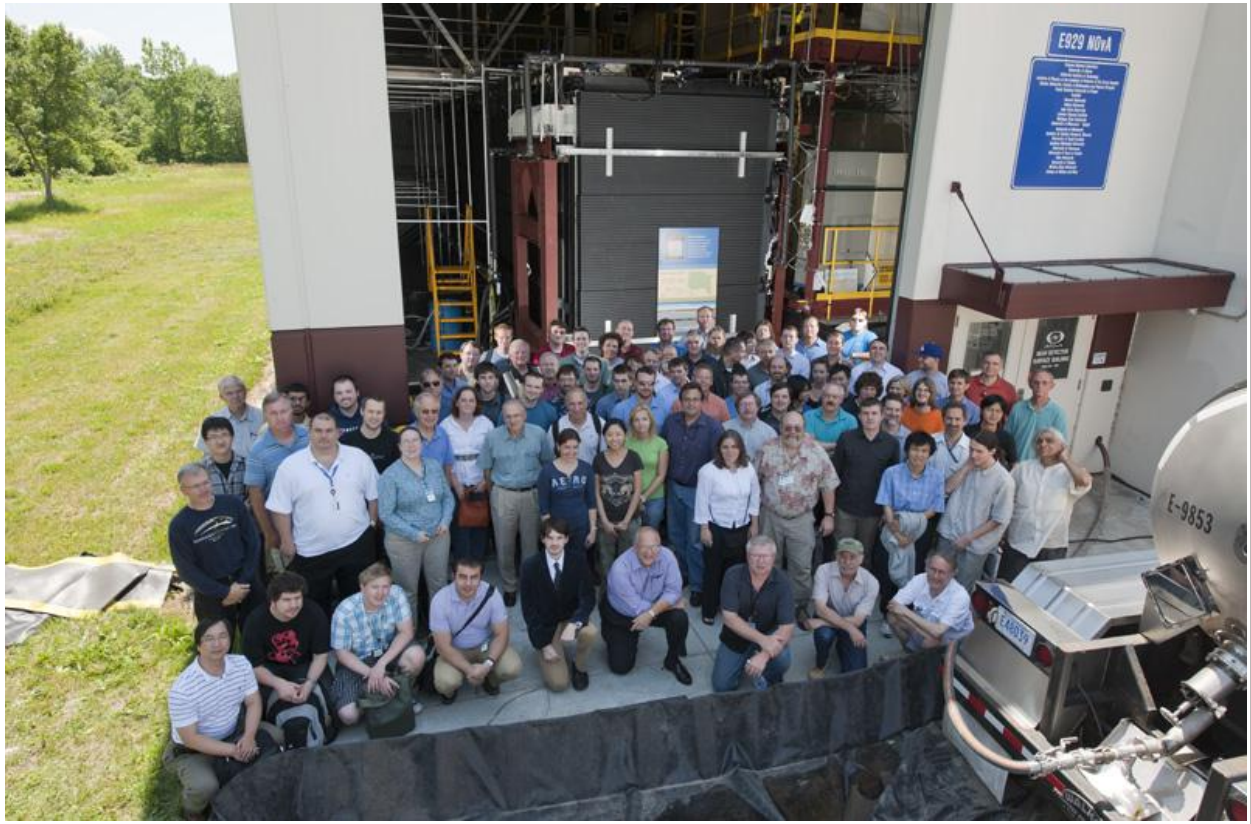
May 8th – 10th 2012

NOvA in light of non-zero θ_{13}

The NOvA Collaboration

NuMI* Off-axis ν_e Appearance

Argonne National Laboratory
University of Athens
California Institute of Technology
Institute of Physics of the Academy of Sciences of the Czech Republic
Charles University in Prague
Fermi National Accelerator Laboratory
Harvard University
India Universities Consortium
Indiana University
Iowa State University
Lebedev Physical Institute
Michigan State University
University of Minnesota, Crookston
University of Minnesota, Duluth
University of Minnesota, Twin Cities
The Institute of Nuclear Research, Moscow
University of South Carolina, Columbia
Southern Methodist University
Stanford University
University of Tennessee, Knoxville
University of Texas, Austin
Tufts University
University of Virginia, Charlottesville
Wichita State University
The College of William and Mary



150+ scientists and engineers from 25 institutions, 5 countries

* Neutrinos at the Main Injector

Outline

- The NOvA Experiment
  - Overview of physics goals
  - Experimental setup
- The NOvA Detectors
  - Detector Design and Technology
  - NOvA prototype detector
- NOvA Status
  - NOvA prototype data
  - Construction schedule
- NOvA Physics
  - The new θ_{13} landscape
  - Electron-neutrino appearance
  - Sensitivity to Mass Ordering
  - Opportunities in CPV phase space

Far Detector Building Entrance

The NOvA Experiment

Physics Goals:

- Measure the oscillation probabilities of

  $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

  - Measure the mixing angle θ_{13}
  - Determine neutrino mass hierarchy
  - Study the phase parameter for CP Violation δ_{CP}
- Precision measurements of Δm^2_{32}, θ_{23}
- As well as:
  - ν cross sections
  - Sterile neutrinos
  - Supernova signals

The NOvA Experiment

Experimental Setup

- 810 km baseline from Fermilab to Ash River, MN
  - ND: 1 km from NuMI target
    - ✓ 105 m underground
    - ✓ 220 ton
  - FD: On the surface
    - ✓ 3 m overburden of excavated rock
    - ✓ 14+ kton
- Detectors off-axis (14 mrad)
- NuMI beam upgraded to 700 kW
  - Narrow band beam peaked at 2 GeV
- Long underground path to Far Detector → matter effects ~ 30%

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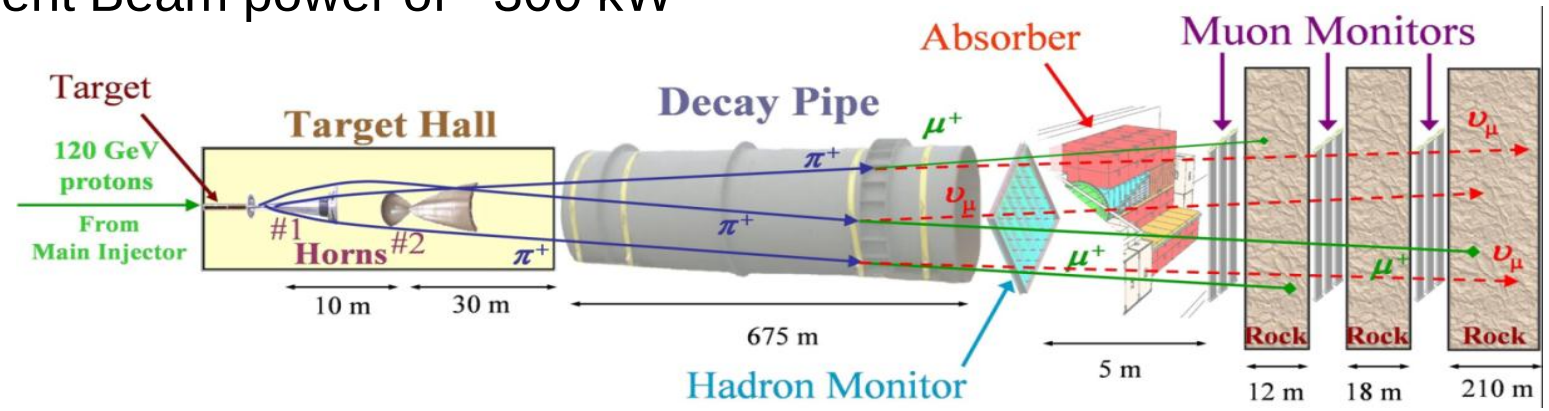
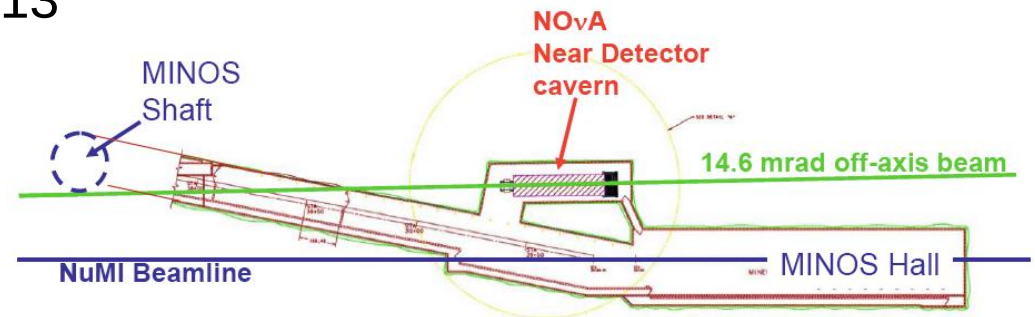
NuMI Beam at Fermilab

- Pions and kaons produced in the target are focused by the magnetic horns into the decay pipe where they decay into muons and neutrinos
  - Horn current selects neutrinos or anti-neutrino enhanced beam
- Current Beam power of ~300 kW



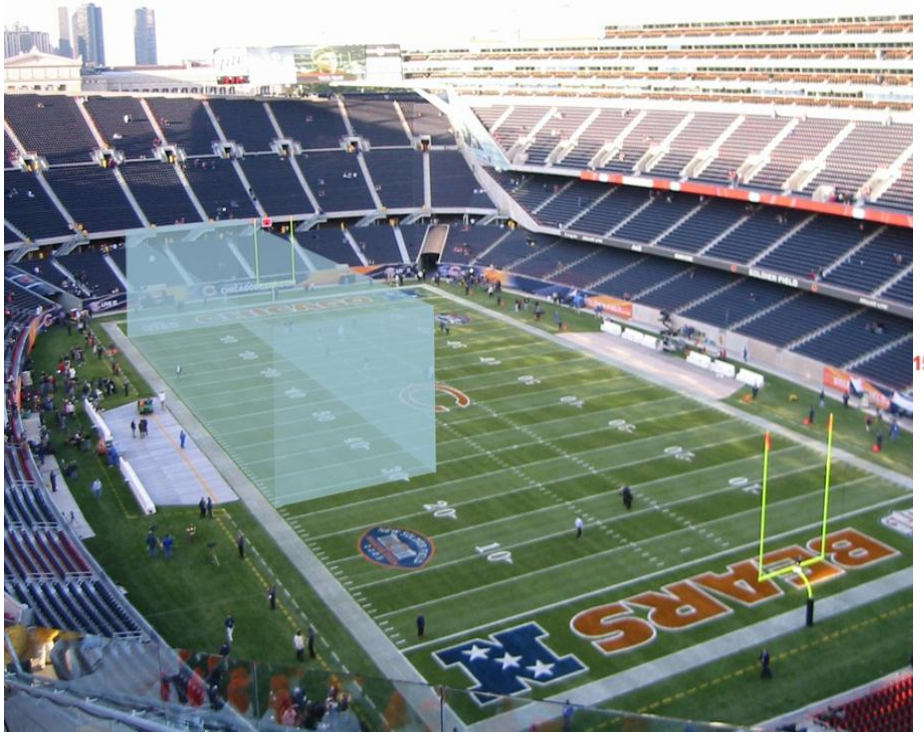
- Beam supplied to MINOS, MINERvA and ArgoNeut since 2005

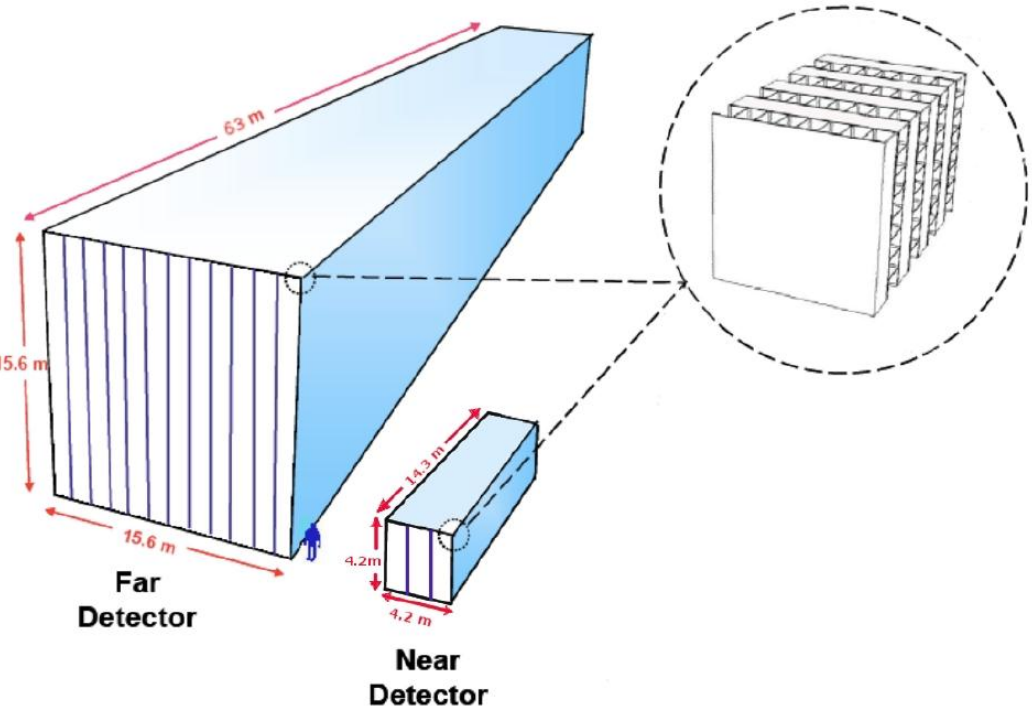
- Beam shutdown May 1st – April 2013
  - Beam upgrades
  - ND cavern excavation



- NOvA Upgrades:
  - Increase beam power to 700 kW
  - Reduce cycle time from 2.2 s to 1.33 s
  - Upgrade target and horns

The NOvA Detectors



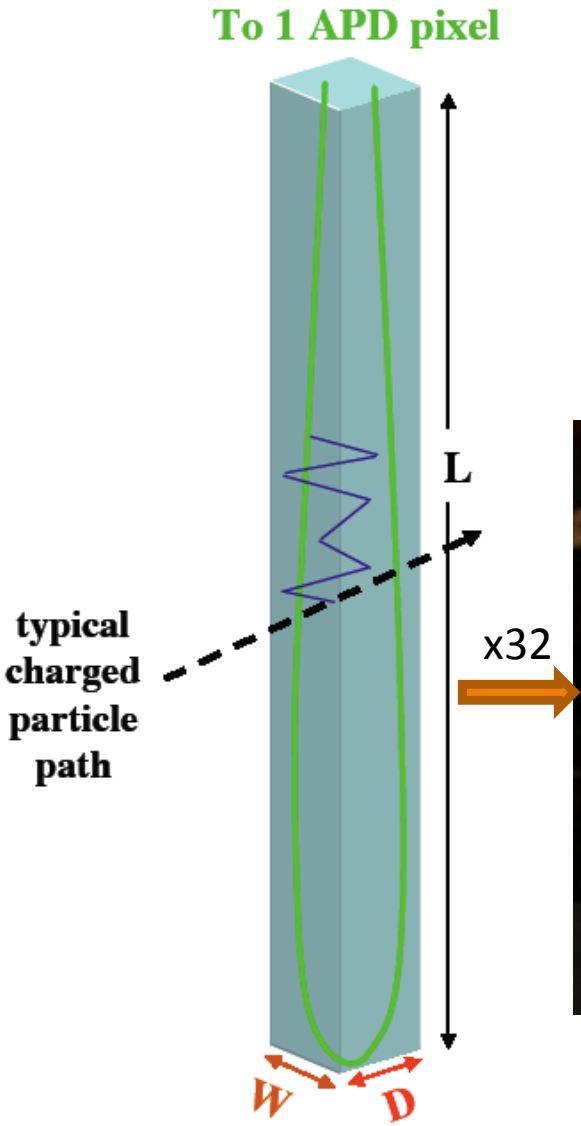


- Massive 14+ kton Far Detector
- Functionally equivalent Near Detector
  - Mitigate systematic uncertainties

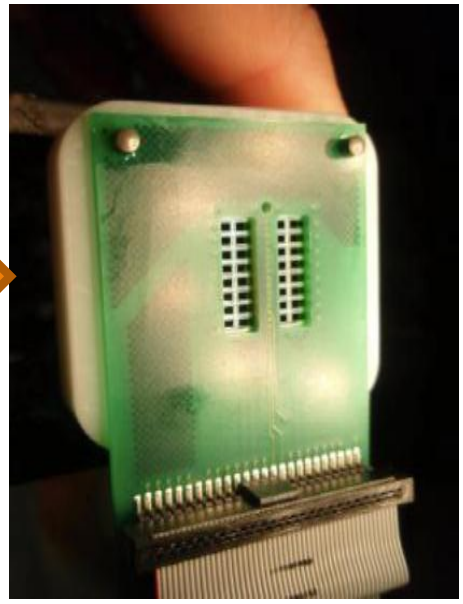
- Highly segmented (alternating X/Y)
- 65% Active Volume
- Low Z materials (PVC and Oil)
  - Radiation length ~ 40 cm
  - Molière Radius ~ 11 cm

- Optimised to distinguish ν_e CC and ν NC events

NOvA Detector Technology



- Cell readout via looped WLS fibre to APD sensor
  - Each FD cell measures 3.9 x 6.0 cm x 15.m
- Each APD read out with NOvA custom electronics
  - 11.5 k APDs on Far Detector
- Free running, continuous readout



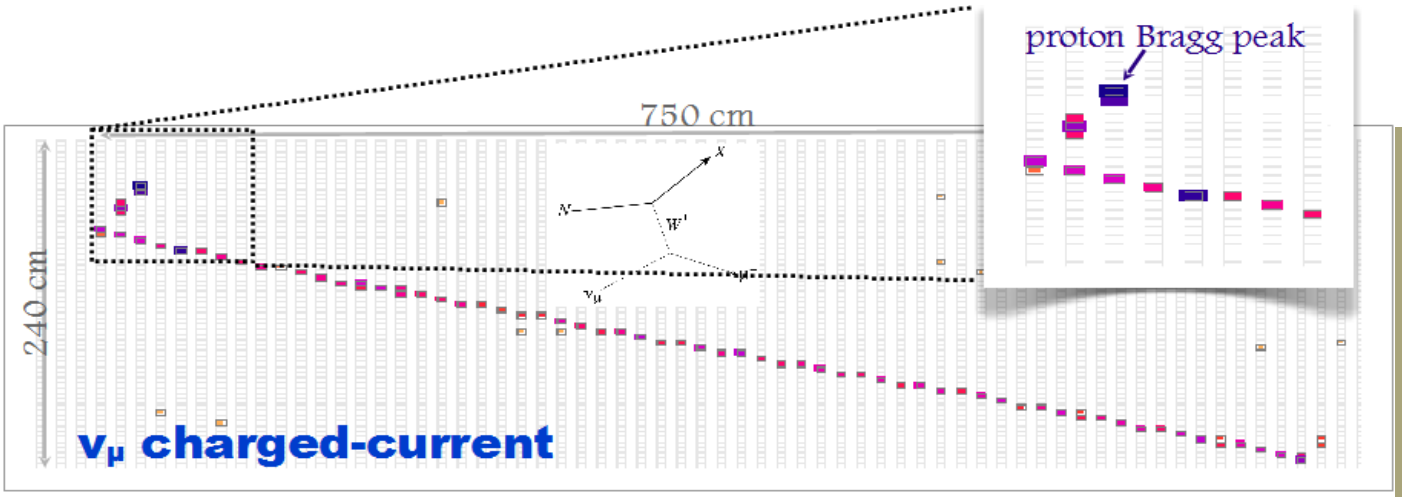
32-pixel APD
(Avalanche Photo-diode)

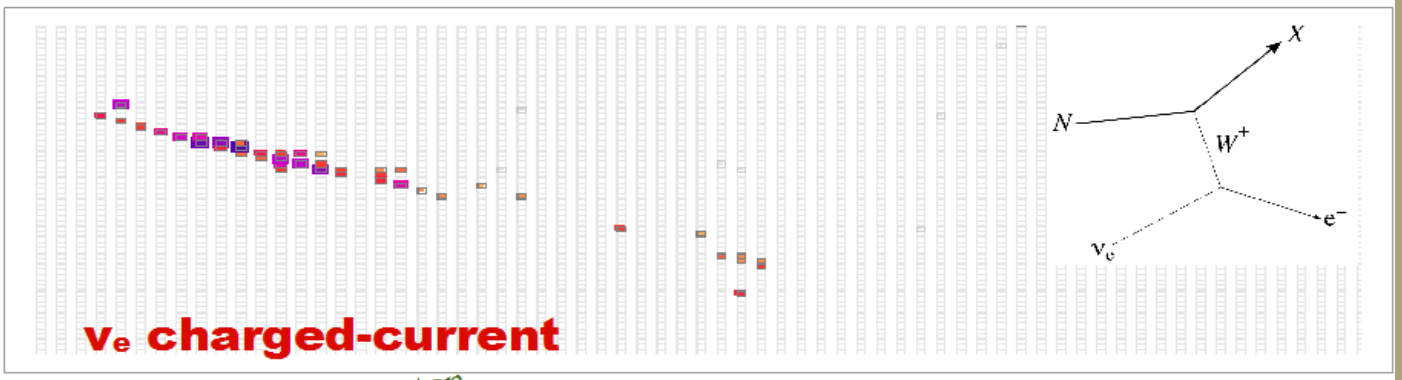
Installing APDs on the prototype

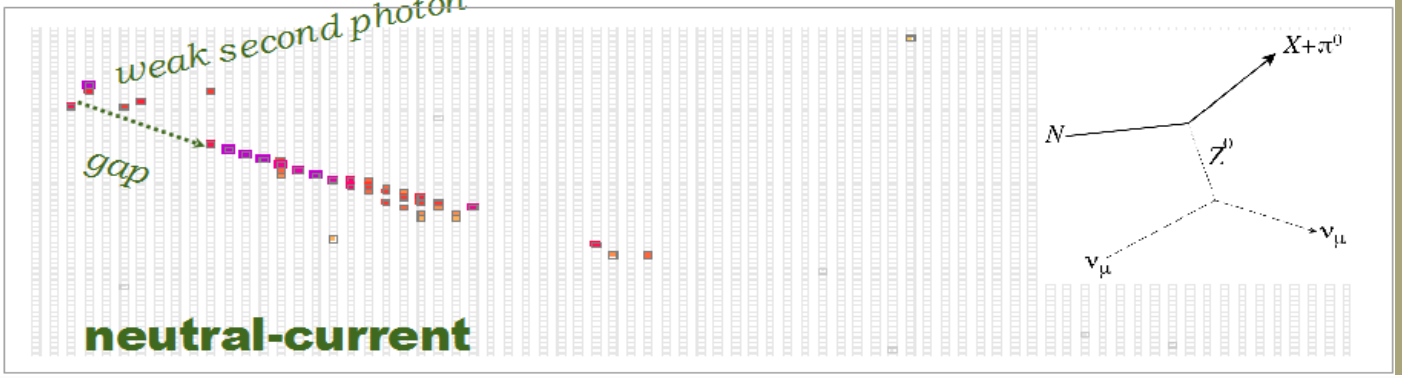
Near Detector On Surface (NDOS)

- Designed to prototype all detector systems prior to any installation at Ash River as a full end-to-end test of systems integration and installation
- Gained experience in qualifying oil and testing our oil filling procedures in advance
- Tested APDs in realistic operating conditions
- NDOS has 64 cells x 100 planes (X) + 96 cells x 99 planes (Y)
  - Far Detector has 384 cells x 960 planes
- Installation completed May 9th 2011
- Commissioning and neutrino data collection 11/2010 – April 30th 2012

Neutrino Interaction* Signatures







V_μ Charged-current

Long well-defined muon track, proton is a short track with large energy deposition at the track end.

V_e Charged –current

Single shower with characteristic e-m shower development.

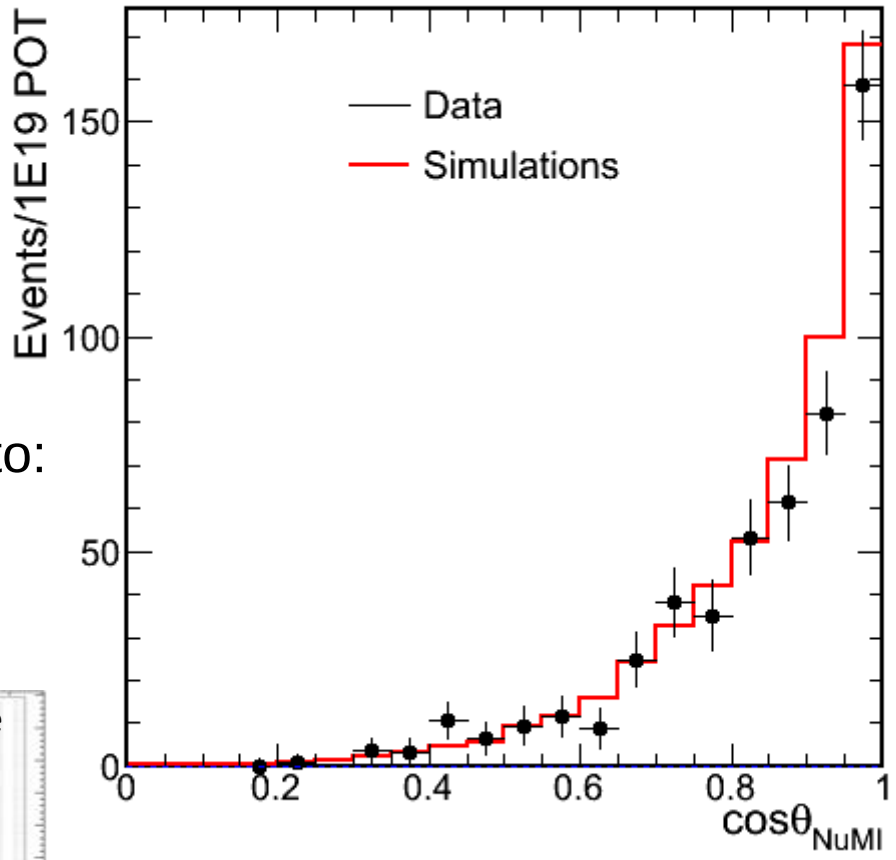
NC with π^0 in final state

Possible gaps near event vertex, multiple displaced e-m showers.

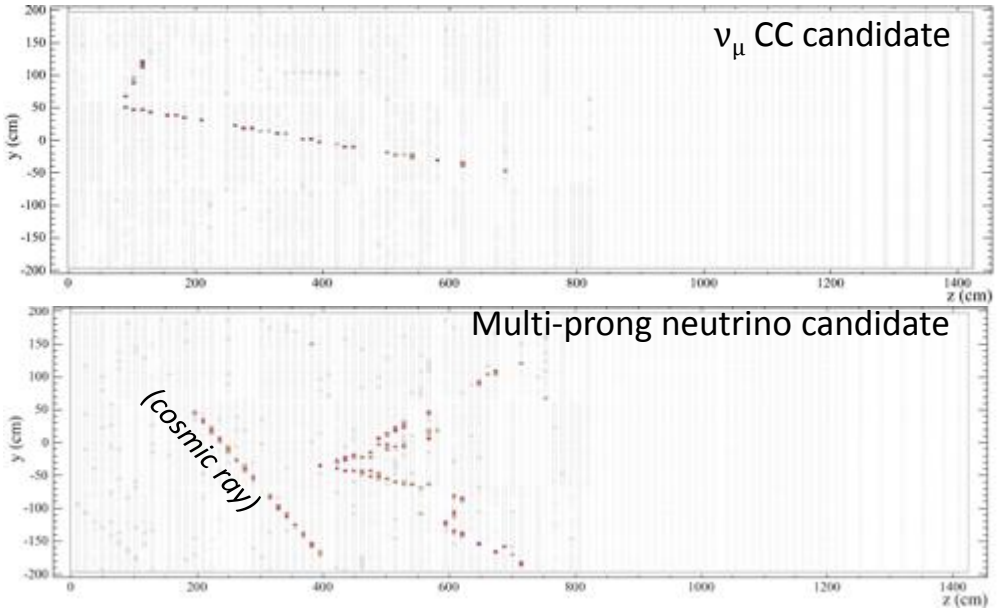
*simulated interactions

NDOS Data

- 5000 neutrino events from NuMI
- Neutrino candidate data matches well to Monte Carlo simulations

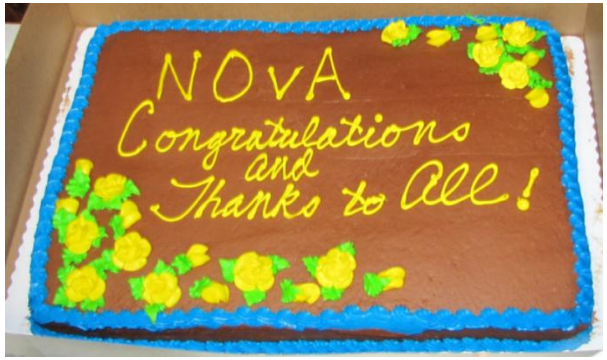


- NDOS data are being used in order to:
  - Study response of detector to neutrinos
  - Investigate the cosmic ray background
  - Develop calibration techniques



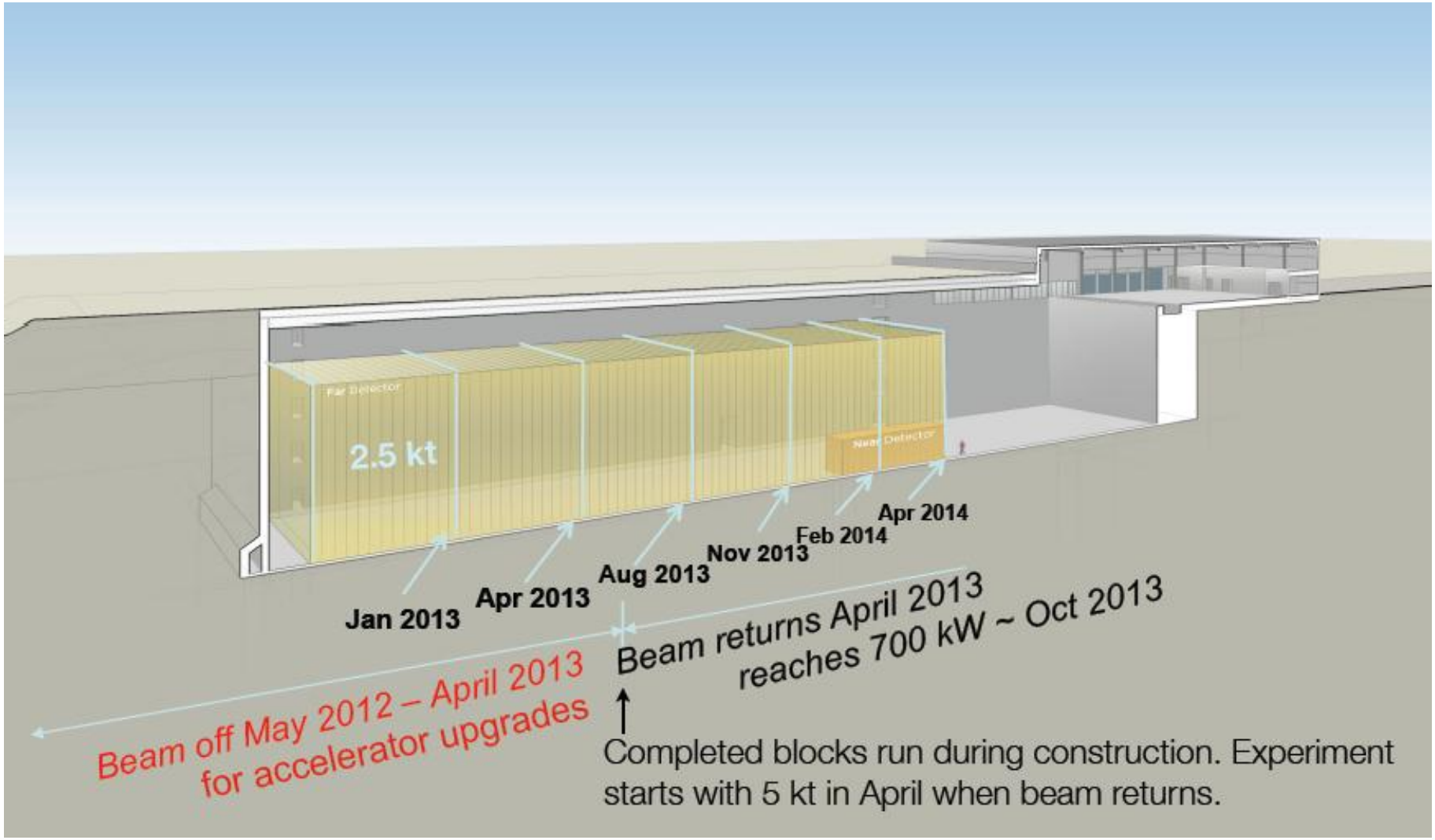
Events from the NuMI beam seen at 110 mrad

- NDOS neutrino run ended April 30th

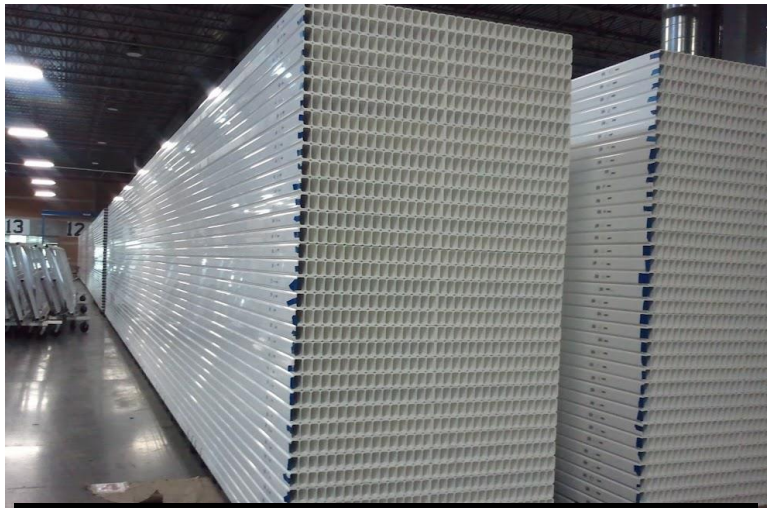


Construction Schedule

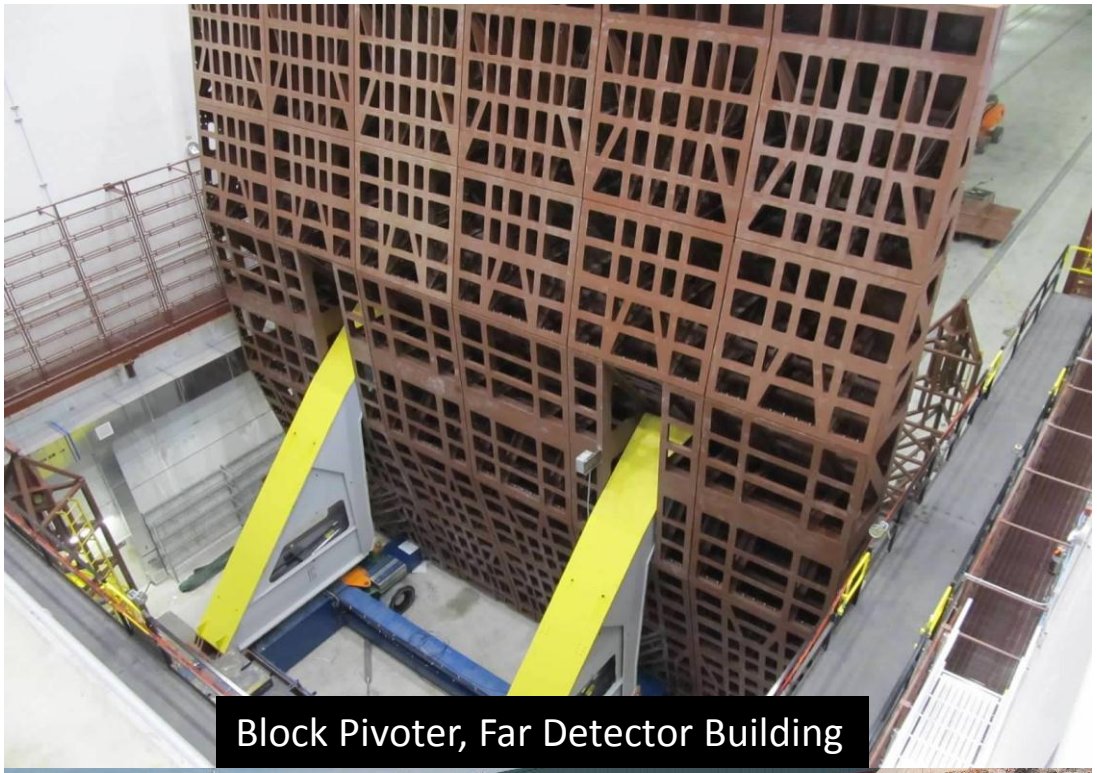
- NOvA will turn on April 2013 with 5 kton of Far detector in place and beam operating at ~ 400 kW
- We will add detector mass at a rate of ~ 1 kton/month
- Beam intensity will ramp up to 700 kW in approximately 6 months



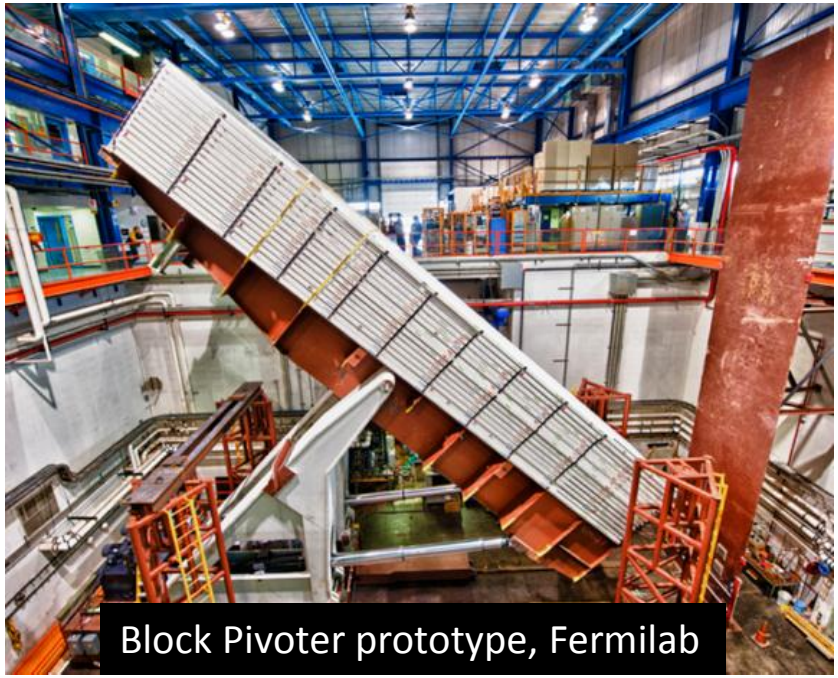
Far Detector: Full steam ahead



Module factory, University of Minnesota



Block Pivoter, Far Detector Building

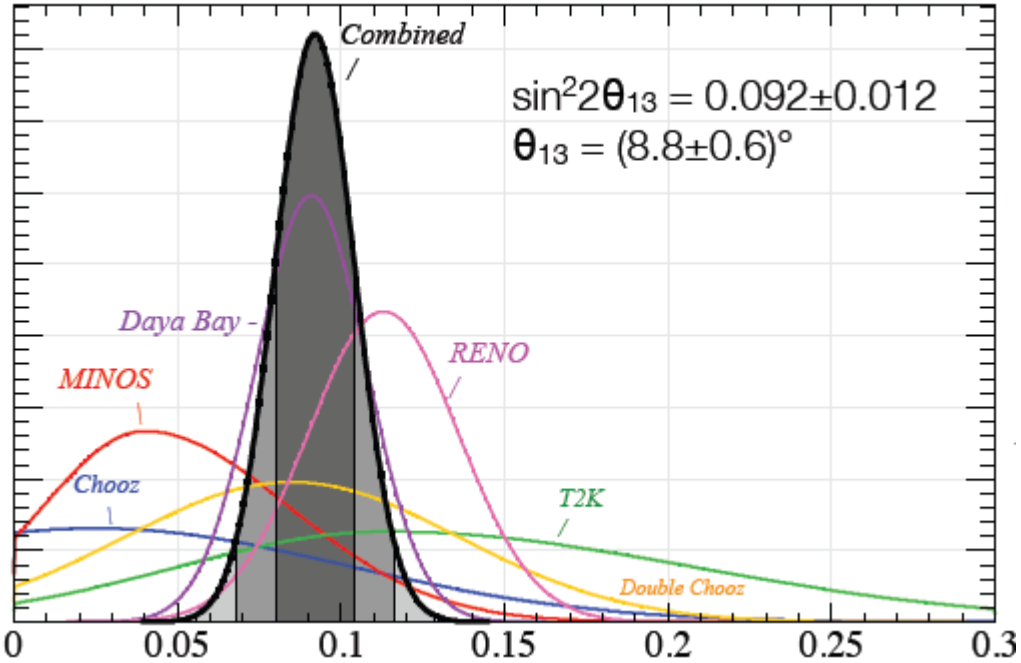


Block Pivoter prototype, Fermilab

Far Detector Building dedication ceremony

The new θ_{13} landscape

- Value of $\sin^2(2\theta_{13})$ has been measured and will be improved very soon
- NOvA will take the next steps to finding the neutrino mass hierarchy and to begin the study of CPV in the lepton sector
- Combining data from NOvA at long baseline with T2K and with reactors will enable tests of the U_{PMNS} framework



- Daya Bay 0.092 ± 0.017
  - ✓ arXiv:1203.1669v2 [hep-ex]
- RENO 0.113 ± 0.023 (revised)
  - ✓ arXiv:1204.0626v2 [hep-ex]
- Reactor Average
  - ✓ 0.099 ± 0.014
- Combined Average
  - ✓ 0.092 ± 0.012

M. Messier (Indiana)

Electron-neutrino Appearance in NOvA

- NOvA measures the probability of ν_e appearance in a ν_μ beam:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$\overset{(+)}{(-)}\, 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$
$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \qquad \Delta = \Delta m^2_{31} L/(4E) \qquad A = \overset{(-)}{(+)} G_f n_e L/(\sqrt{2}\Delta)$$

- $\sin^2(2\theta_{13})$ can be accessed in long baseline searching for ν_e events
- $\sin^2(2\theta_{13})$ has been measured which allows us to make measurements of δ_{CP}
- Note that we can gain information about the θ_{23} octant since $\sin^2(\theta_{23})$ is a coefficient on the leading-order term above
- Probability is enhanced or suppressed due to matter effects which depend on the mass hierarchy, i.e the sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ as well as neutrino vs. anti-neutrino running

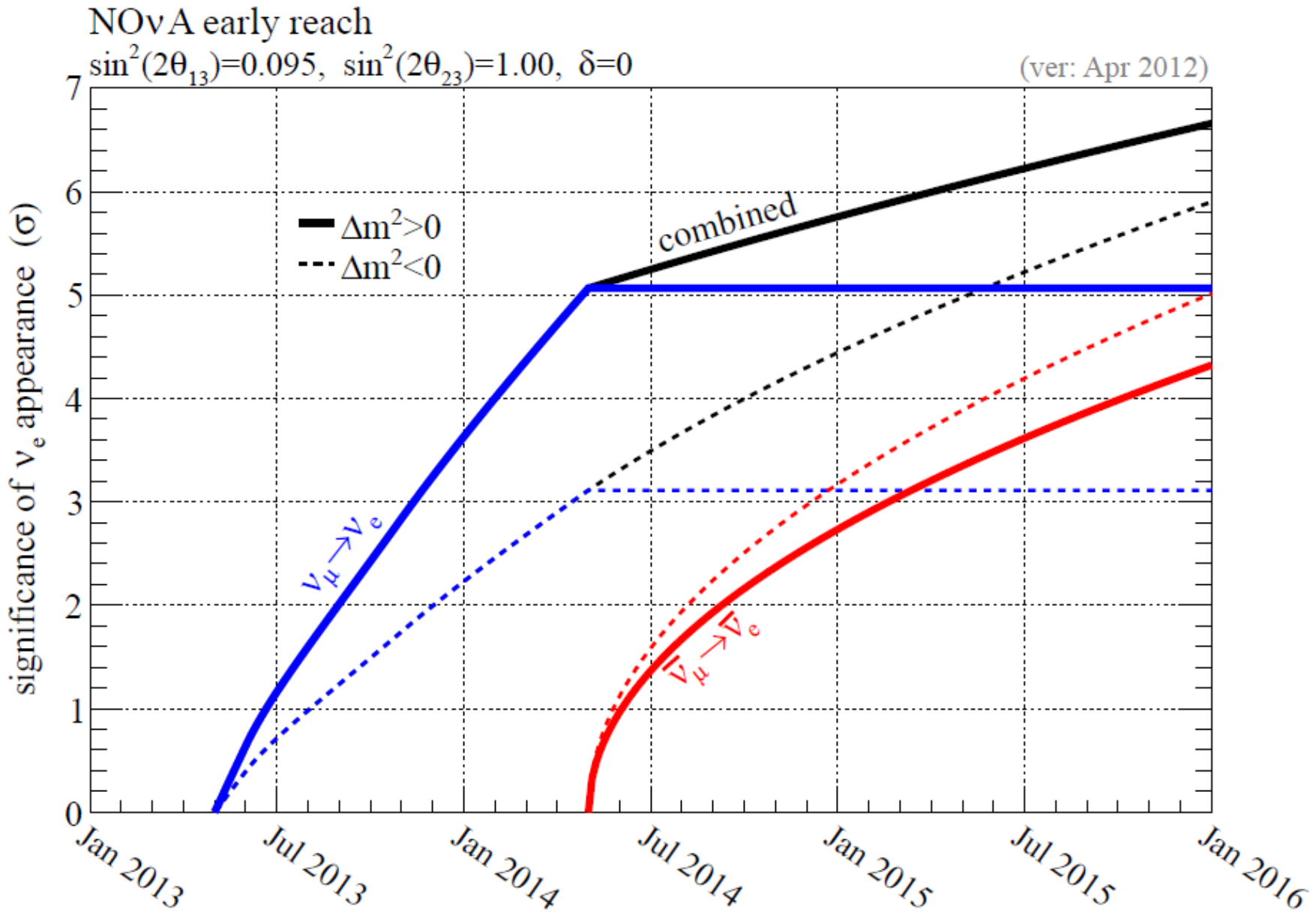
Electron-neutrino Appearance in NOvA

- NOvA measures ν_e appearance in a ν_μ beam
- Assume $\sin^2(2\theta_{13}) = 0.095$
- The following sensitivities use our earlier analysis approaches but include the latest knowledge of θ_{13}
  - Optimised for average expected signal (~4% oscillation probability) with ~ 10% uncertainty on the background
  - 41% (ν) and 48% ($\bar{\nu}$) signal efficiency

	signal	total bkgd	NC bkgd	ν_μ CC bkgd	ν_e CC bkgd
ν (3 yrs)	72.6	34.5	20.8	5.2	8.4
$\bar{\nu}$ (3 yrs)	33.8	16.3	10.6	0.7	5.0

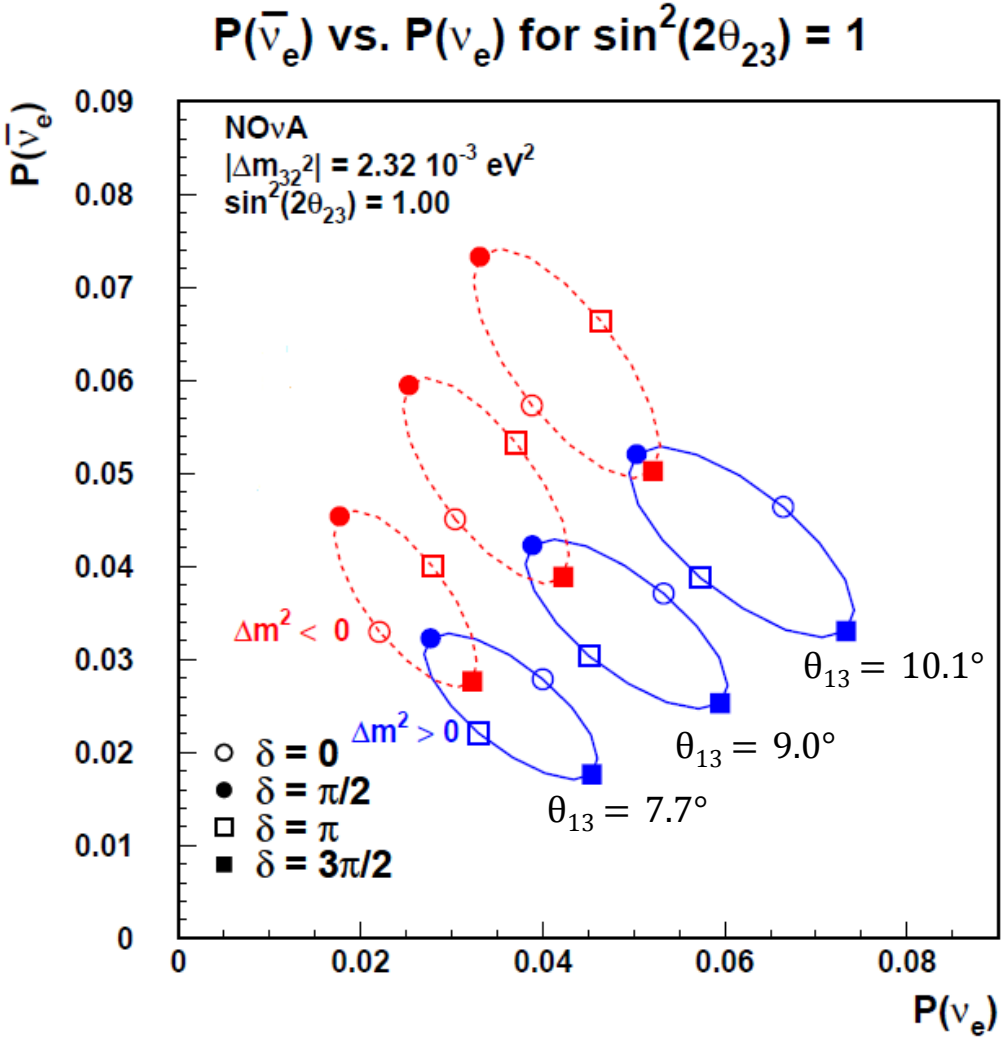
- Estimated numbers based on:
  - 15 kton, 18 x 10^{20} POT (3 years each neutrino-mode running)
  - No solar-atmospheric terms and no matter effects
- Measuring probability of $\nu_\mu \rightarrow \nu_e$ (as well as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) allows NOvA to disentangle the mass hierarchies and CP violation phase space

NOvA Early Reach



How well does NOvA do?

- Large θ_{13} is good news for NOvA
- It reduces the overlap between these bi-probability ellipses, reducing the likelihood of degeneracies



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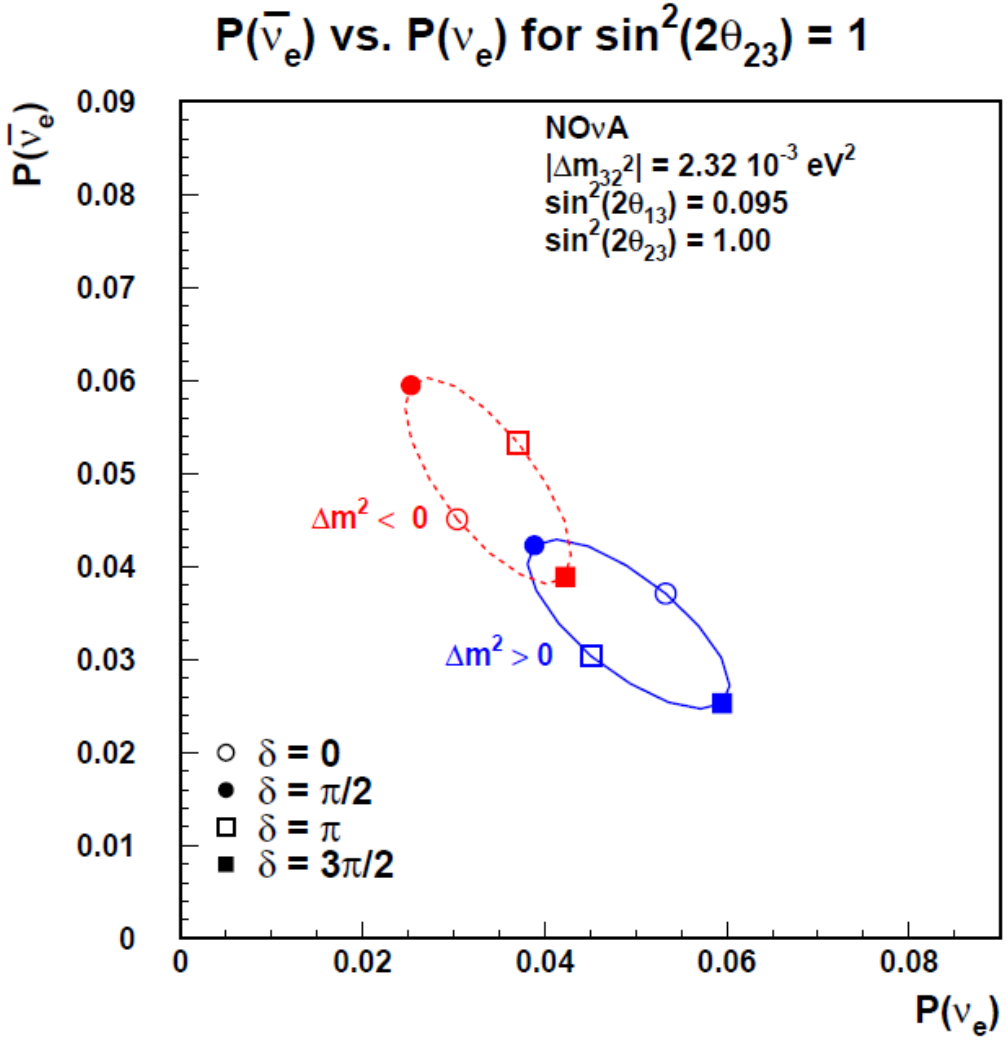

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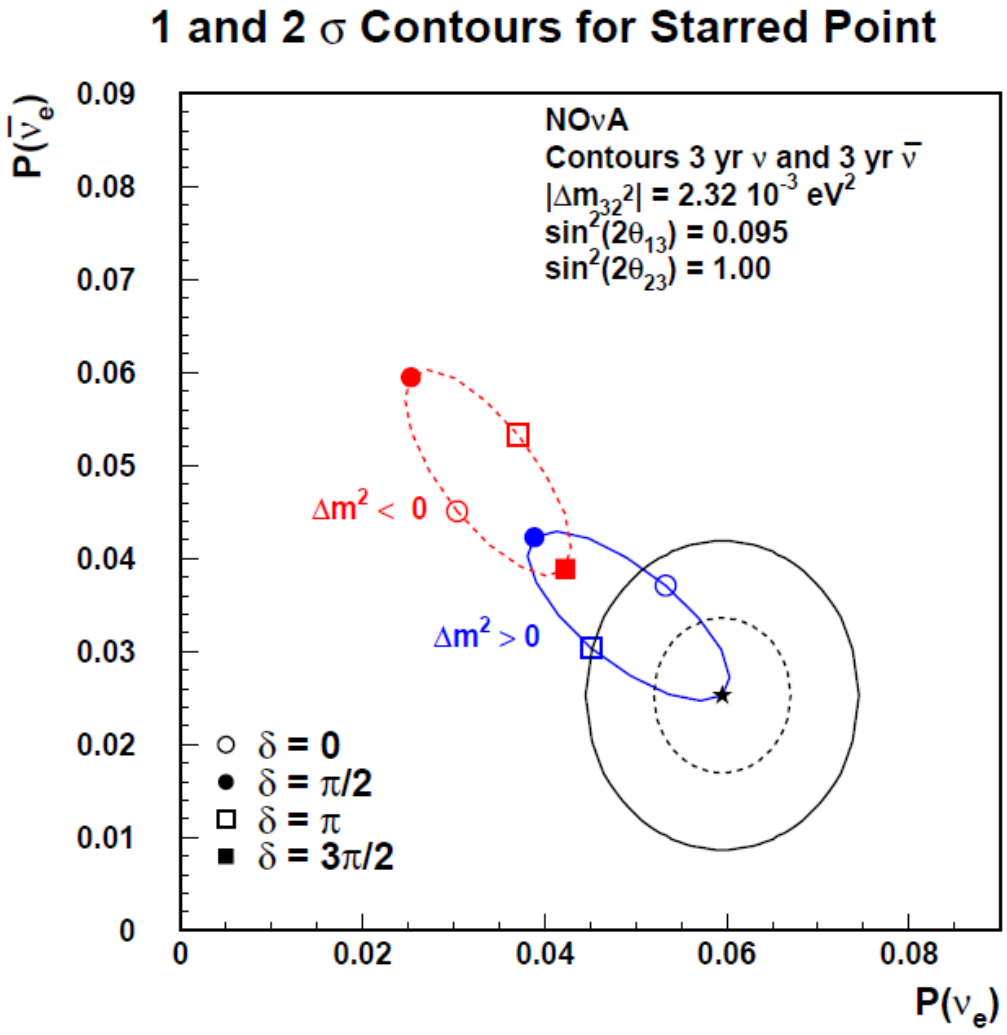
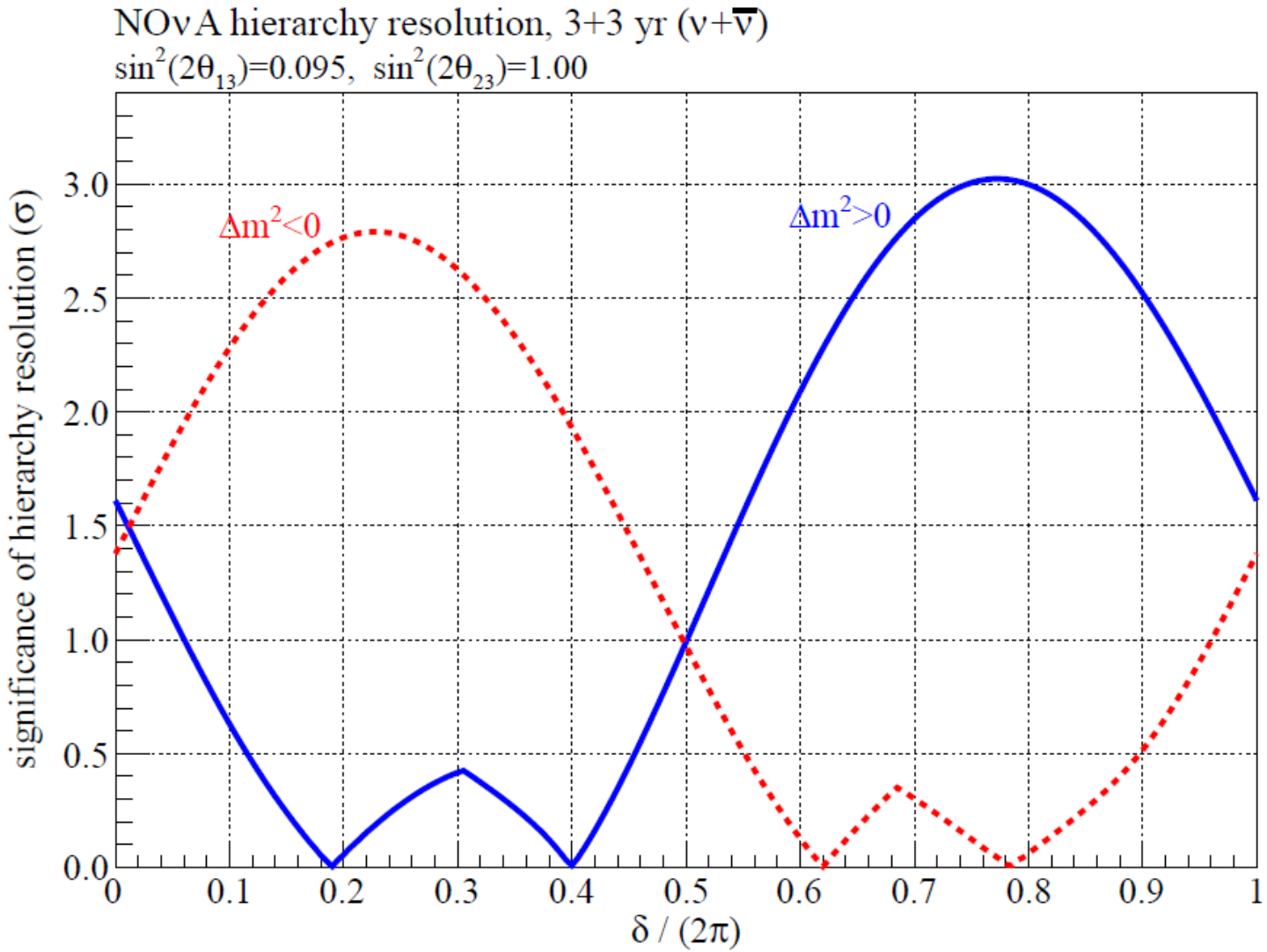


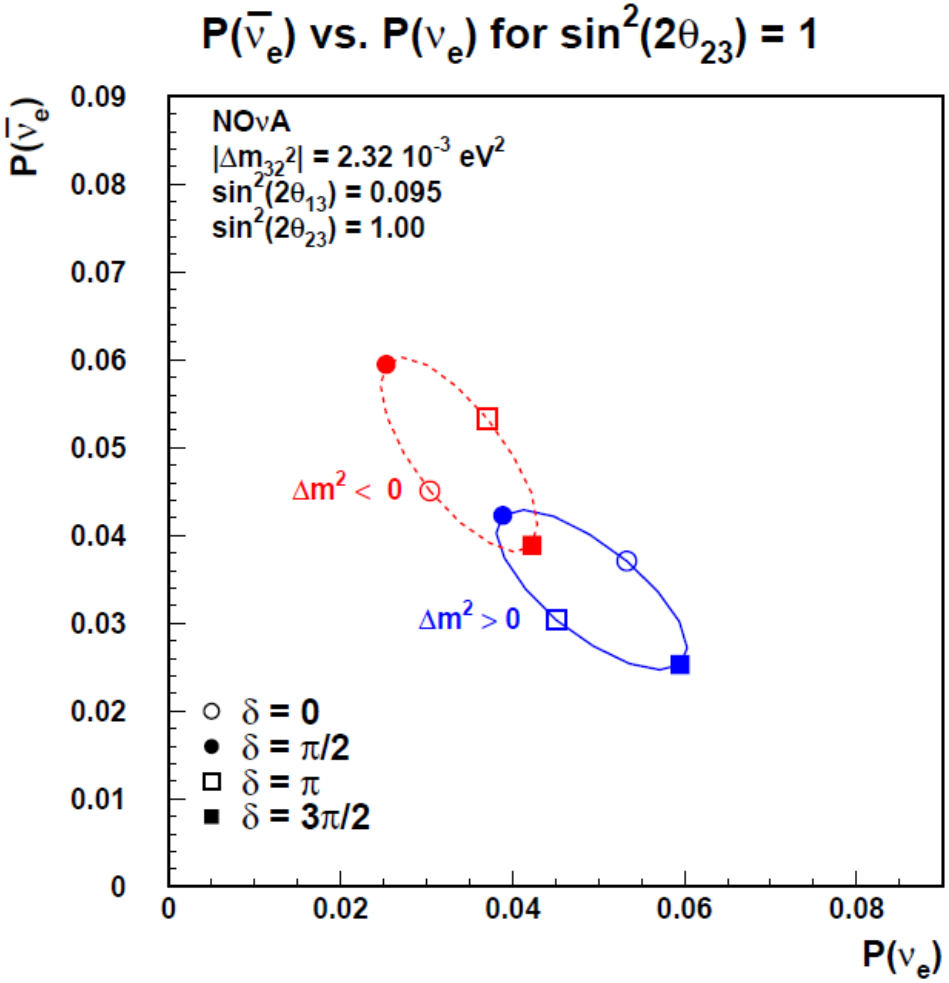
NOvA's Mass Ordering Resolution

- 3+3 years example counting experiment, 10% background systematic error
- Full energy fit actively being pursued



Non-maximal $\sin^2(2\theta_{23})$

- If $\sin^2(2\theta_{23})$ is not maximal there is an ambiguity as to whether θ_{23} is larger or smaller than $45°$



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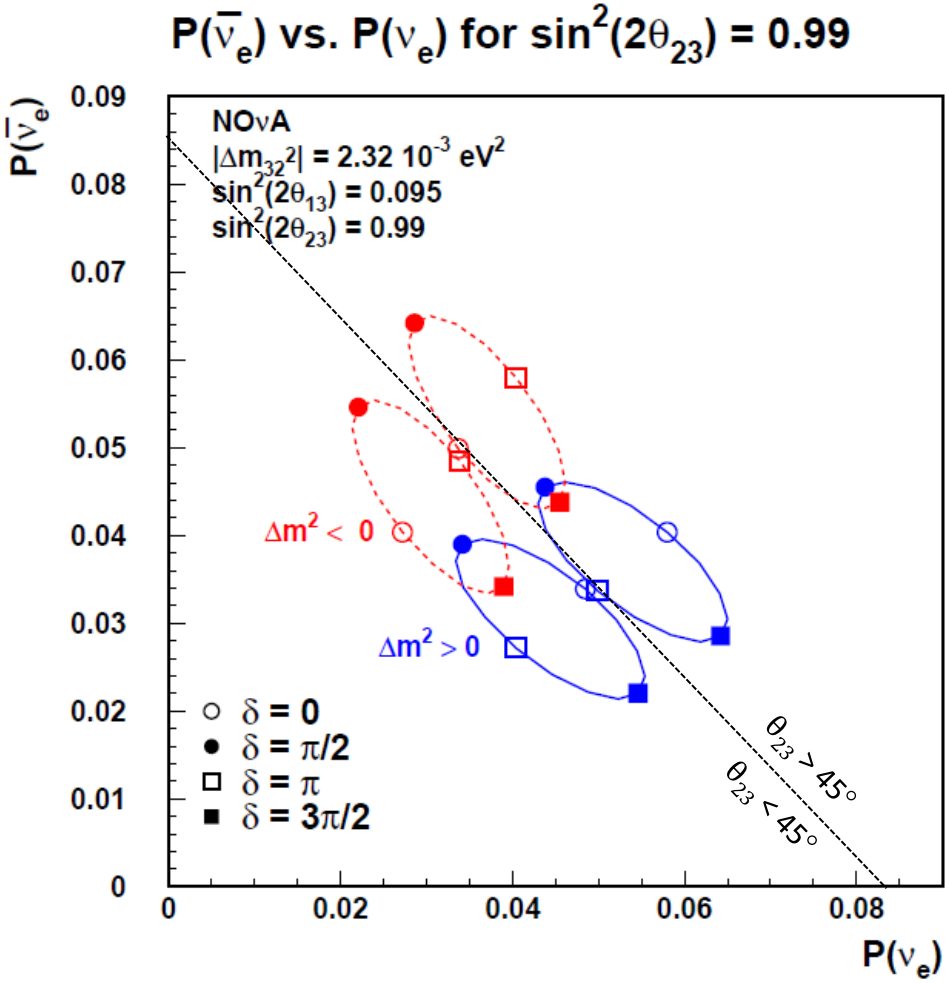

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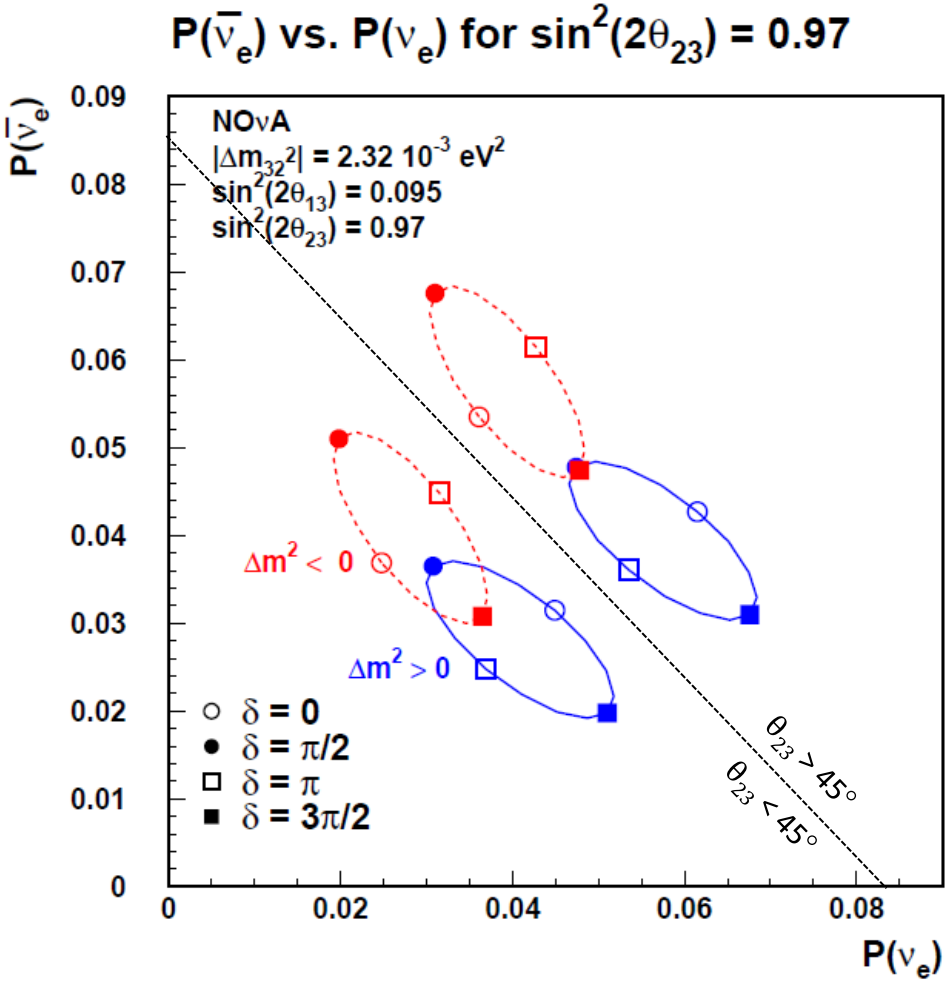
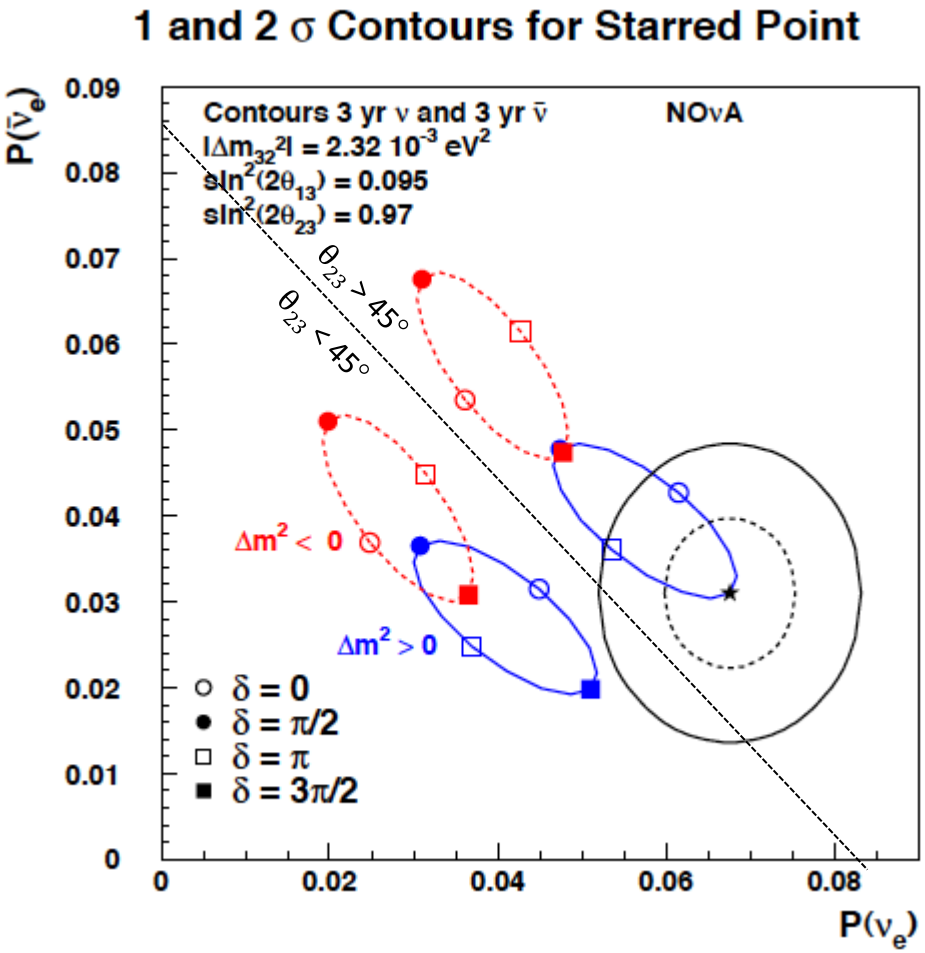
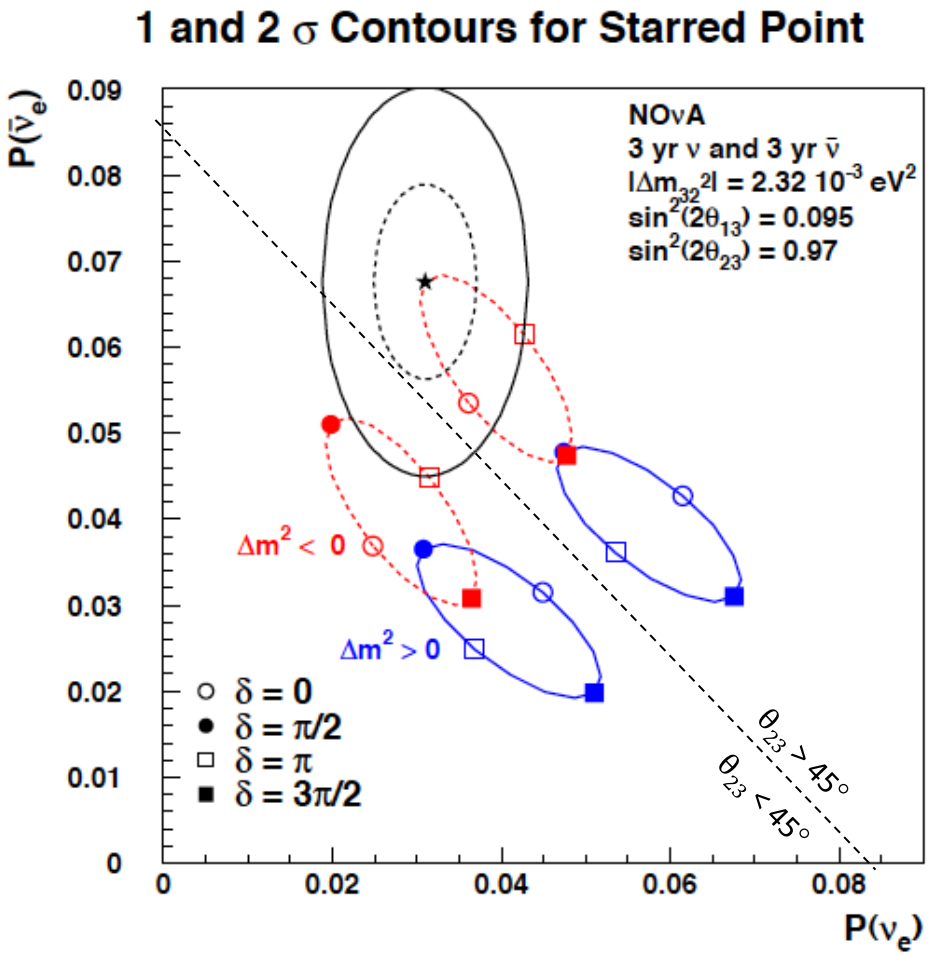


- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments

NOvA and Non-maximal $\sin^2(2\theta_{23})$

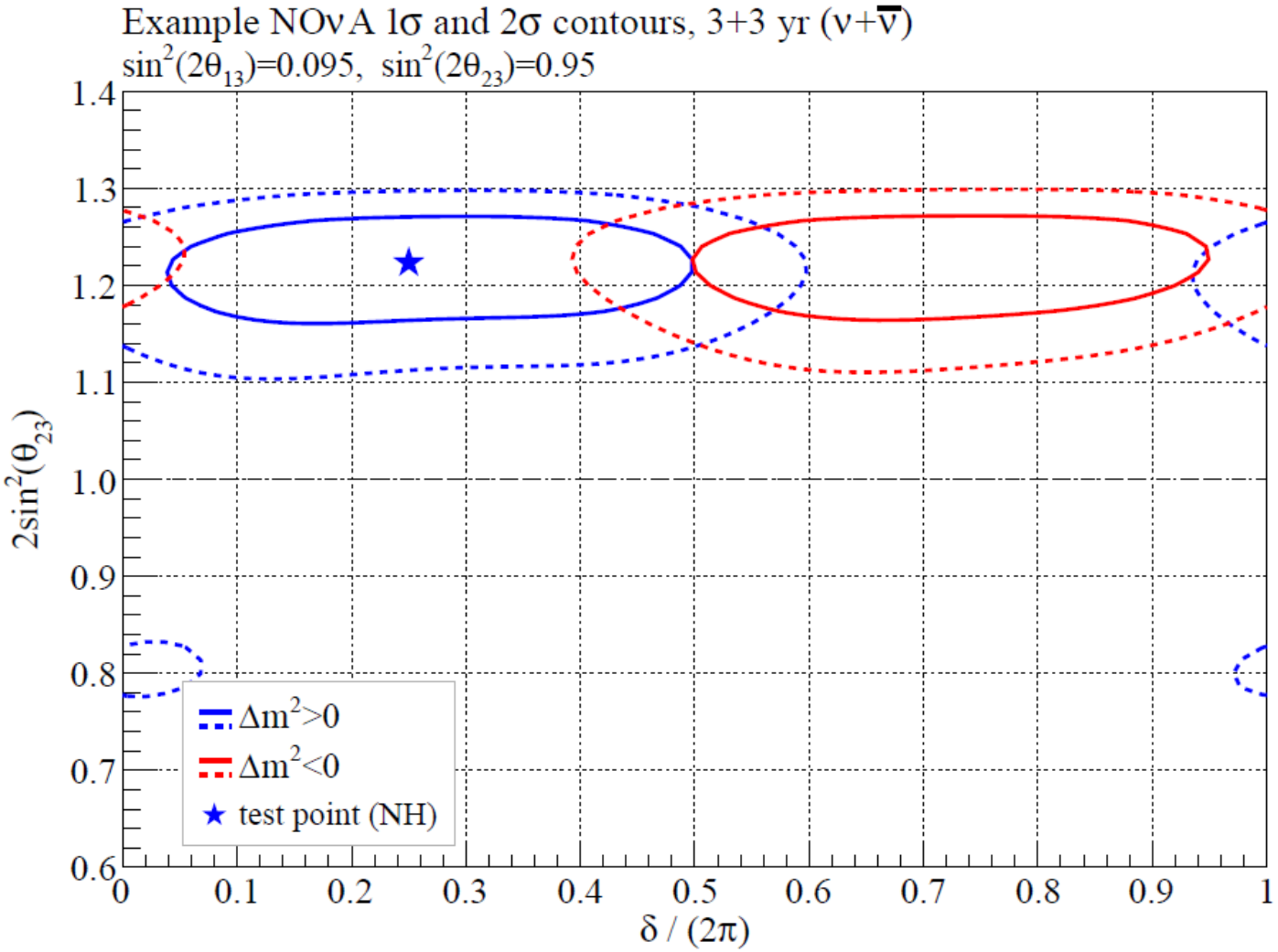
- 3 Years each neutrino and anti-neutrino
  - 41% (48%) signal efficiency for ν ($\bar{\nu}$)
  - $\theta_{23} > 45°$ starred point





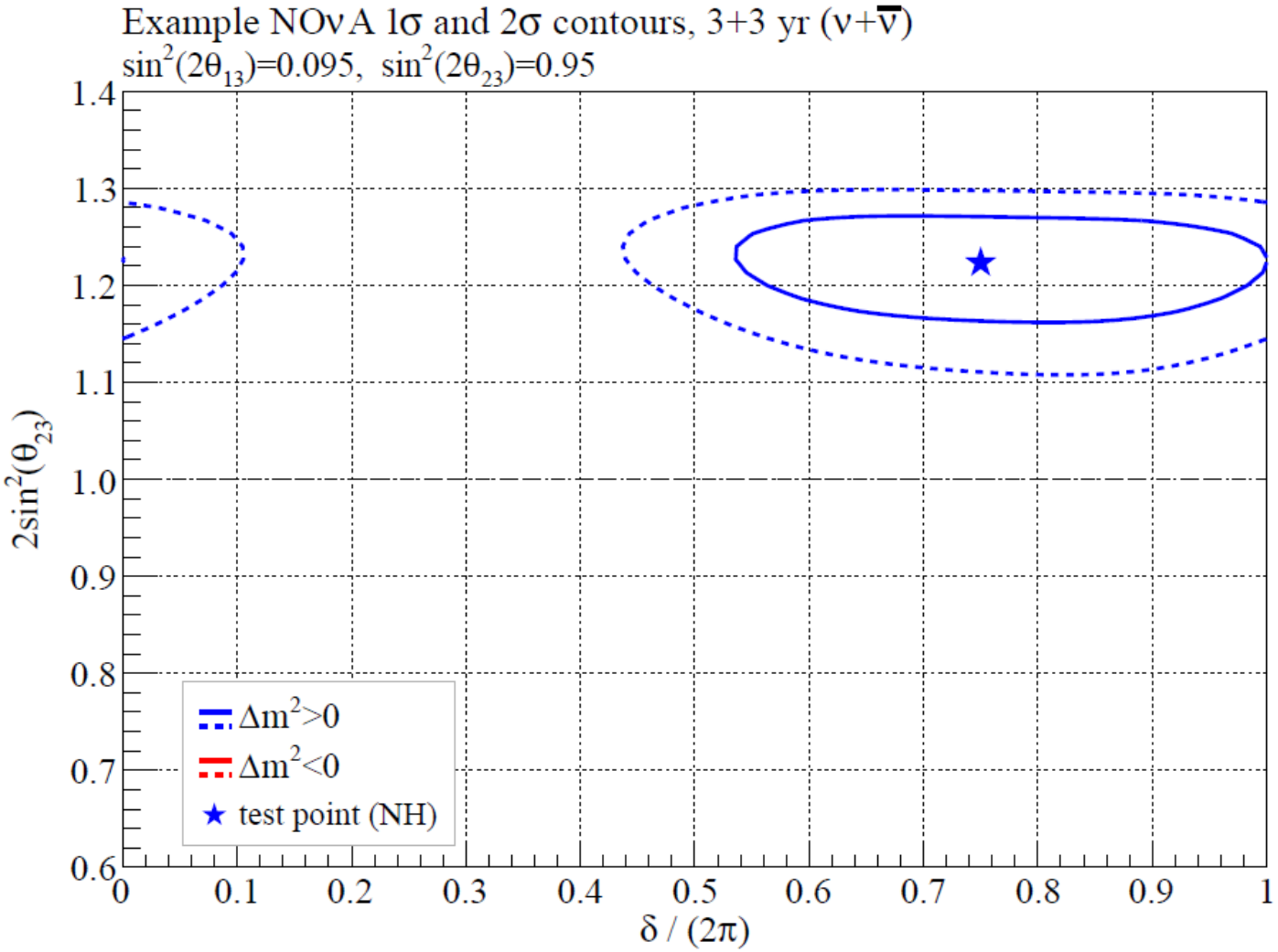
A Total View

- Non-maximal mixing, non-resolved hierarchy ($\delta = \pi/2$)
- Now $\sin^2(2\theta_{23}) = 0.95$, which is constrained by our ν_μ CC sample



A Total View

- Non-maximal mixing, resolved hierarchy ($\delta = 3\pi/2$)
- Now $\sin^2(2\theta_{23}) = 0.95$, which is constrained by our ν_μ CC sample



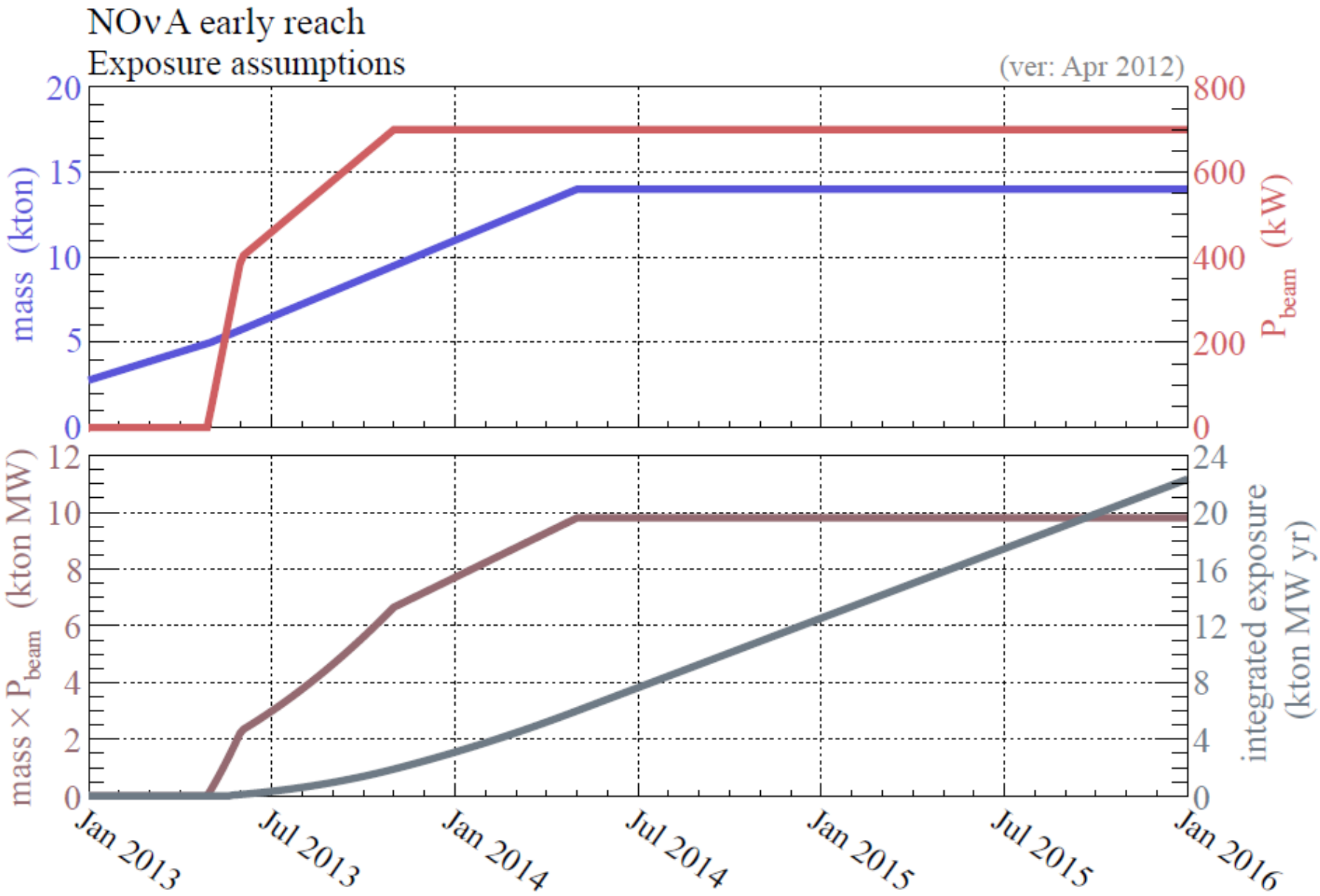
Summary

- The measured value of θ_{13} is great news for NOvA
- NDOS prototype run was very successful
  - Beam shutdown on May 1st for upgrades
  - Provided a jump start to our operations, calibration and analysis efforts
- Far Detector construction underway
  - Expect 5 kton of detector when upgraded beam switches on April 2013
- Sensitivities shown here use an earlier analysis approach but now include our knowledge of θ_{13}
  - Working to update the analysis approaches
- Exciting reach for resolving mass hierarchy and exploring the CPV parameter space
  - NOvA will be the first experiment to provide constraints on δ
- We are actively working to surpass these as analysis development continues

Thank you for listening!

Backup

Exposure Assumptions



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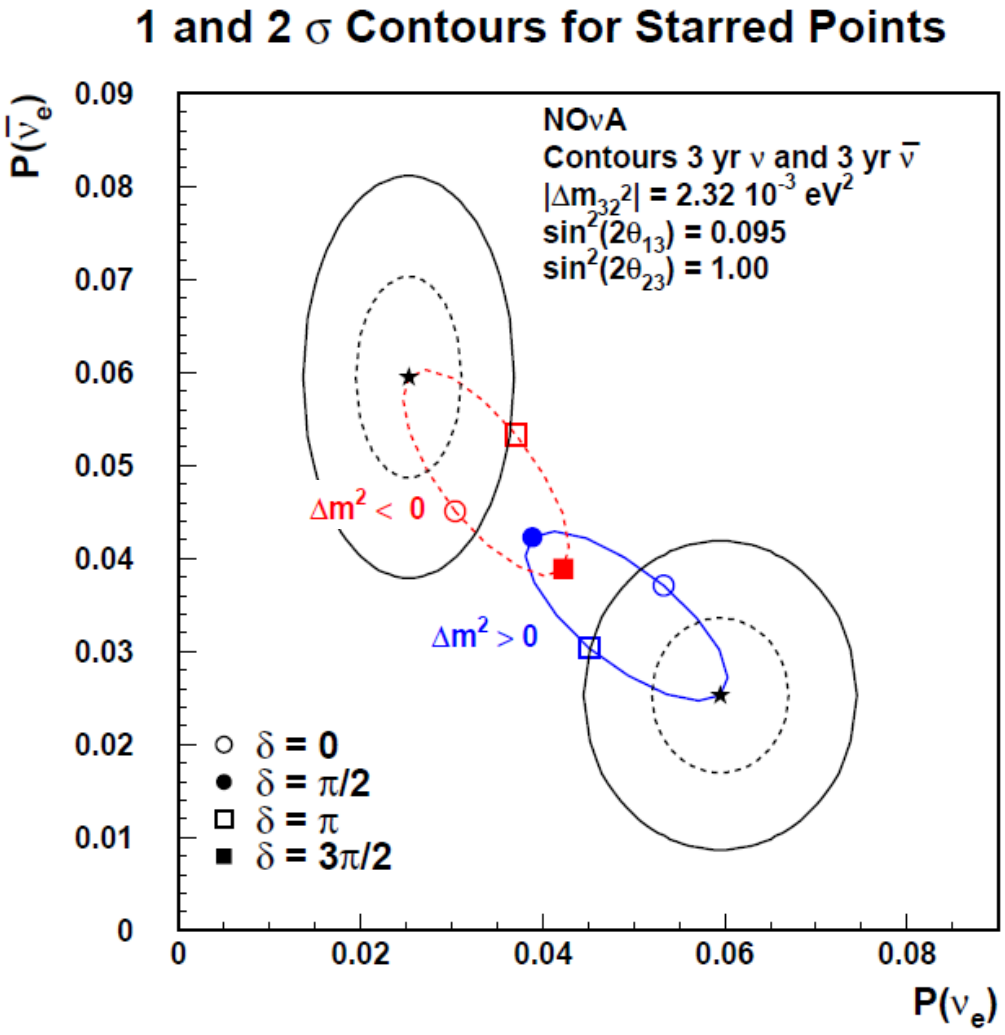
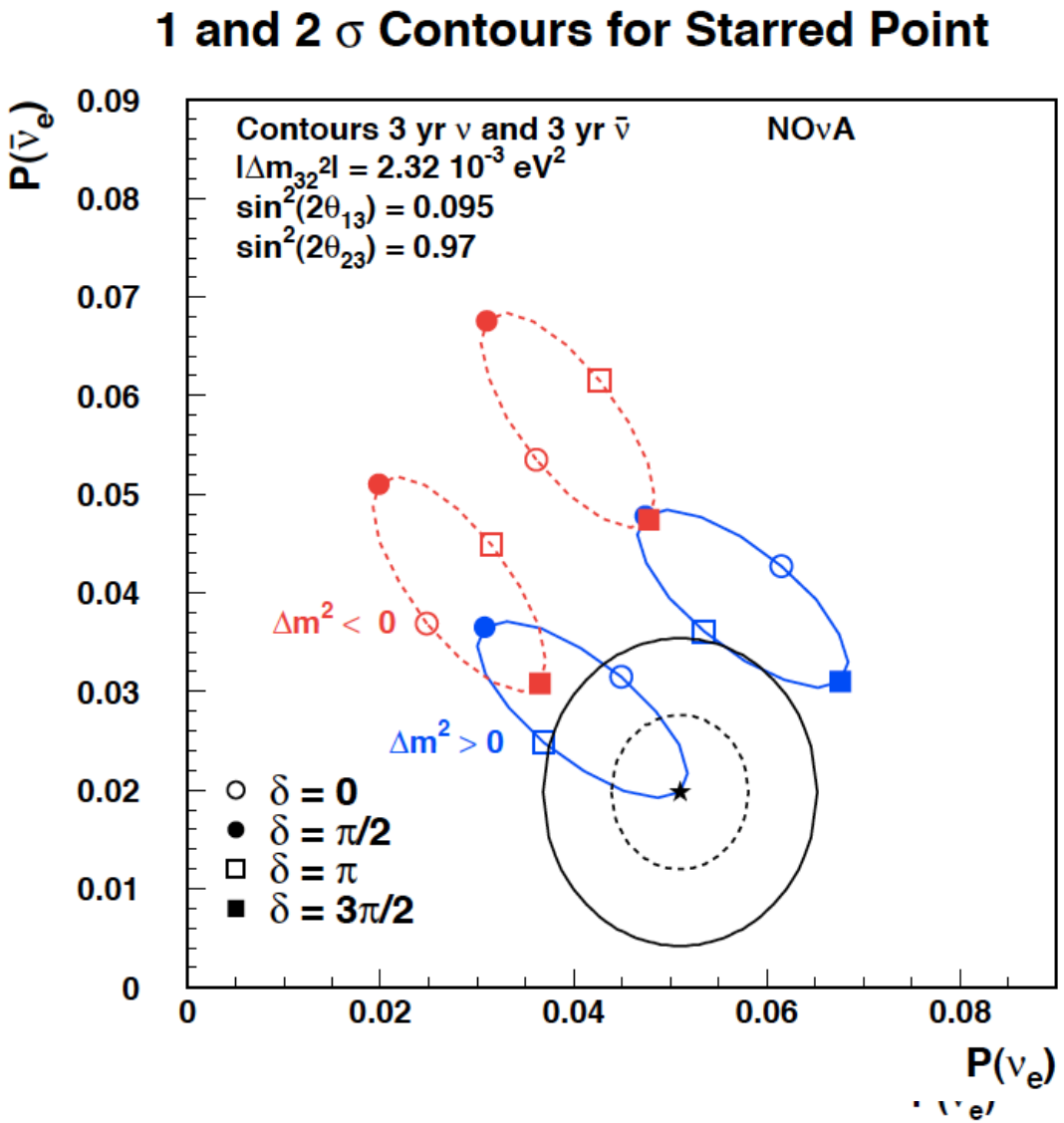
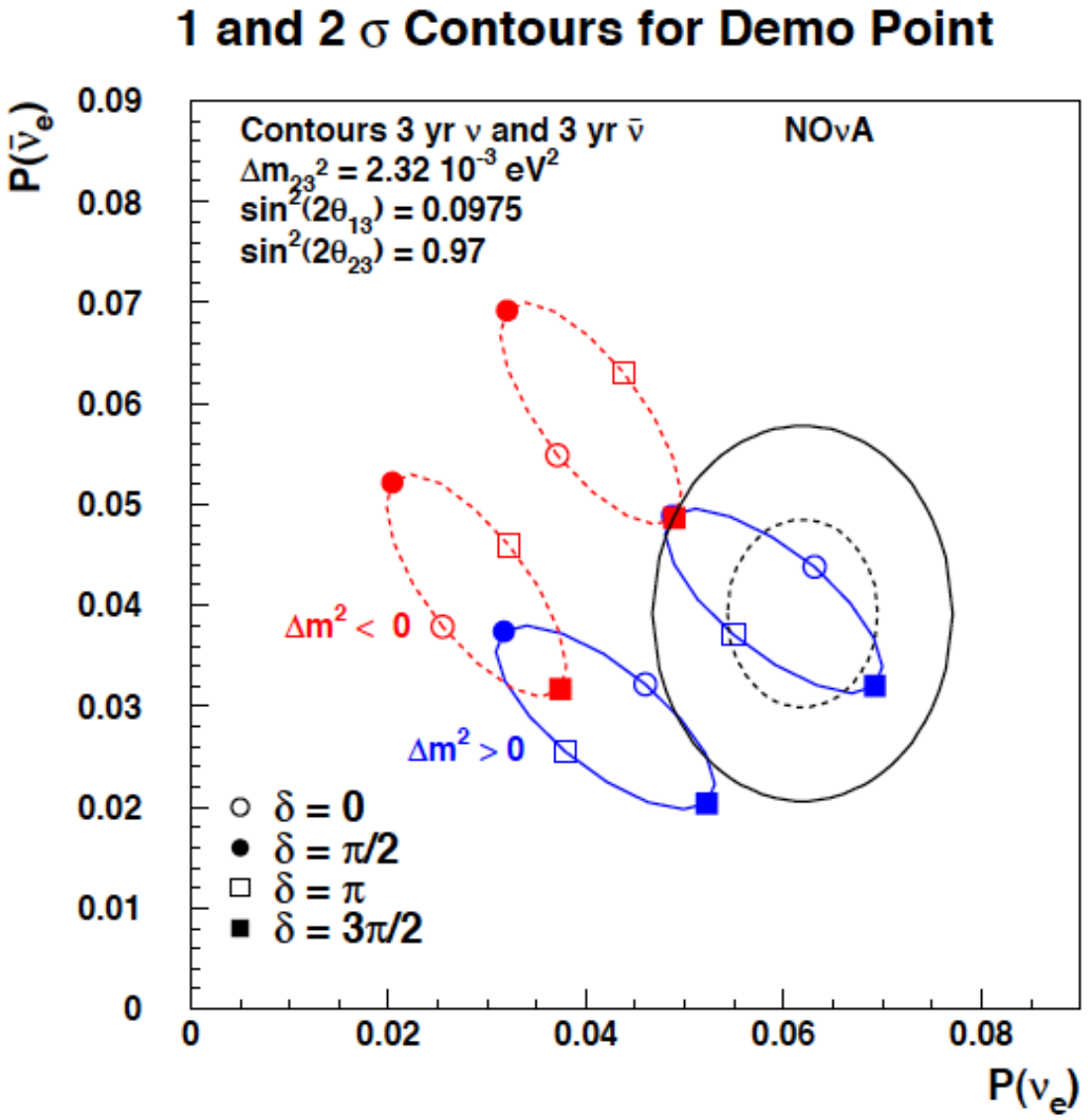


How about $\theta_{23} < 45°$

- Statistics are worse, but the conclusions are the same

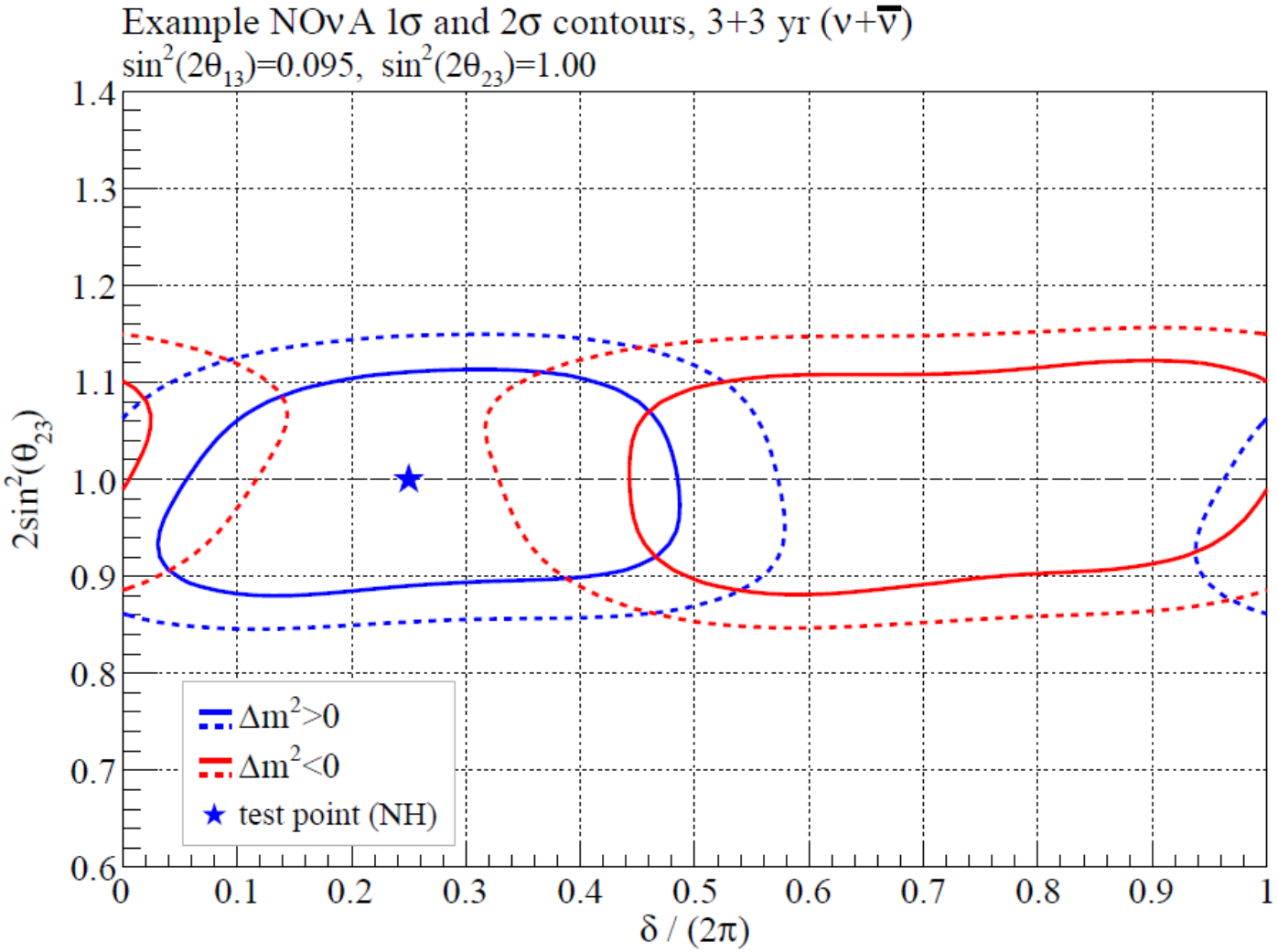


Note on 1 d.o.f contours



A Total View

- θ_{23} Octant, δ and Mass Ordering all on one plot
- Maximal mixing, non-resolved hierarchy ($\delta = \pi/2$)



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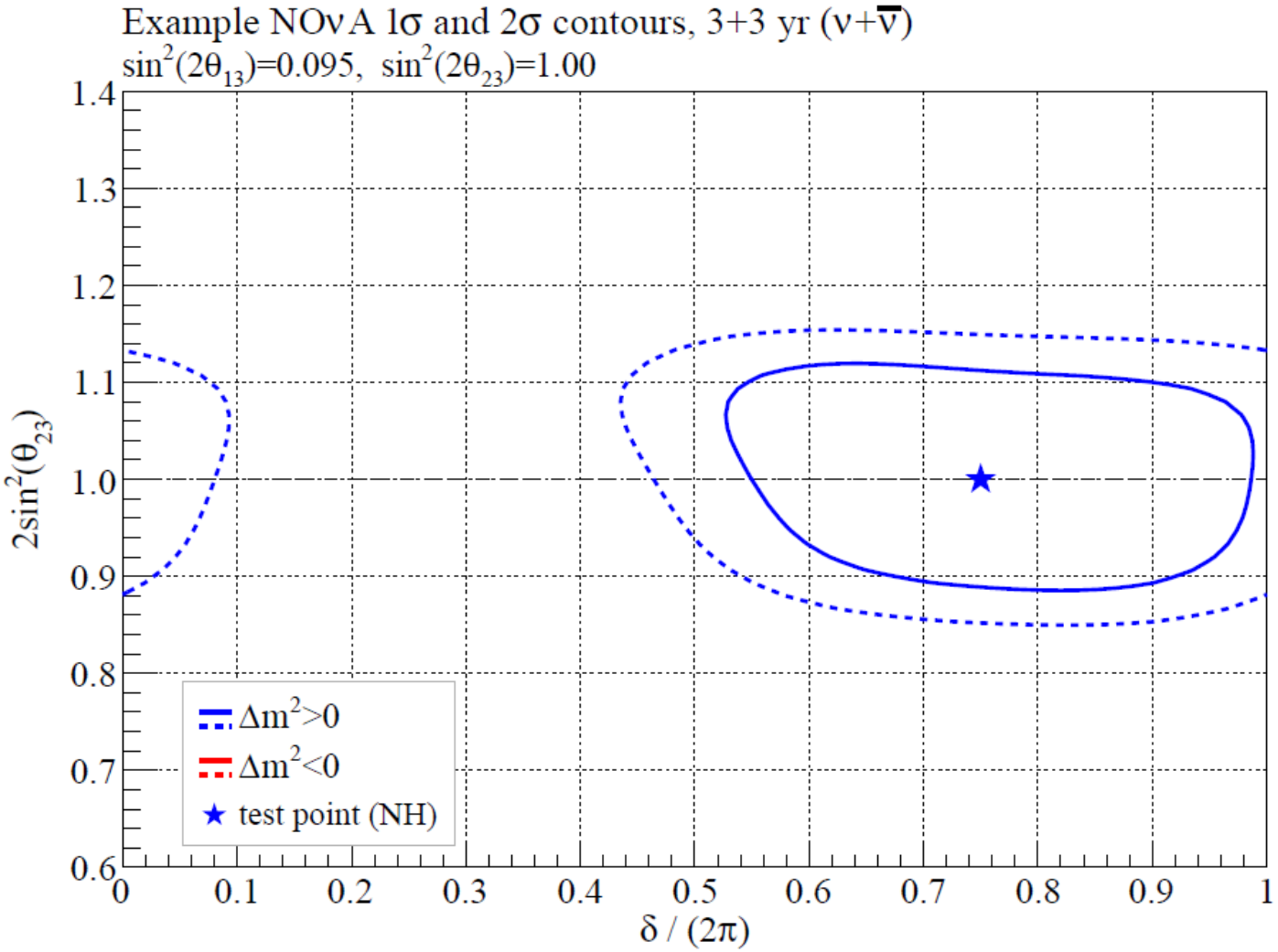
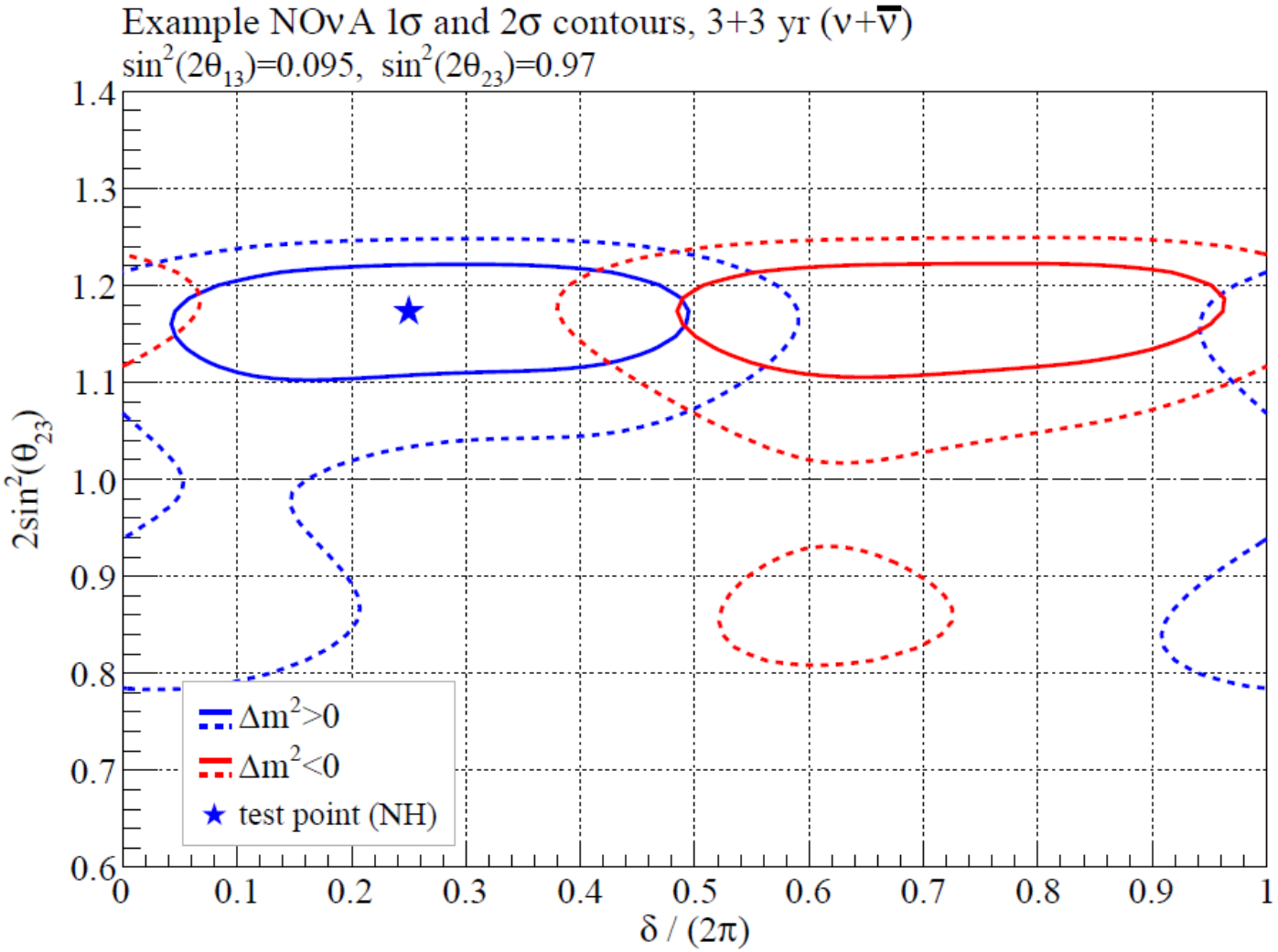
- θ_{23} Octant, δ and Mass Ordering all on one plot
- Maximal mixing, resolved hierarchy ($\delta = 3\pi/2$)



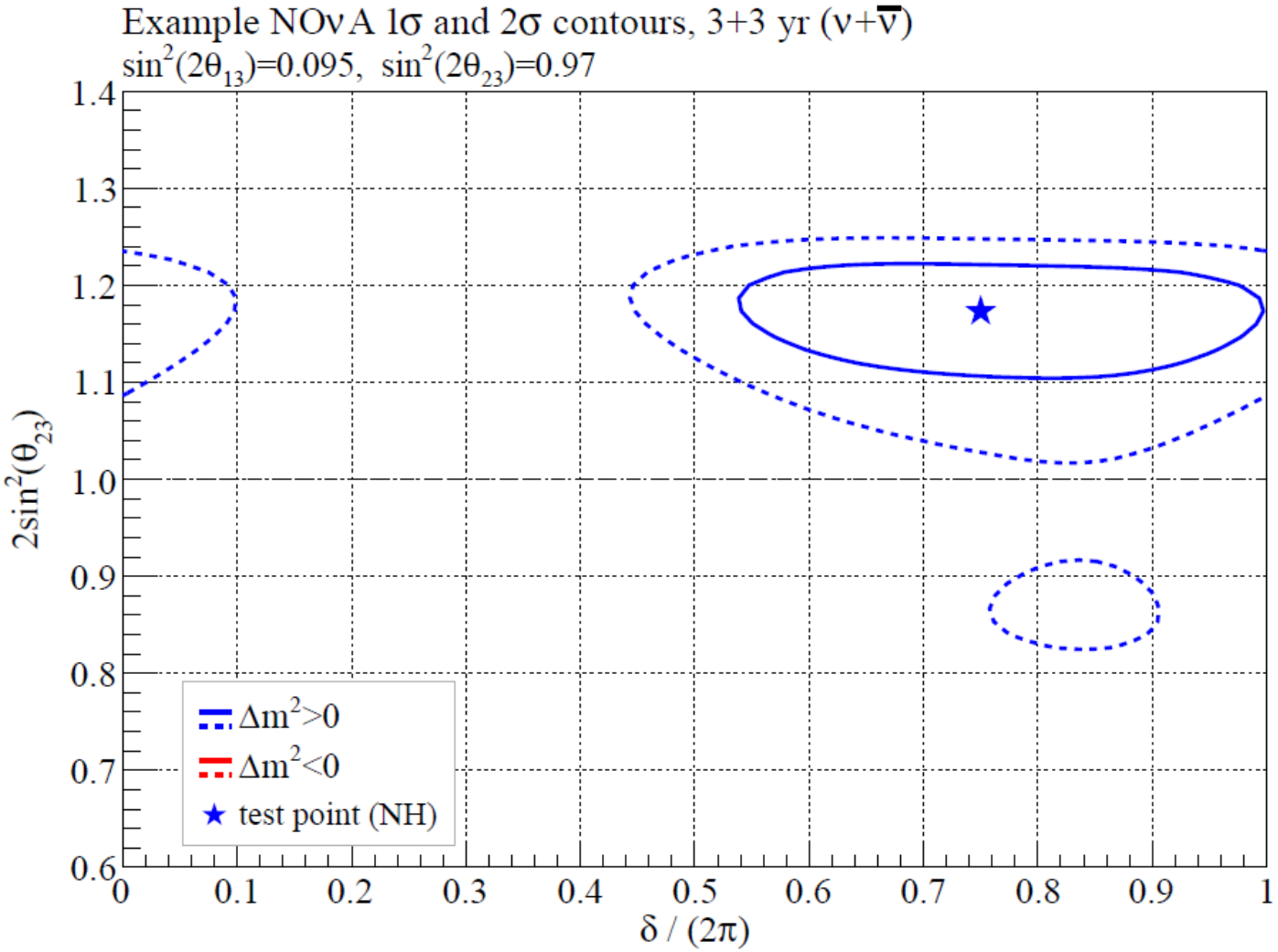
A Total View

- Non-maximal mixing, non-resolved hierarchy ($\delta = \pi/2$)
- Now $\sin^2(2\theta_{23}) = 0.97$, which is constrained by our ν_μ CC sample

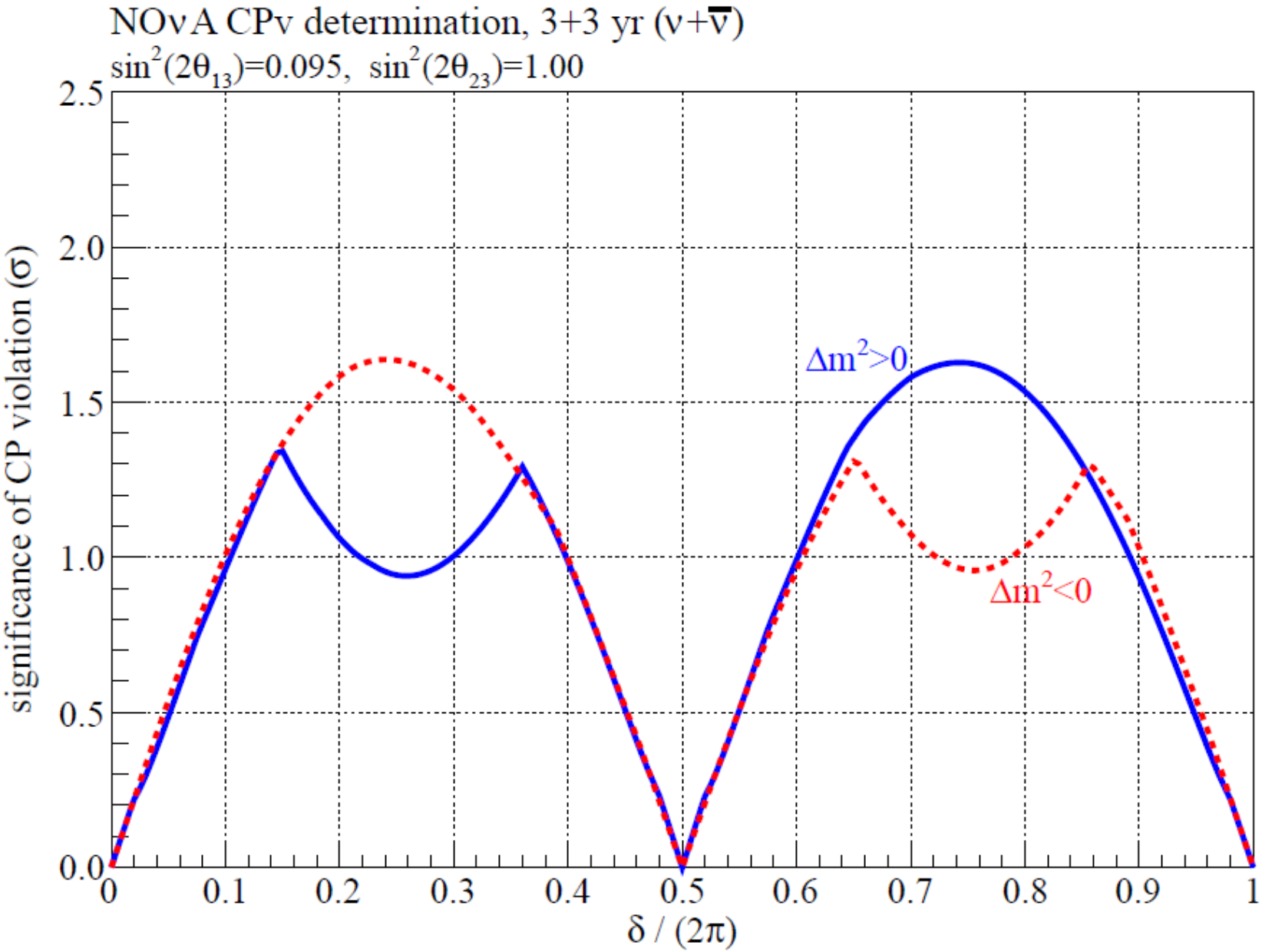


A Total View

- Non-maximal mixing, resolved hierarchy ($\delta = 3\pi/2$)
- Now $\sin^2(2\theta_{23}) = 0.97$, which is constrained by our ν_μ CC sample

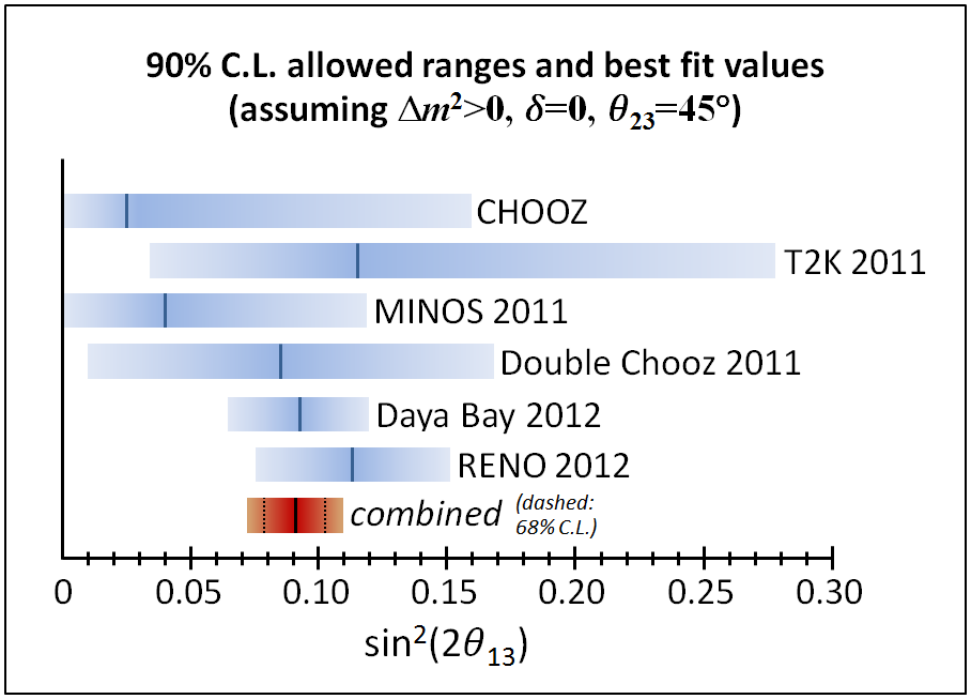


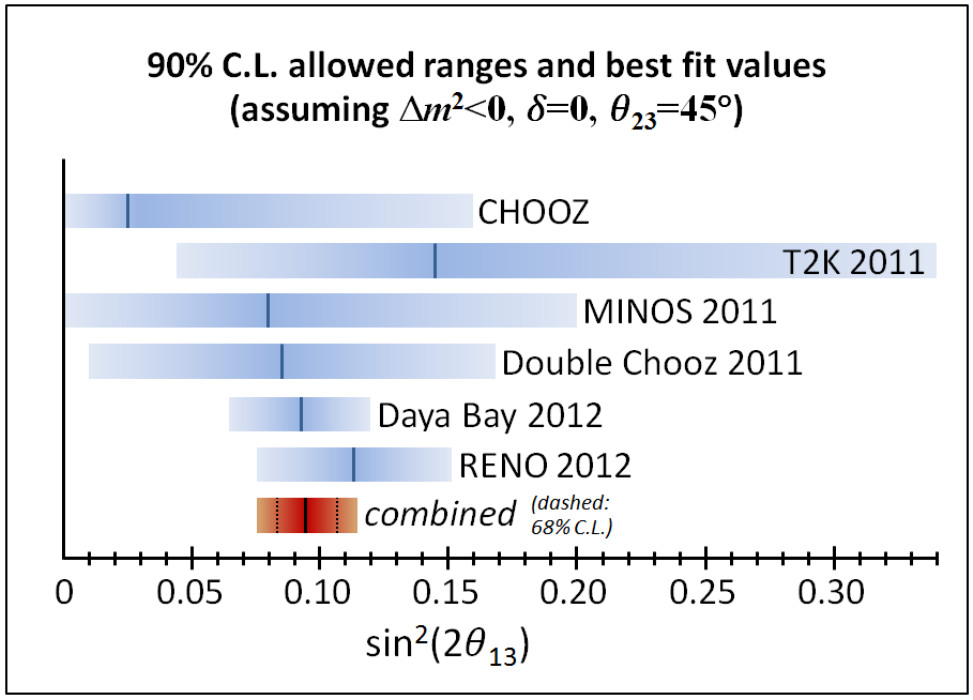
CP Violation Significance



The new θ_{13} landscape

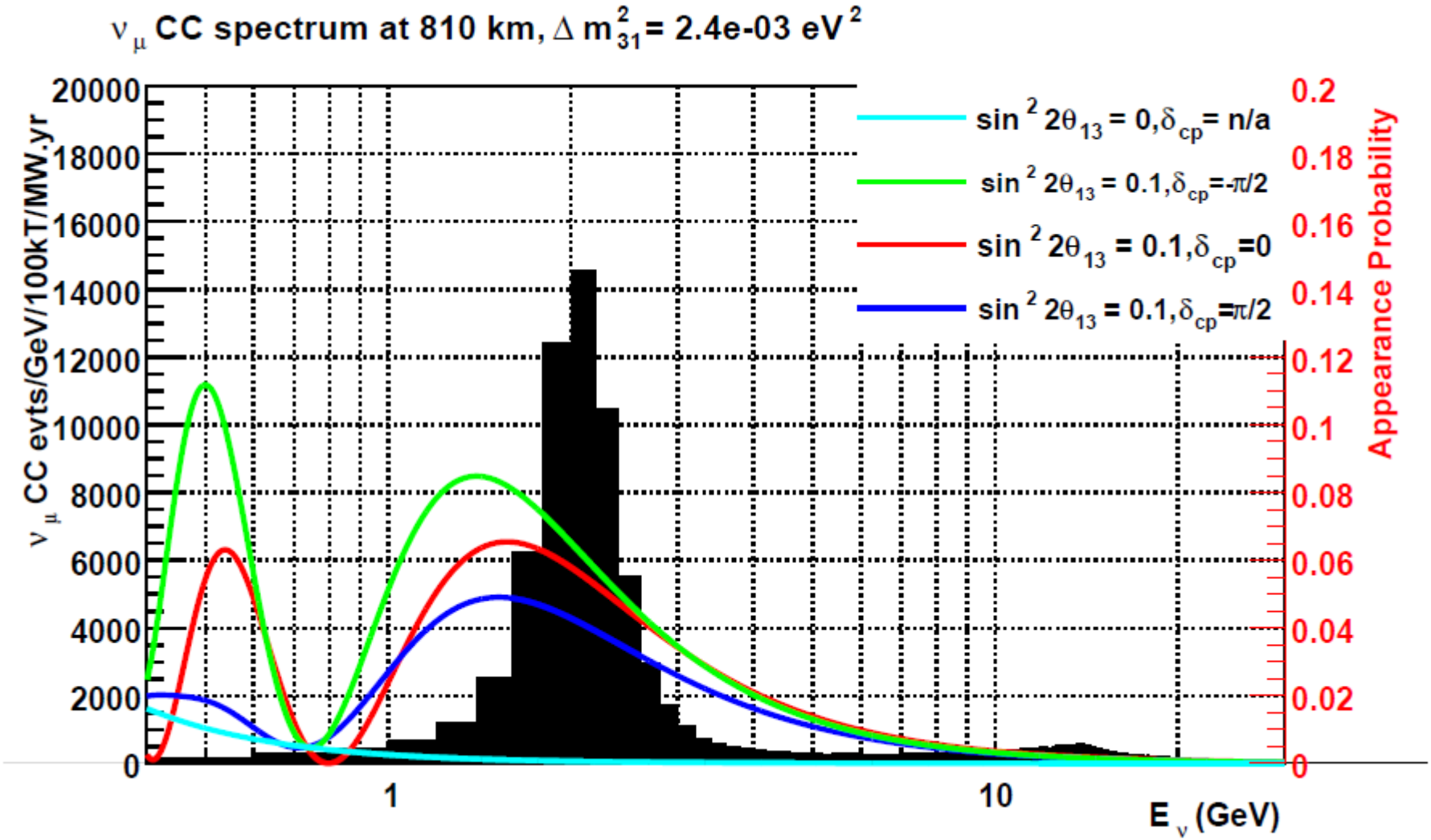
- Value of $\sin^2(2\theta_{13})$ is now well measured and will be improved very soon
- NOvA will take the next steps to finding the neutrino mass hierarchy and to begin the study of CPV in the lepton sector
- Combining data from NOvA at long baseline with T2K and with reactors will enable tests of the U_{PMNS} framework





R. Patterson (Caltech)

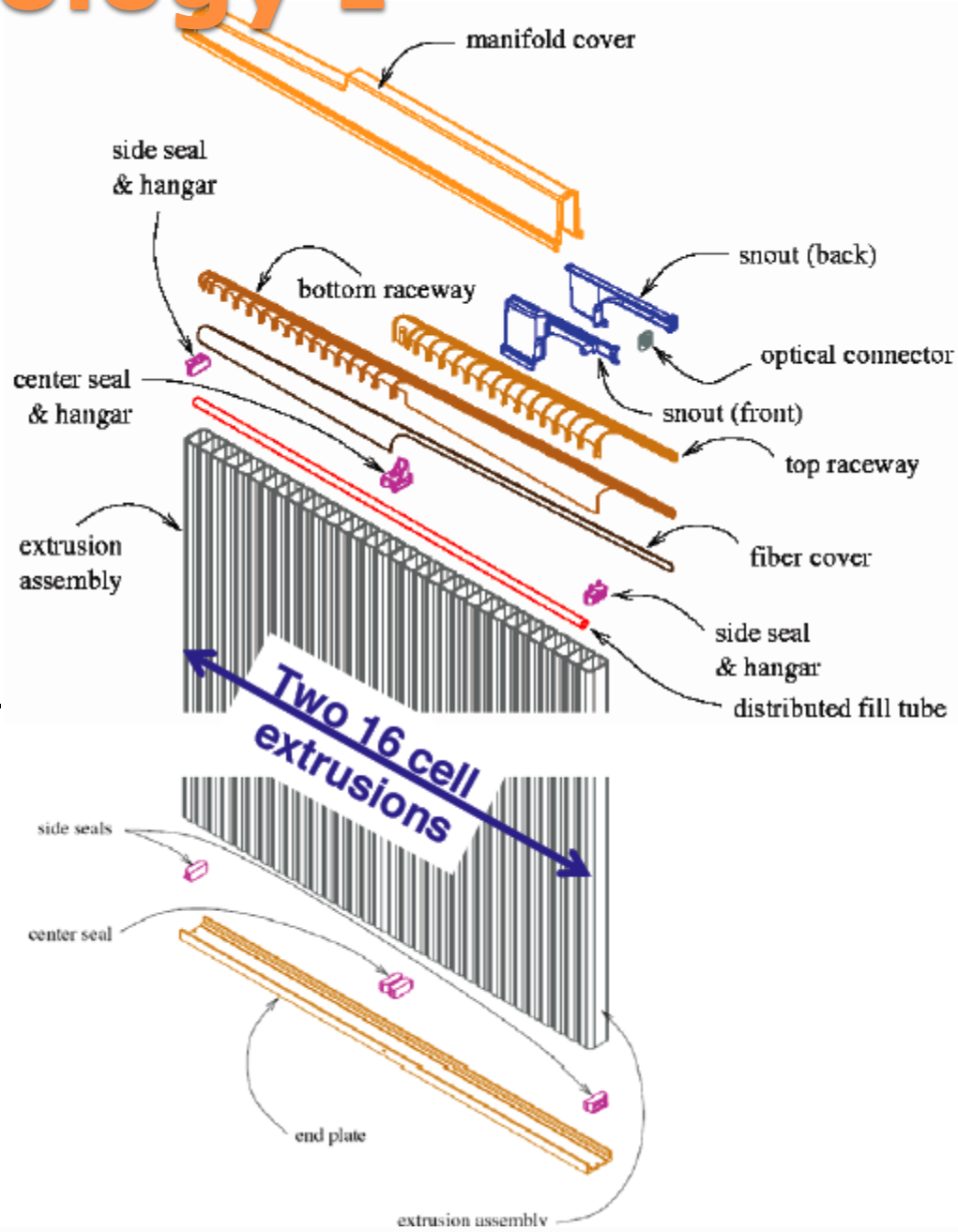
- NH combined: 0.0906 ± 0.012 (68% C.L.)
- IH combined: 0.0949 ± 0.012 (68% C.L.)



M. Bishai (BNL - LBNE)

Detector Technology I

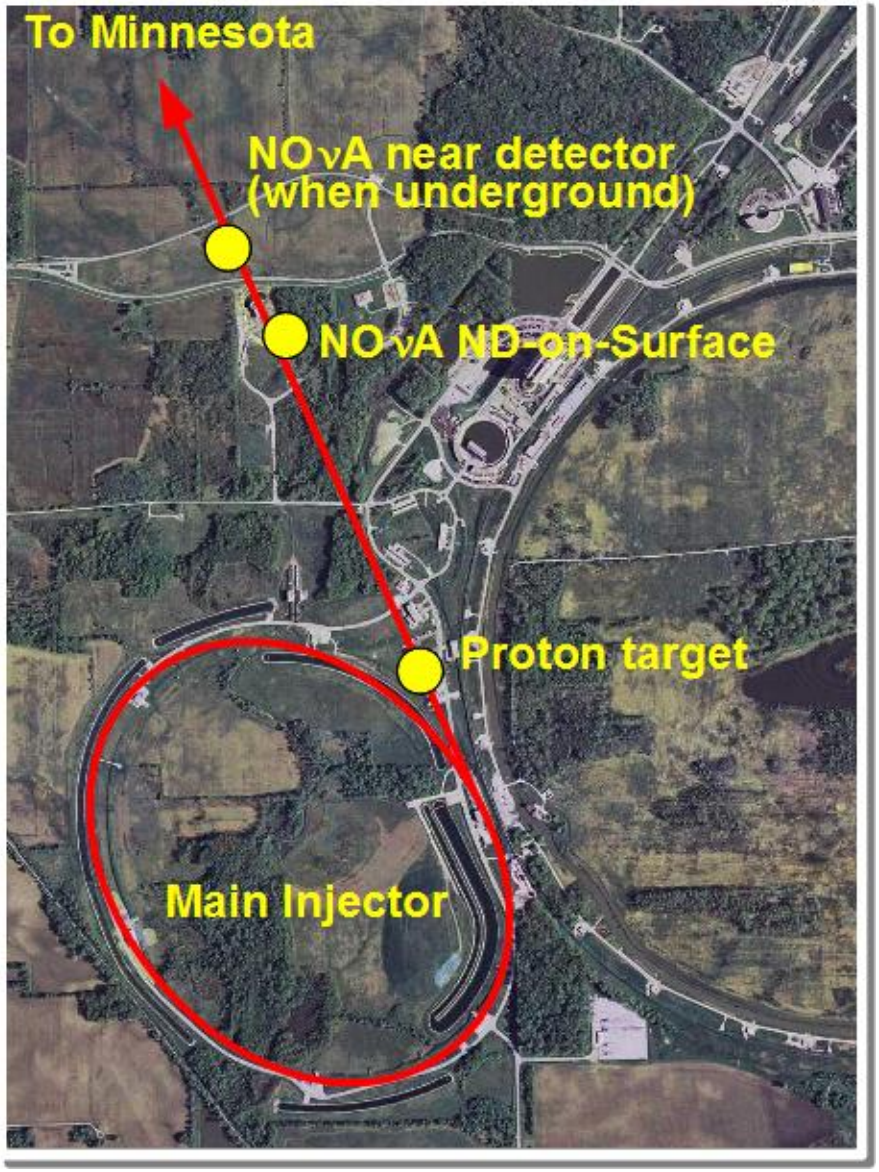
- 16-cell PVC extrusions coated with 15% TiO2
- 2 x 16-cells in a sealed module
  - approx. 360,000 cells (Far), 16,000 cells (Near)
- Cells filled with liquid scintillator
  - 4.98% psuedocumene scintillator dopant
  - 3.2 million gallons (Far) mineral oil
  - 65% active volume
- Cells contain a looped wavelength-shifting fibre
- Avalanche Photo-Diode (APD) readout
  - > 11.5k 32-pixels APDs
- Basic detector unit is a block
  - 32 planes of alternating horizontal and vertical modules



NDOS Assembly and Operations

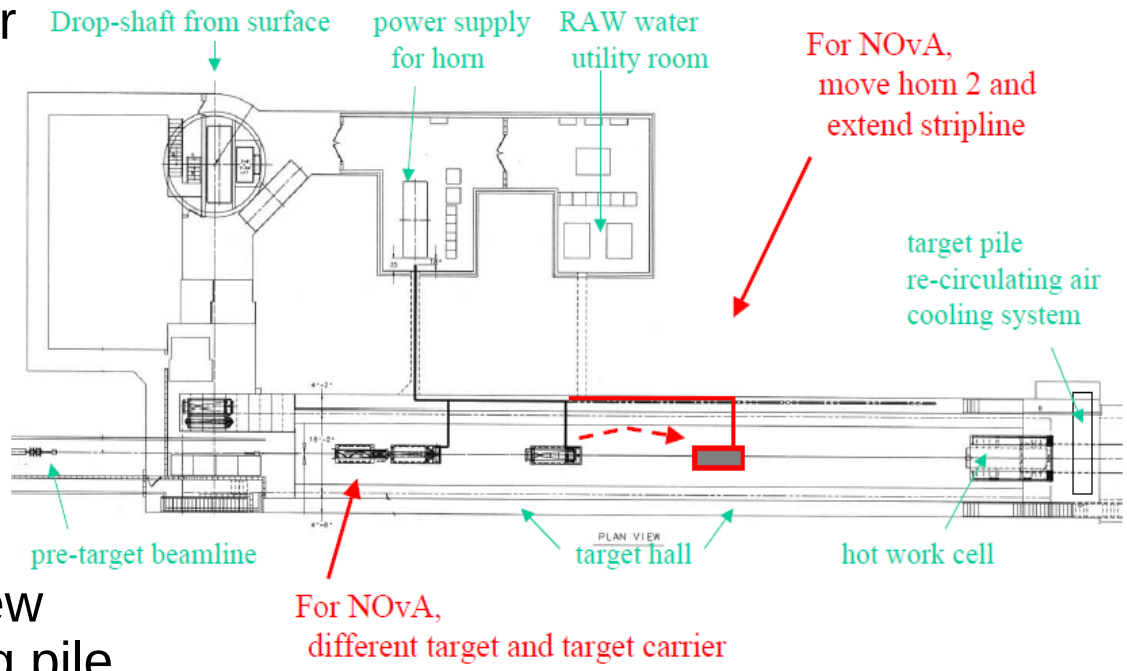
- Designed to prototype all detector systems prior to any installation at Ash River as a full end-to-end test of systems integration and installation
  - Redesigned module manifold and changed module pressure testing procedure to avoid potential cracks
- Gained experience in qualifying oil and testing our oil filling procedures in advance
- Tested APDs in realistic operating conditions
  - Modified installation procedures
  - Developed surface coating for bare APDs to protect the silicon surface from potential contact with contaminants
  - Added an active air drying system to keep out condensation due to cooling

Experiment Setup



Accelerator and NuMI upgrades

- During the shutdown (May 1 – April 2013) the recycler will be converted to an accumulator and the cycle time of the Main Injector will be reduced to 1.33 seconds to double the beam intensity available for NOvA



- NuMI will be outfitted with a new target and horns. The shielding pile will be unstacked to move horn 2 to its optimal location for NOvA 10m downstream of its current location