The NOvA Experiment

A long baseline neutrino experiment at the Intensity Frontier

Andrew Norman, Fermilab
for the NOvA Collaboration

Heavy Quarks and Leptons 2012, Prague CZ

The NOvA Collaboration

NOvA is a growing collaboration of 150 Scientists & Engineers from 25 institutions and 5 countries

2006

2010

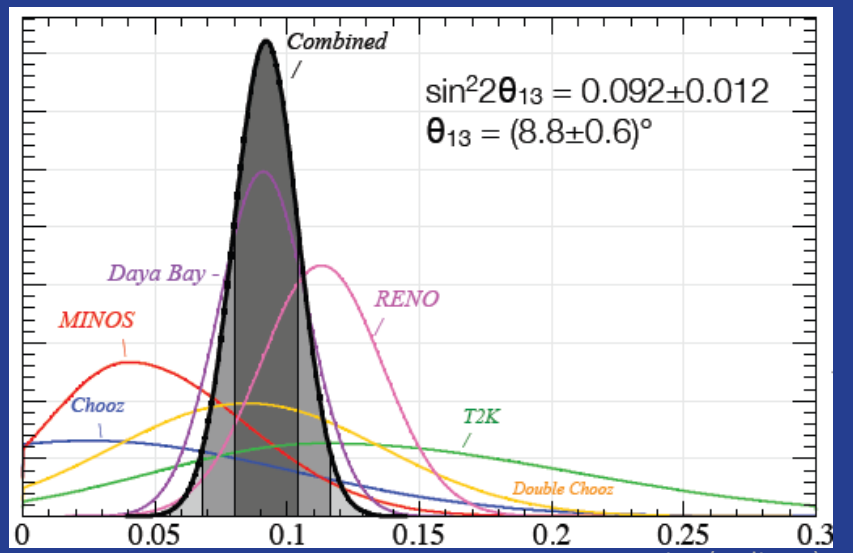
2011

Neutrino Landscape

Our knowledge of neutrino mixing has changed dramatically over the last year (and the last week! see: Neutrino 2012 results)

We have gone from having no information on θ_{13} to knowing that:

- θ_{13} is large ≈9°
- θ_{13} is the most precise neutrino measurements we have.



M.Messier (Indiana)

This has dramatically changed the experimental landscape and opened up new possibilities in the ν sector

Latest ν Oscillations Global fit:

$$\sin^2\theta_{12} = 0.320^{+0.015}_{-0.017} \qquad \Delta m^2_{21} = 7.62 \pm 0.19$$

$$\sin^2\theta_{23} = 0.49^{+0.08}_{-0.05} \qquad |\Delta m^2_{31}| = 2.53^{+0.08}_{-0.10}$$

$$\sin^2\theta_{13} = 0.026^{+0.003}_{-0.004}$$

Forero, Tortola, Valle 2012 arXiv:1205.4018

Neutrino Landscape

The experimental picture for neutrino physics now shifts from trying to measure ***if*** $\theta_{13} \neq 0$ to three general experimental thrusts:

1. Is $\delta \neq 0$?
   Is there CP violation in the ν sector?
2. Is $\Delta m_{13} > 0$?
   Is the neutrino mass hierarchy normal or inverted?
3. Make precision measurements of θ_{23}, θ_{13}, θ_{12}
   Over constrain the standard mixing model to look for new physics.

NOvA

- NOvA is a program to investigate the properties of neutrinos
- It includes:
  - Doubling of the Fermilab NuMI beam power to 700 kW
  - An 15kTon totally active *surface* detector, 14 mrad off axis at 810km (first oscillation max for 2GeV)
  - A 220 Ton totally active near detector
- It has been optimized as a segmented low Z calorimeter/range stack to:
  - Reconstruct EM showers
  - Measure muon track
  - Detect nuclear recoils and interaction vertices

Nova Measurements

- NOvA has a broad physics scope that has been been optimized to address these experimental goals:

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

- Measure θ_{13} via ν_e appearance
- Determine ν mass hierarchy
- Probe for CP violation in ν's
- Determine θ_{13} octant

Measuring $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$

- Precision θ_{23} measurement
- Determine θ_{23} non-maximal
- Over-constrain atmospheric sector

Short Baseline/Near Detector and other ...

- Measure ν cross sections
- Short baseline oscillations
- Probe for sterile ν's
- Cosmic ν's
- Supernova ν's
- Exotic Searches

Nova Measurements

- NOvA measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\mu}_\nu \to \bar{\nu}_e)$ over an 810 km baseline at a central energy of 2GeV.

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$
$$+ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

$$\text{Where:} \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \quad \Delta = \Delta m_{31}^2 \frac{L}{4E} \quad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

  - The transition probability is dependent on θ_{13},θ_{23},δ_{CP} and Δm_{31}
  - The reactor measurements do not have the these dependencies

Estimated ν_e Appearance Signal

The large θ_{13} is extremely good for NOvA since it leads to large event rates in the far detector and enhancing early sensitivities.

The following sensitivities use our earlier analysis approaches but include the latest knowledge of θ_{13}

- $\sin^2 2\theta_{13}=0.095$
- Optimized for ~4% oscillation probability
- 10% uncertainty on backgrounds
- 41% (ν) and 48% (anti-ν) signal efficiency

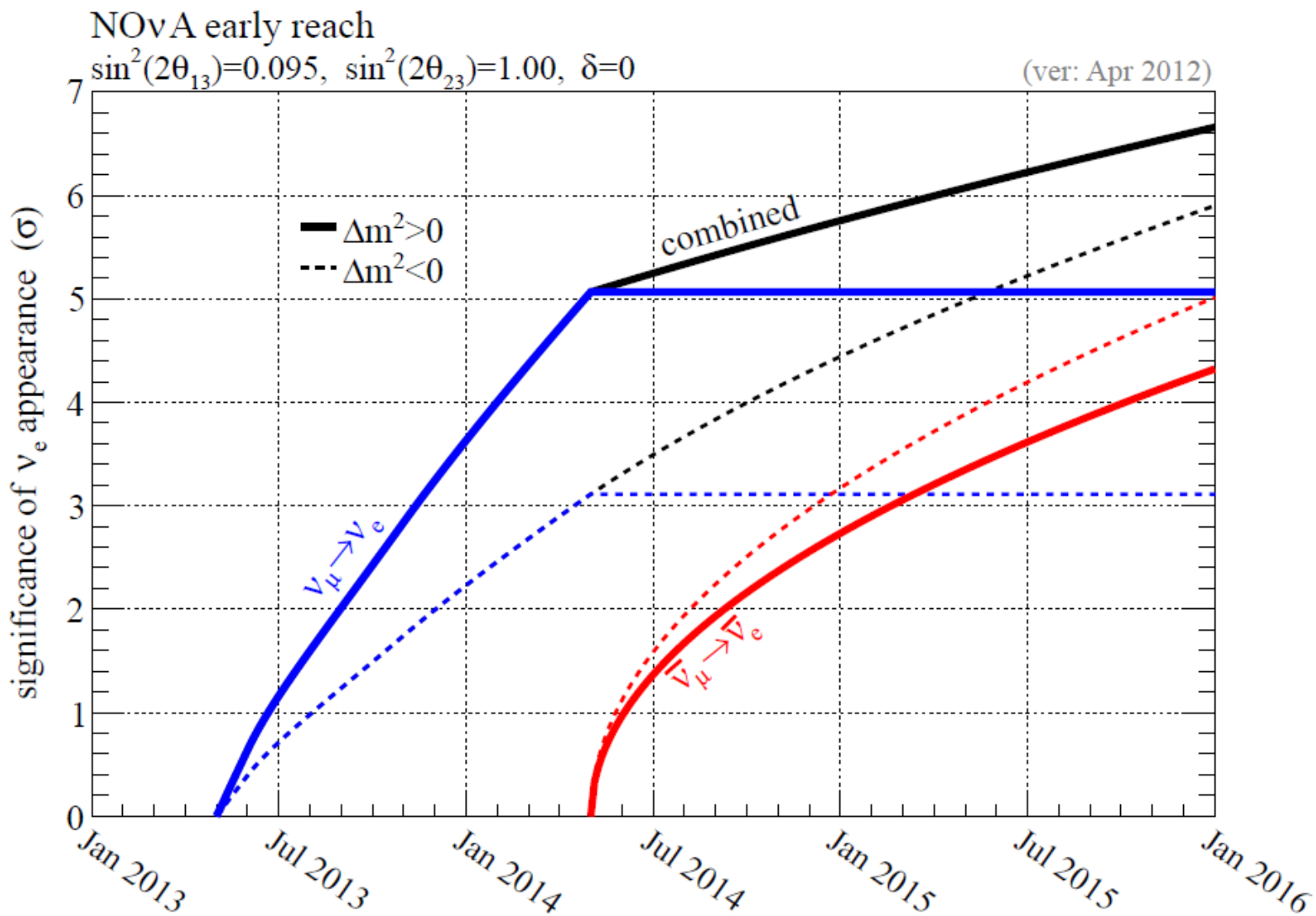
Beam	Signal	NC Bkg	ν_μ CC	ν_e CC	Total Bkg
ν (3 yr)	72.6	20.8	5.2	8.4	34.5
$\bar{\nu}$ (3 yr)	33.8	10.6	0.7	5.0	16.3

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

N_e Appearance Sensitivities



Hierarchy Sensitivities

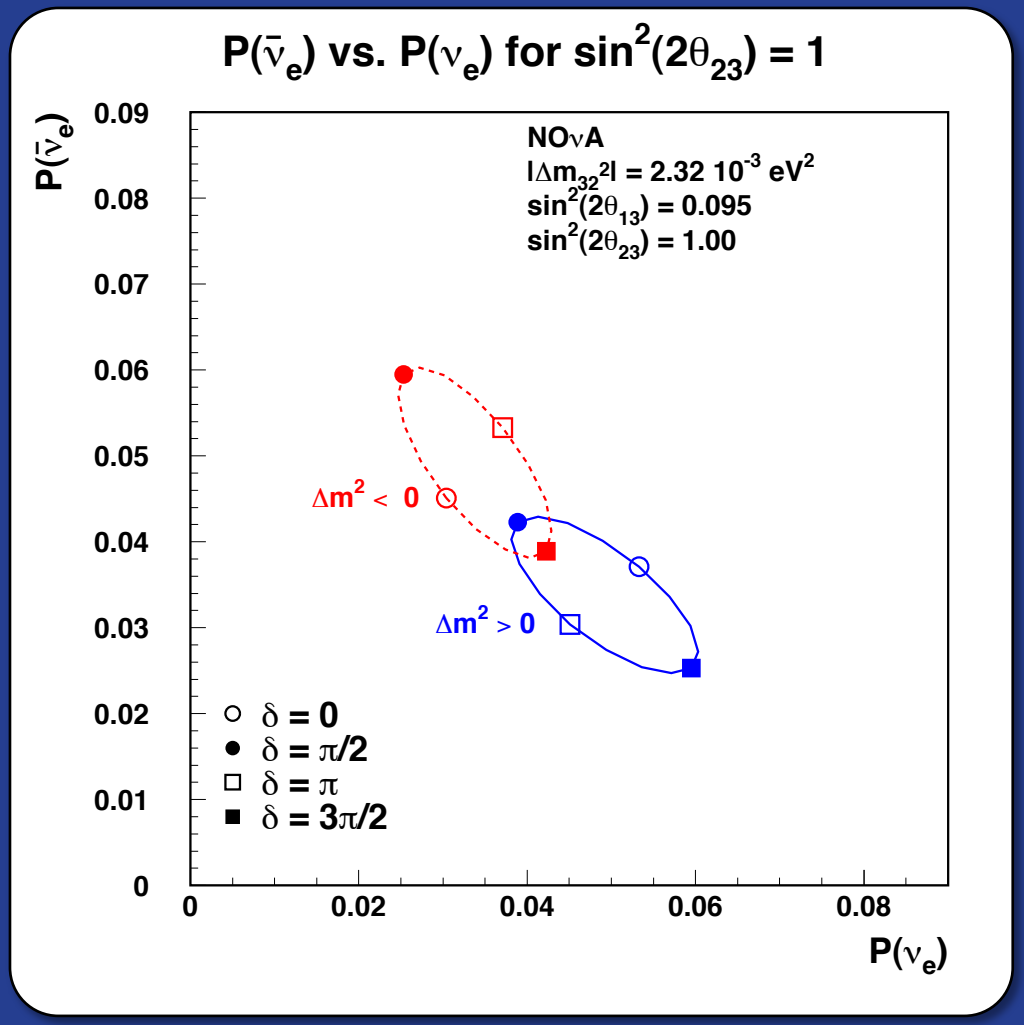
The transition probabilities for Neutrino & anti-neutrino running are parameterized with respect to δ_{CP} to give the permitted curves for the normal and inverted hierarchy.

NOvA measures separately:

$$P(\nu_\mu \to \nu_e) \text{ at } 2 \text{ GeV}$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \text{ at } 2 \text{ GeV}$$

Which gives a point on one of these curves



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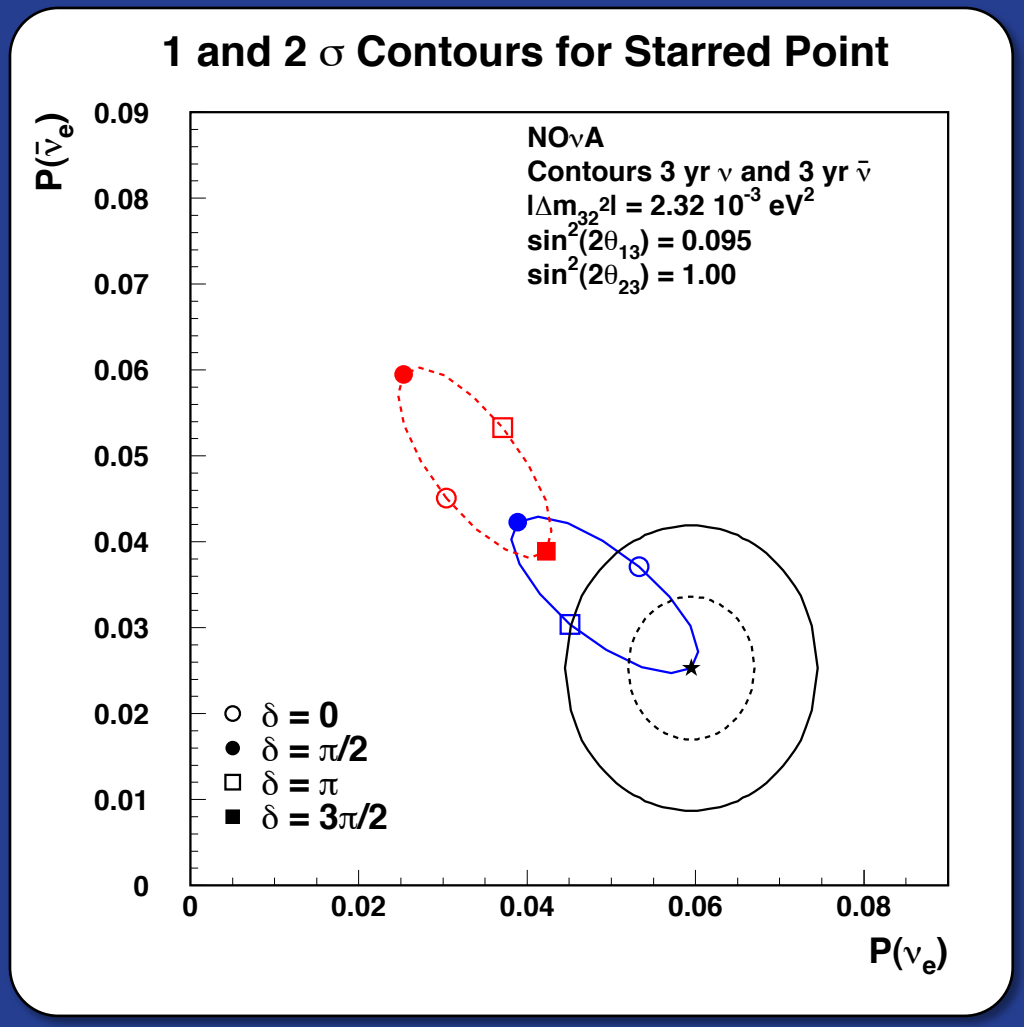
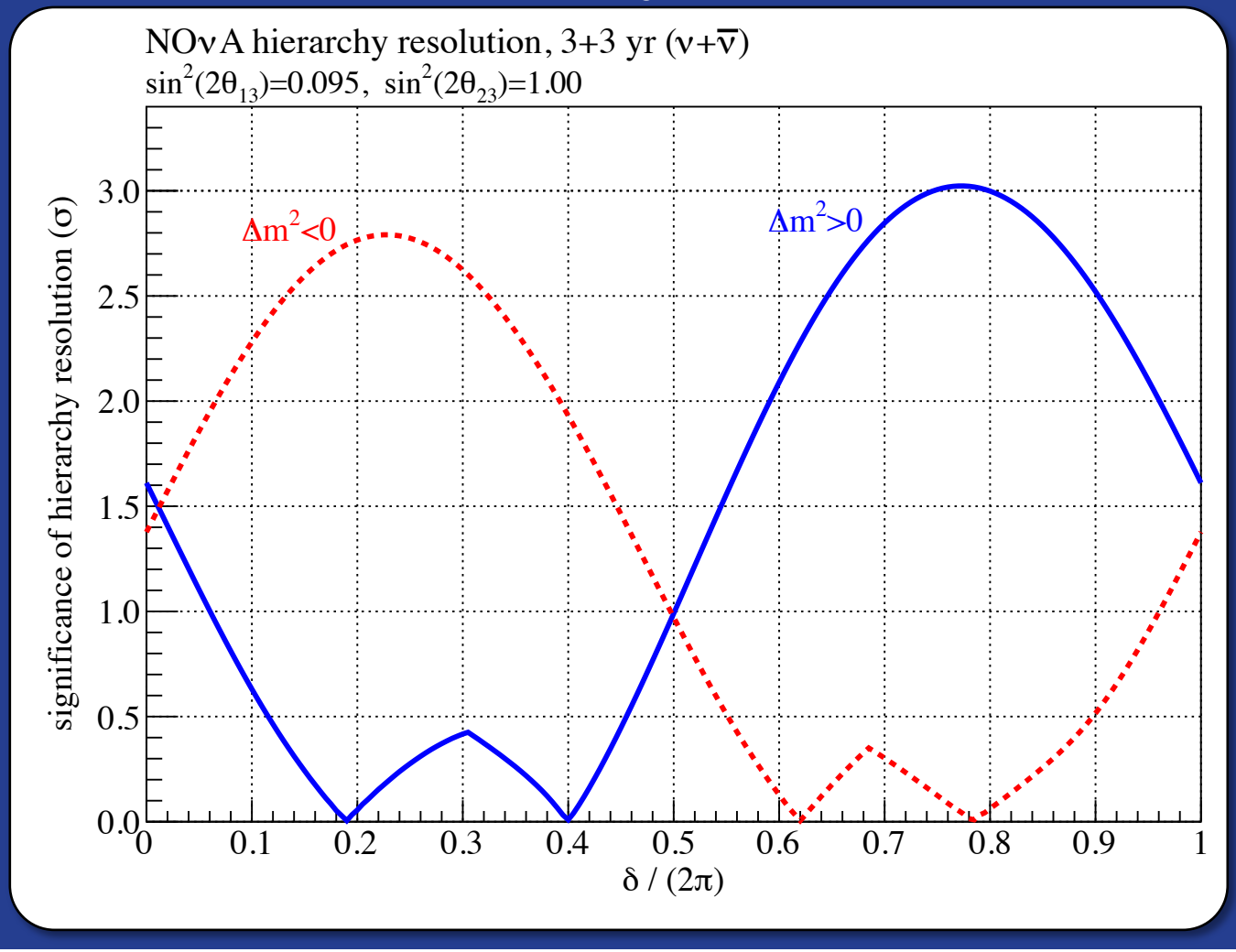
In this case (3π/2, normal hierarchy) the normal hierarchy is established at 2σ.



Hierarchy Sensitivity

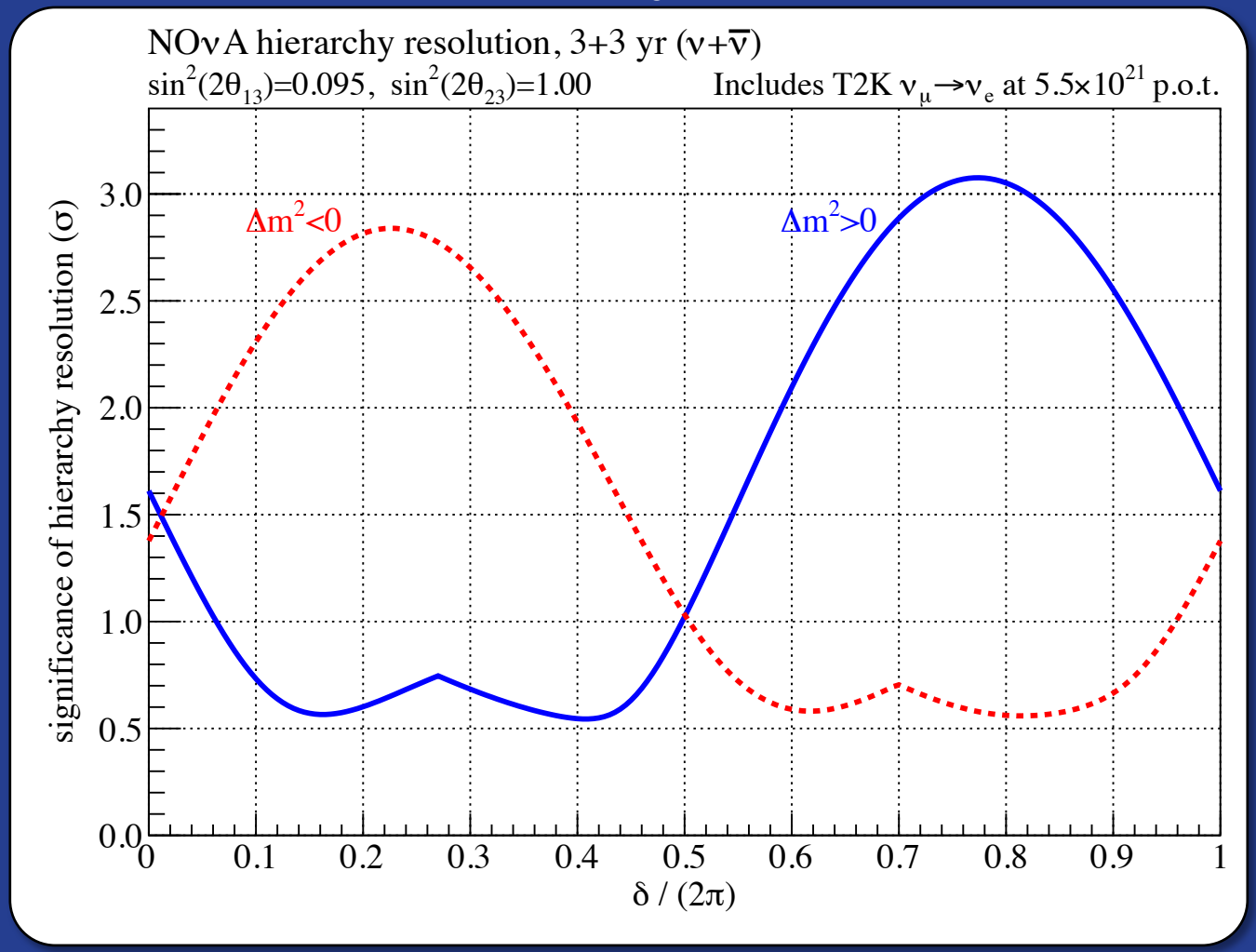
For a maximal θ_{23}, NOvA's sensitivity to the resolution of the hierarchy can be parameterized in terms of the true value of δ_{CP}



Hierarchy Sensitivity

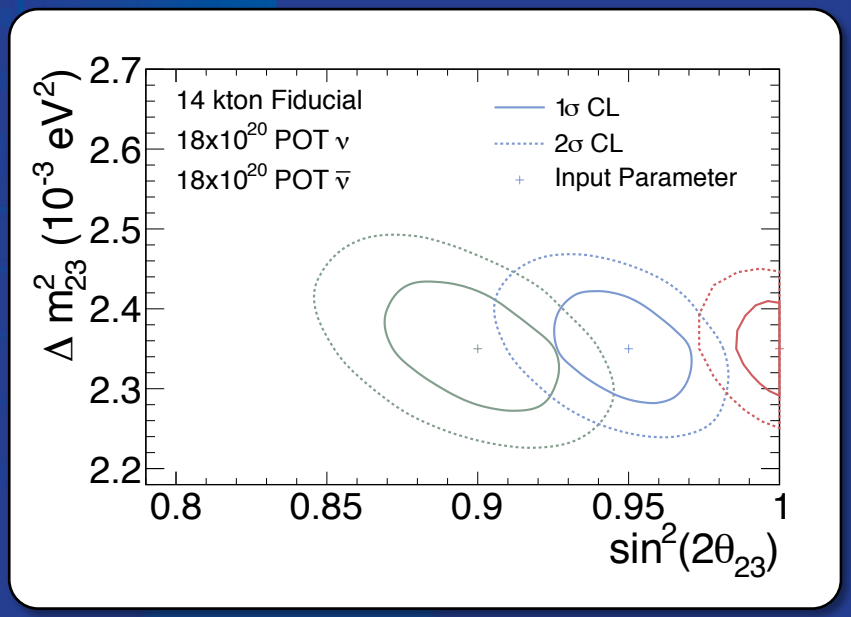
For a maximal θ_{23}, NOvA's sensitivity to the resolution of the hierarchy can be parameterized in terms of the true value of δ_{CP}

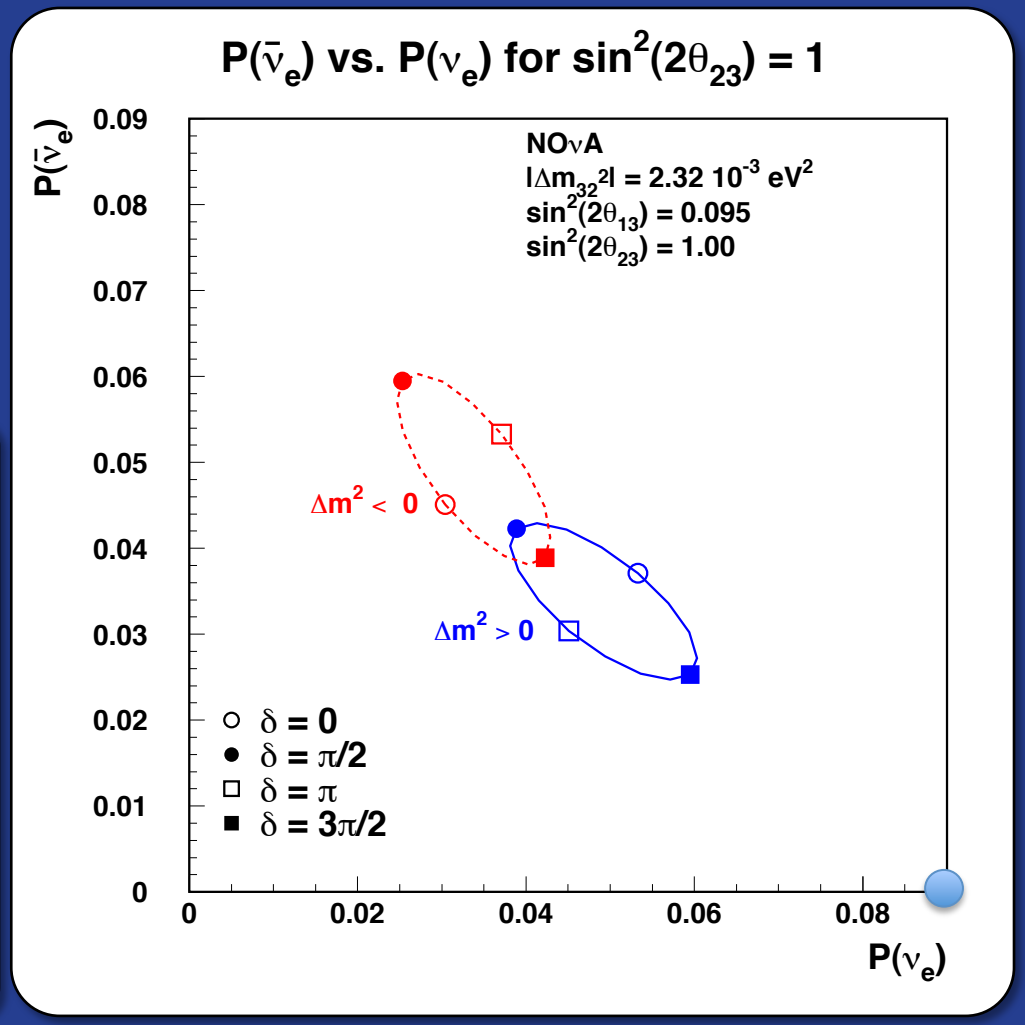
Combining NOvA w/ T2k break the degeneracies in the overlap regions of the curves improves overall resolution significance.



Non-Maximal θ_{23}

NOvA will make a precision measurement of $P(\nu_\mu \rightarrow \nu_\mu)$ which has the potential to establish $\theta_{23} \neq 45°$





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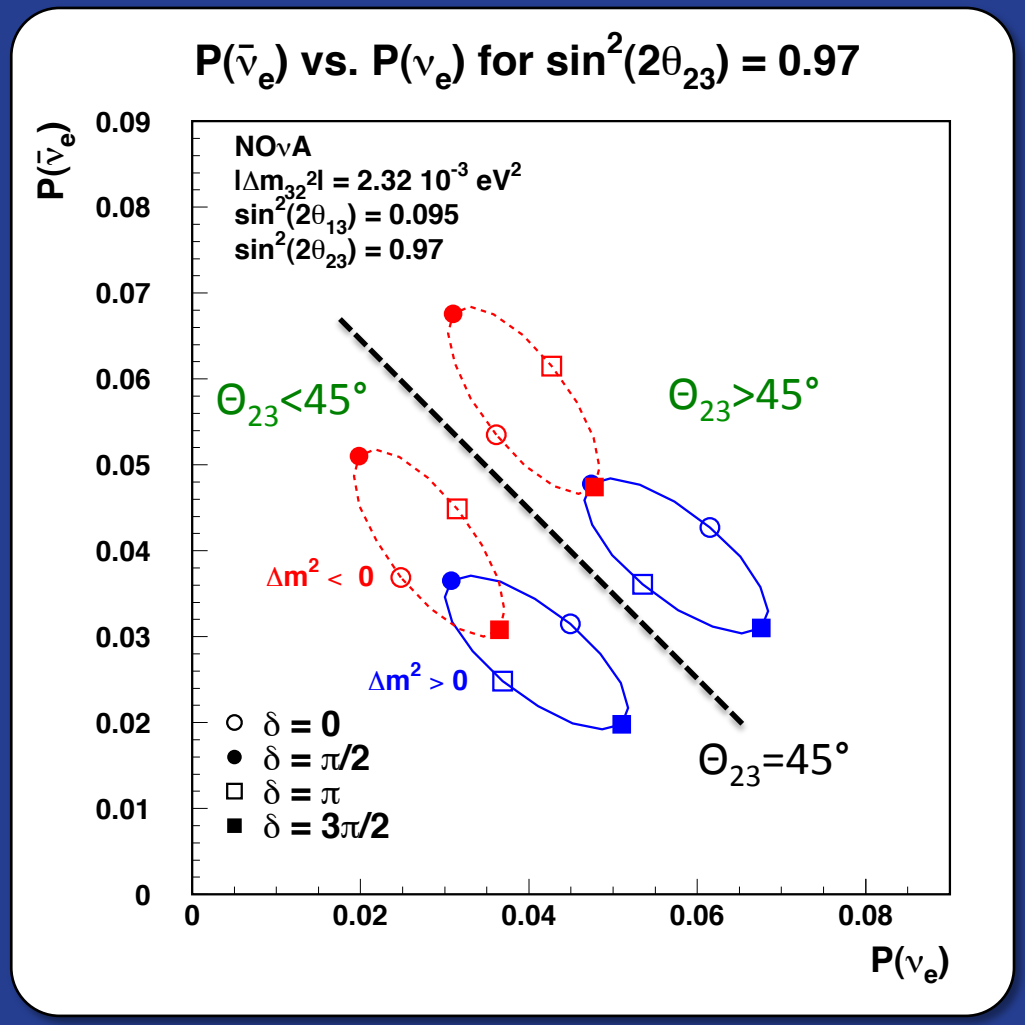
If this is the case then the $P(\nu_\mu \rightarrow \nu_e)$ ellipses shift based on how far θ_{23} differs from 45°.



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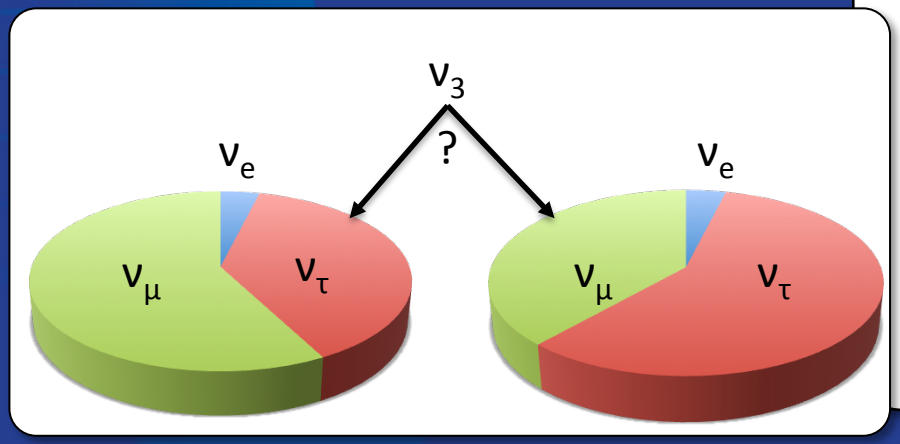
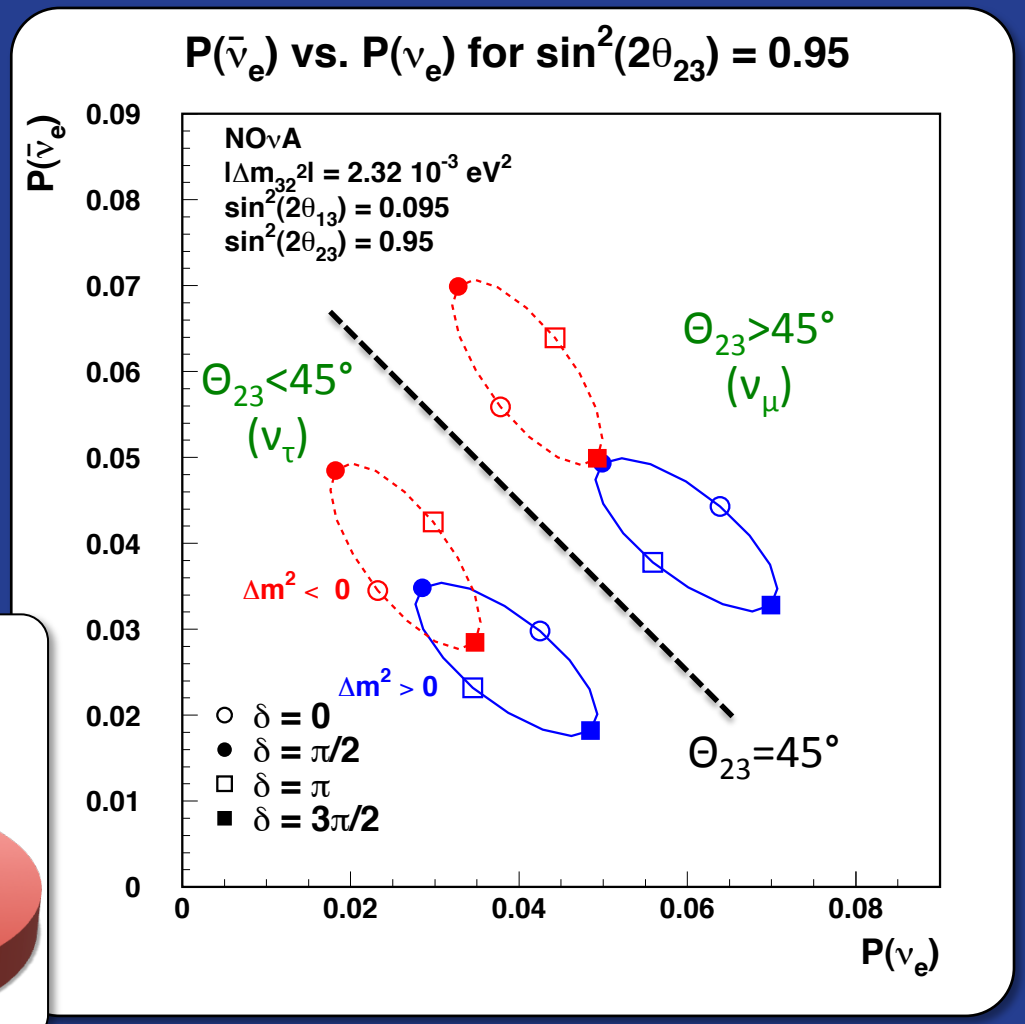
This corresponds to the mass state ν_3 coupling more to ν_τ or ν_μ





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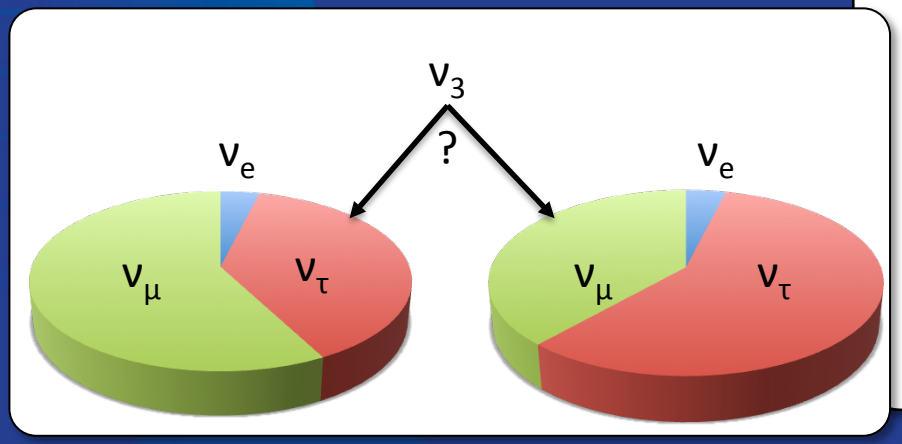
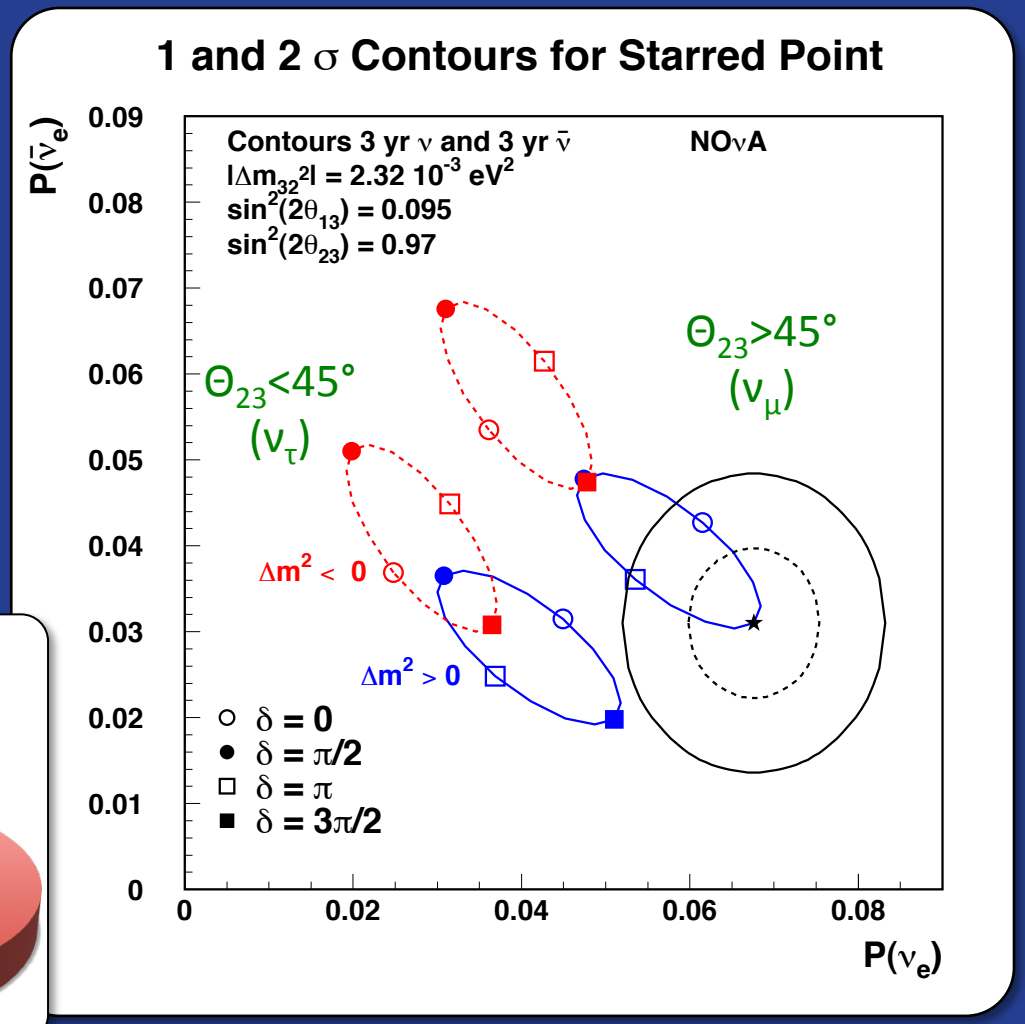
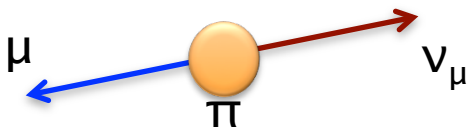




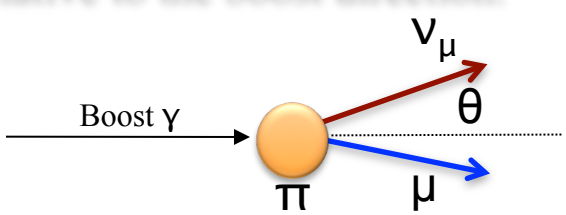
The Off-Axis Beam

The Off-Axis Effect

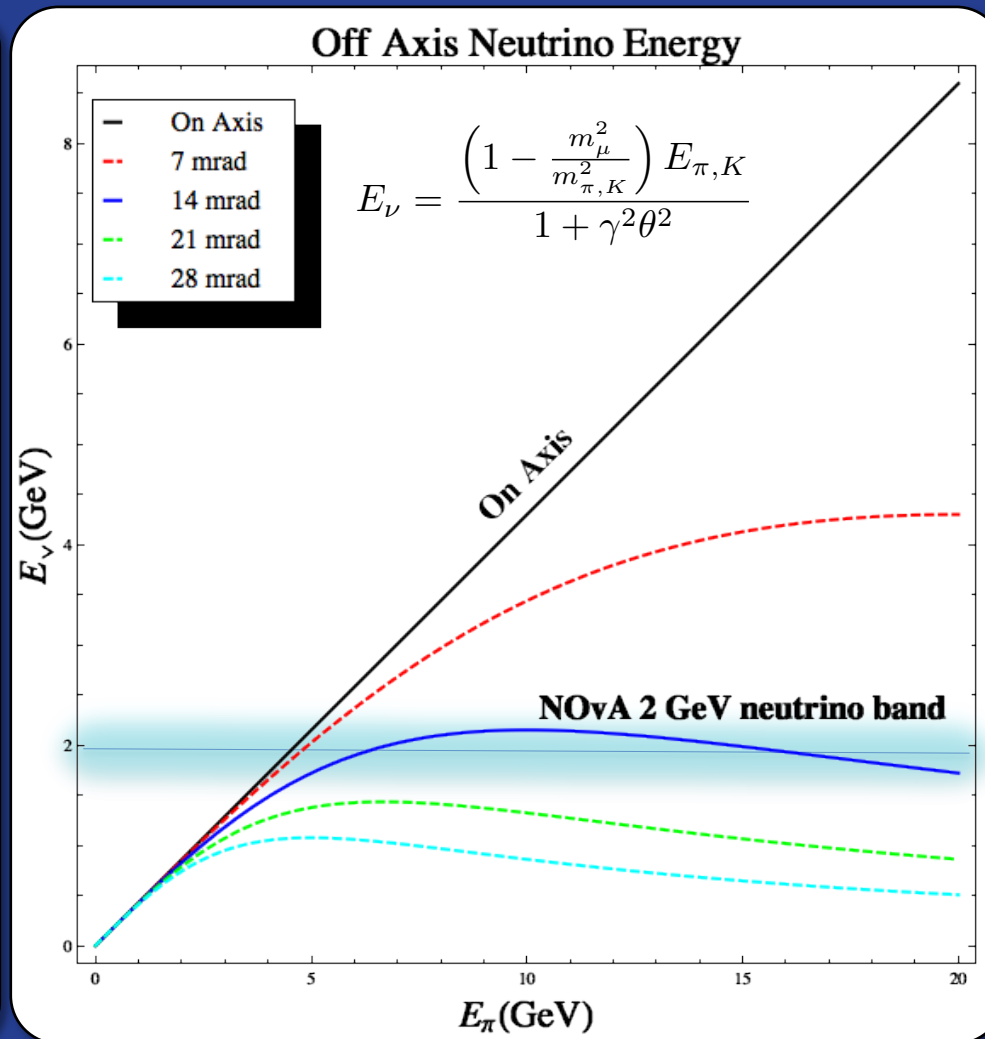
In the pion rest frame the kinematics are all completely determined for the decay



But when we boost into the lab frame the neutrino's energy depends on the angle relative to the boost direction.



This ends up projecting the neutrino energy spectrum down to be almost flat.



Off Axis Far Det. ν Spectrum

Off-Axis Flux

- Moving off-axis, the flux is reduced as:

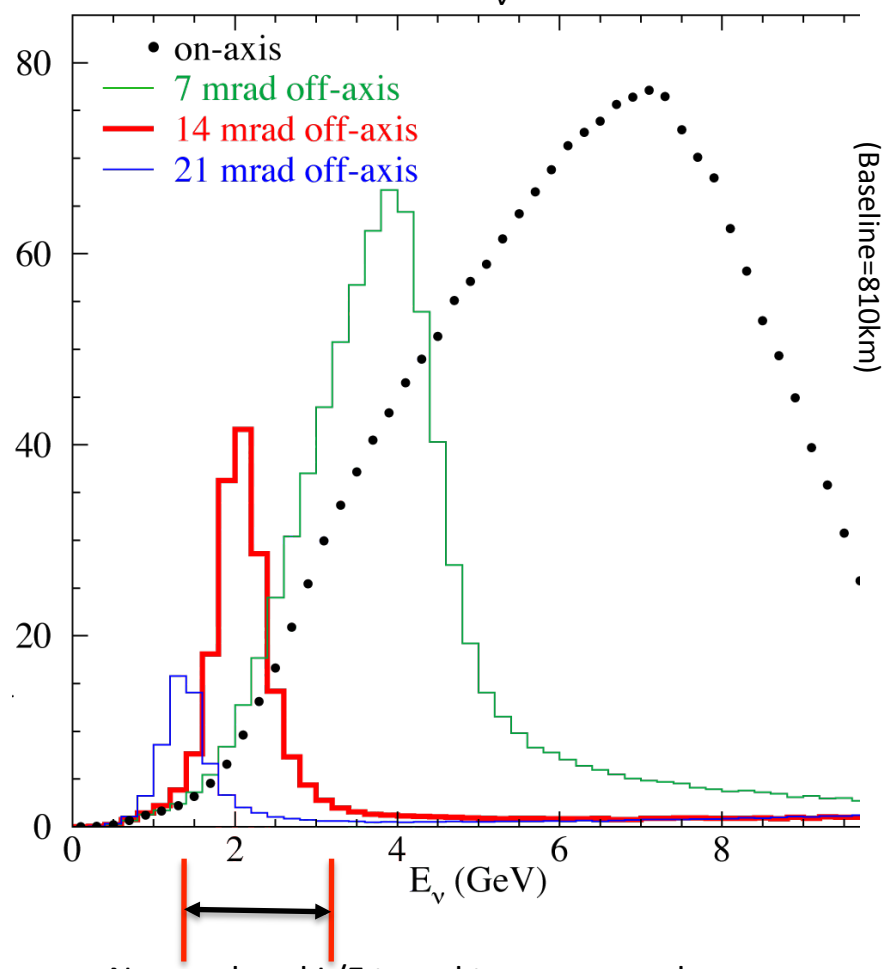
$$F = \left(\frac{2\gamma}{1+\gamma\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

- But the resulting neutrino energy spectrum flattens out (tightens) as:

$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1+\gamma^2\theta^2}$$

- For NOvA, moving 14 mrad off axis yields a narrows band beam
  - peaked at 2GeV
  - with E_ν width ≈20%
- The detector technology, geometry and baseline are then tuned to give:
  - L/E for 1st Oscillation Maximum
  - Energy resolution for ν_μ CC events ≈4%
  - High efficiency EM shower reconstruction in sub 2GeV region

Far Detector Flux × σ_ν



Narrow band L/E tuned to correspond to the first 1 Oscillation Maximum

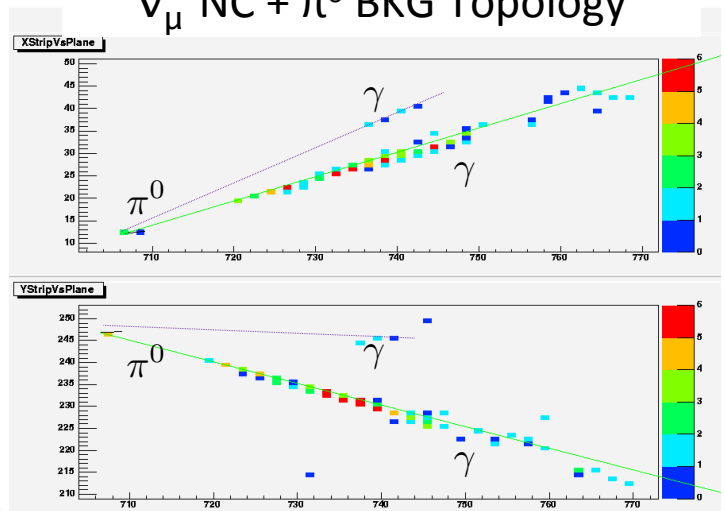
Advantage of Going Off-Axis

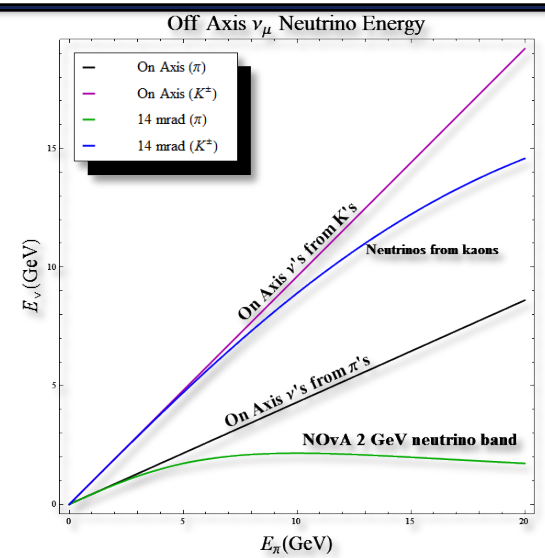
- To Make the ν_e appearance measurement you need to suppress backgrounds
  - Main background for the ν_e CC event topology is a ν_μ NC event with a π^0 that is not fully reconstructed
  - Off-axis projection (narrow energy band) suppresses the high energy NC tail
  - Other backgrounds are the intrinsic ν_e component of the beam (e.g. $K^\pm \to \pi^0 e^\pm \nu_e$) which are small (but so is θ_{13}) which get projected off the energy band.
- To improve the θ_{23} disappearance measurement:
  - Significantly reduces the backgrounds from kaons ($K^\pm \to \mu^\pm \nu_\mu$) by shifting the neutrino energy to a different band

$$(E_{\nu_\mu})_K = \frac{0.96 E_K}{1+\gamma^2\theta^2}$$

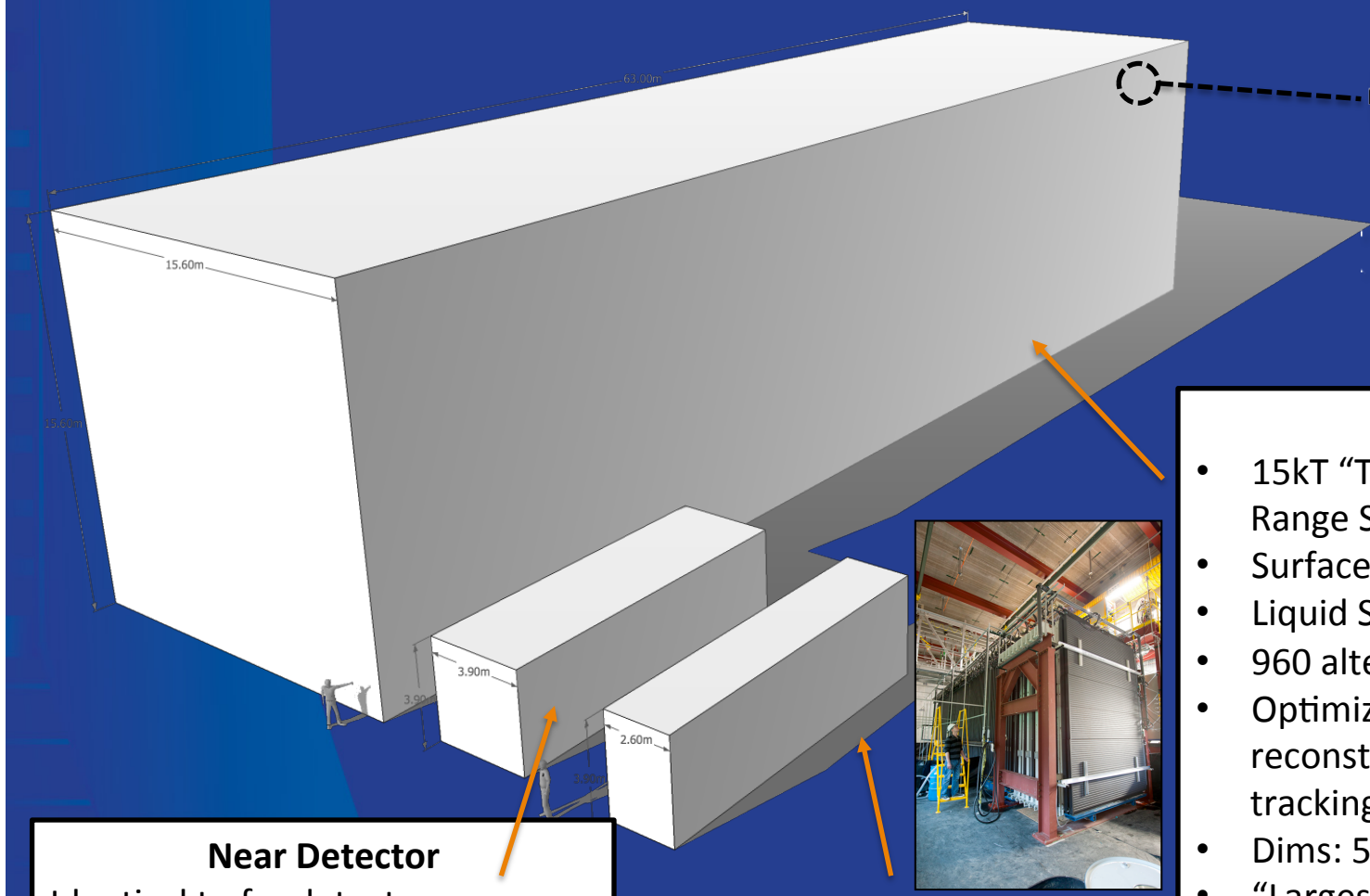
  - Resulting neutrino peak is primarily from π decays
  - Energy spectrum in the signal region becomes almost insensitive to the π/K ratio

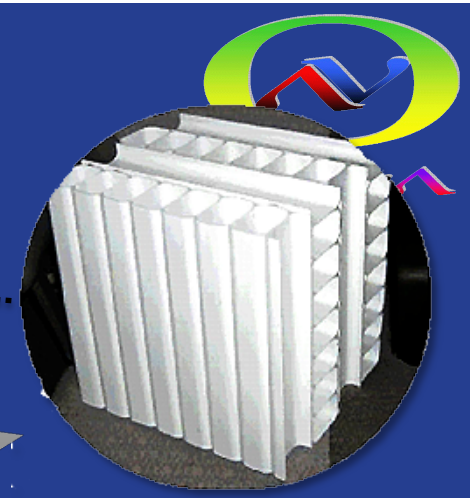
ν_μ NC + π^0 BKG Topology





NOvA Detectors





Near Detector

Identical to far detector
1:4 scale size
Underground Detector
Optimized for NuMI cavern rates
-- 4x sampling rate electronics

Near Det. Protype

In operation 2010-Present on surface at FNAL in NuMI and Booster beam line

Far Detector

- 15kT "Totally Active", Low Z, Range Stack/Calorimeter
- Surface Detector
- Liquid Scintillator filled PVC
- 960 alternating X-Y planes
- Optimized for EM shower reconstruction & muon tracking, $X_0 \approx 40$cm, $R_m \approx 11$cm
- Dims: 53x53x180ft
- "Largest Plastic Structure built by man"
- Began construction May 2012
- First operation est. Sep. 2012 (cosmics)

NOvA Detectors are BIG

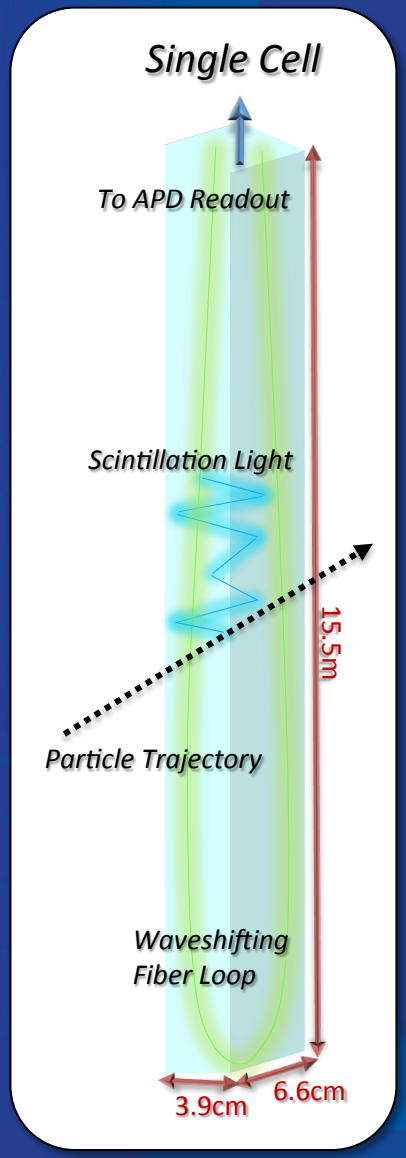
Near Detector
Identical to far detector
1:4 scale size
Underground Detector
Optimized for NuMI cavern rates
-- 4x sampling rate electronics

Near Det. Protype
In operation 2010-Present on surface at FNAL in NuMI and Booster beam line

Airbus A380-800

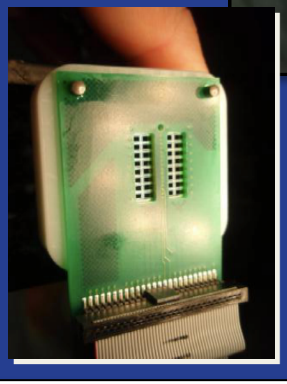
- Similar size to NOvA
- Only 560 tons
- Not totally active
- Unable to measure θ_{13}
- Can not resolve θ_{23} ambiguity
- Optimized for fuel economy and passenger capacity
- Capacity: 853 passengers
- Cost: $389M/ea
- "Largest commercial aircraft built by man"
- Construction start 2004
- First operation Oct. 2007 (Singapore Airlines)

The Readout Cell



NOvA Detection Cell

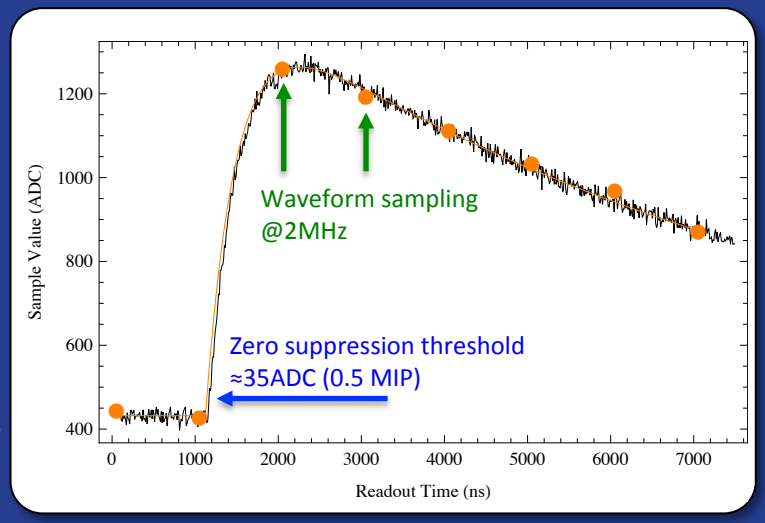
- The base detector unit 3.9x6.6cm cell 15.5m long, filled with a mineral oil based liquid scintillator.
- Passage of MIP through the cell (longitudinal to beam)
  results in dE/dx ≈12.9 MeV across the cell.
  - Roughly 10% of energy loss is in the PVC wall
  - Yields 10-12MeV of deposition in the scint.
- The measured light output is 30-38 p.e. from the far end of the cell into the APD readout
- Light yield gives a minimum Sig/Noise 10:1 (far end)



Waveshifting fiber readout and 32pixel APD used for cell digitization

- Signal is amplified and shaped
- Channel is continuously sampled at 2MHz to obtain wave form
- Zero suppression is performed at (0.5-0.66) MIP (15-20 p.e.) via a dual correlated sampling (dcs) algorithm
- Results in a single cell, lower energy detection threshold of ≈6-8MeV (far end)

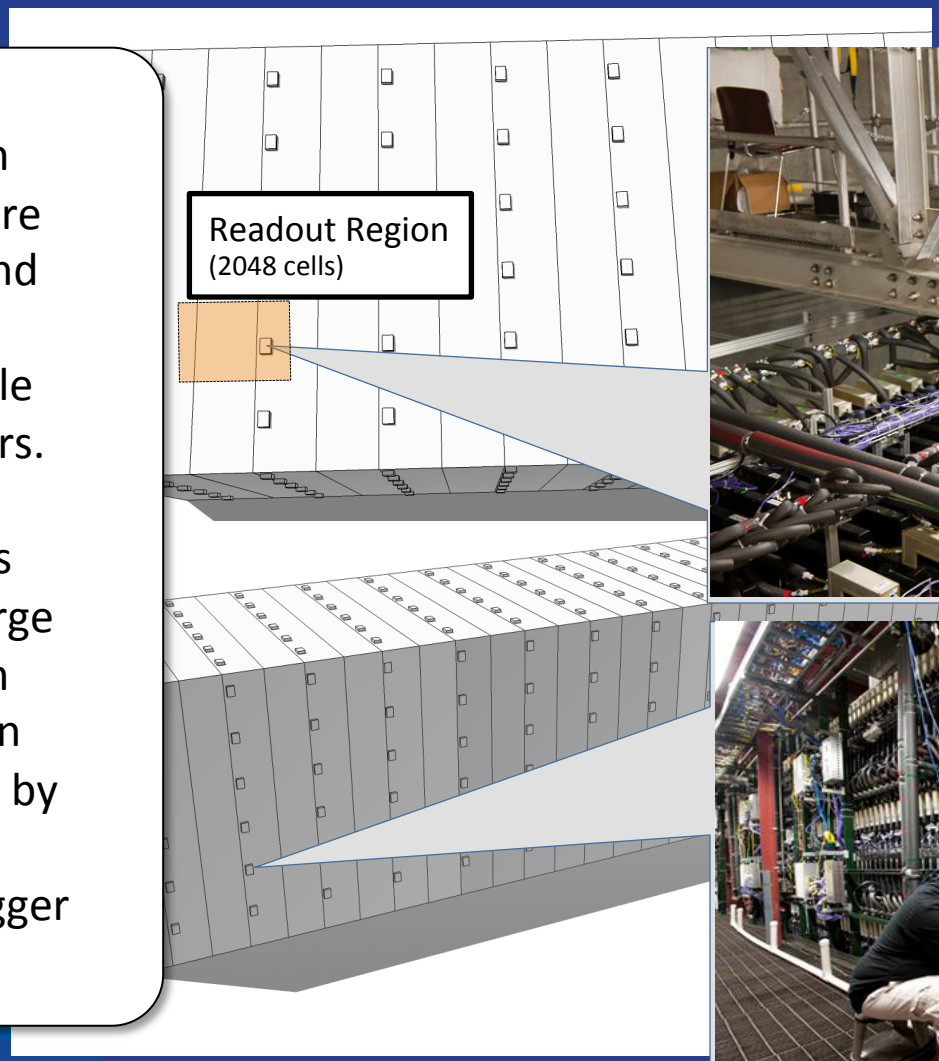
- Fits to the shape of the waveform recover the timing and pulse height information

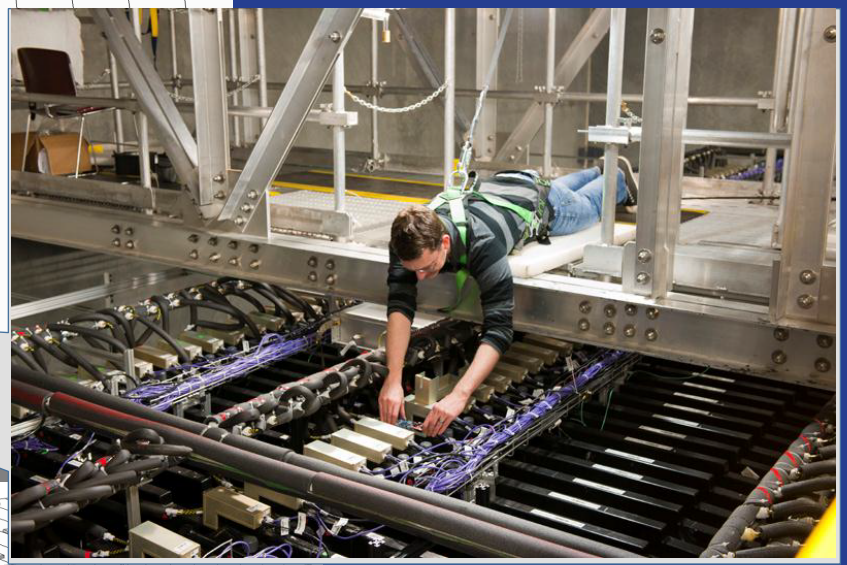


Instrumented Detector

The detector is instrumented in regions which are synchronized and ***CONTINOUSLY*** readout by single board computers.

All of the data is buffered in a large computing farm and triggered on asynchronously by the DAQ and Accelerator Trigger Systems.





Instrumented Detector

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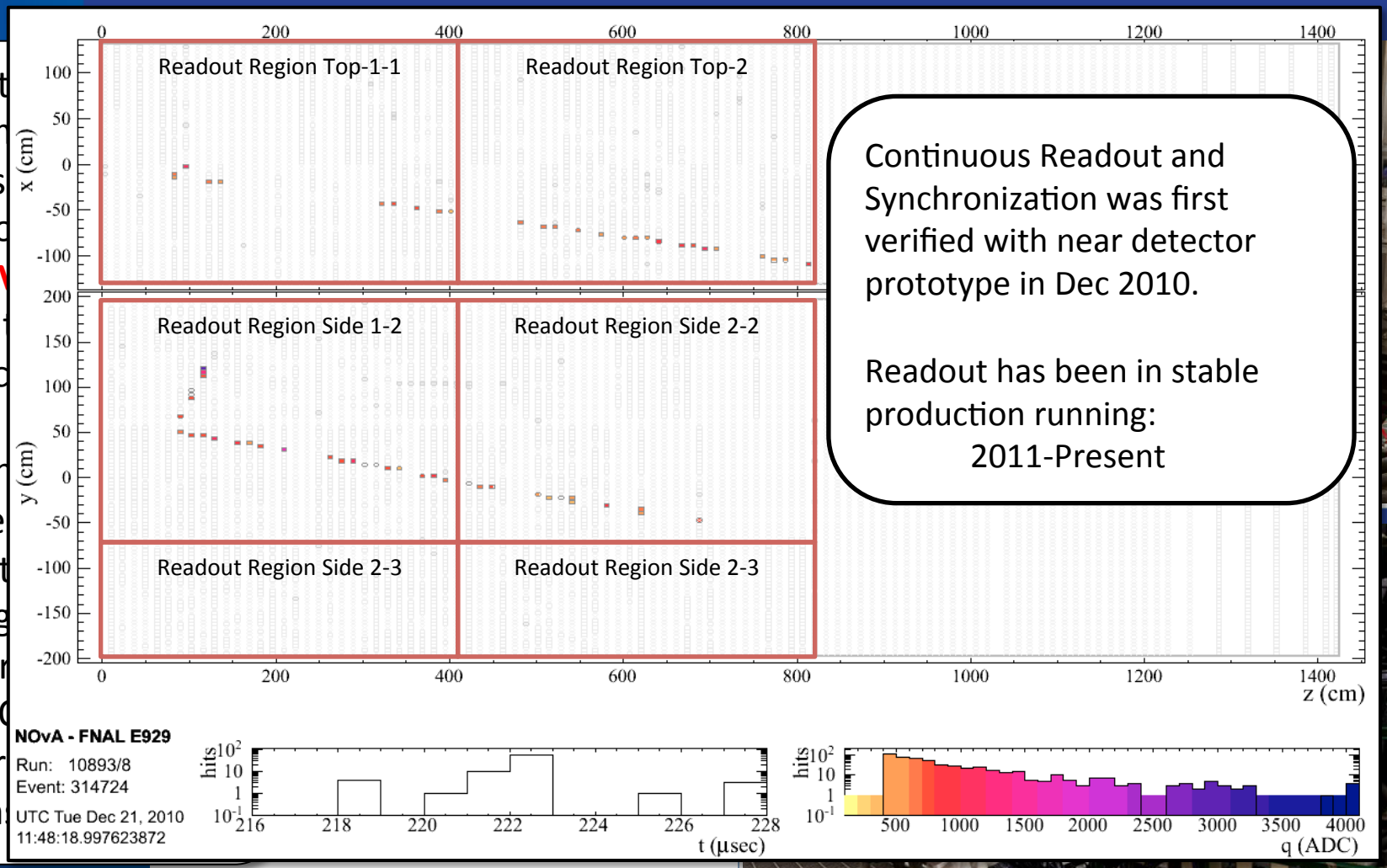
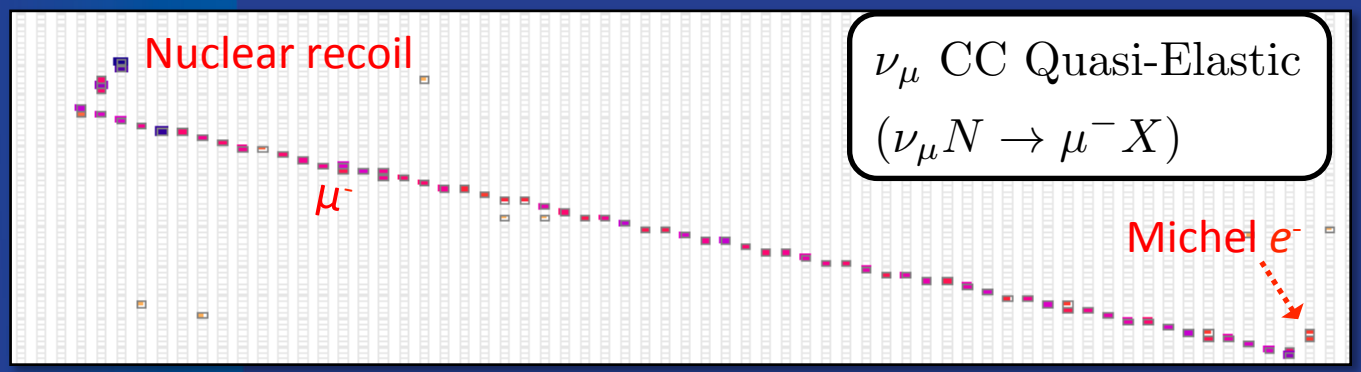


Continuous Readout and Synchronization was first verified with near detector prototype in Dec 2010.

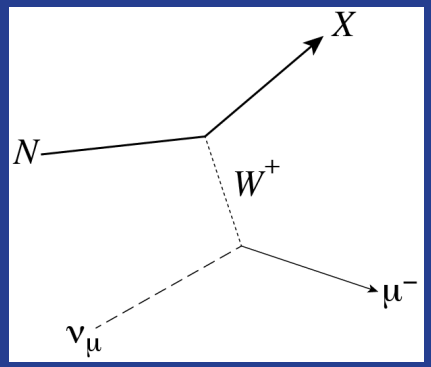
Readout has been in stable production running:
2011-Present

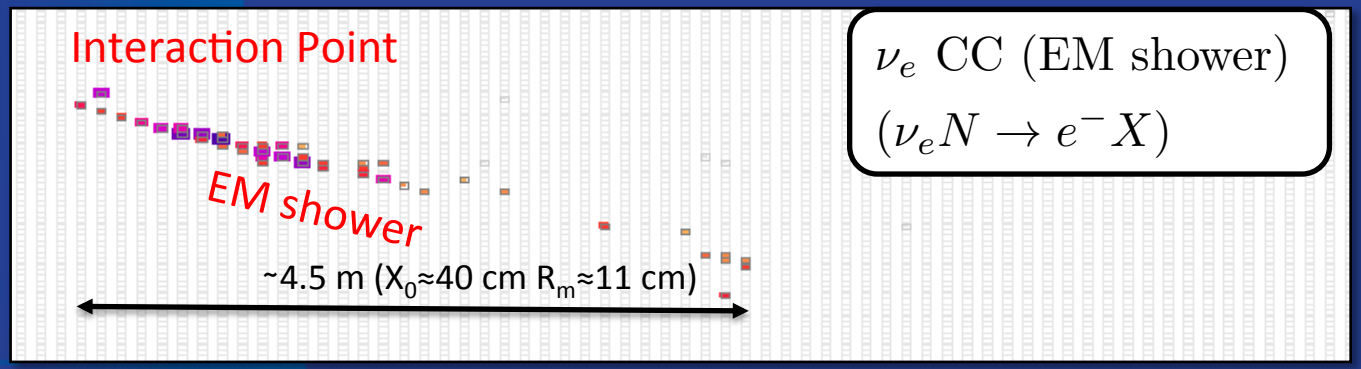
Neutrino Event Topologies



ν_μ CC Quasi-Elastic

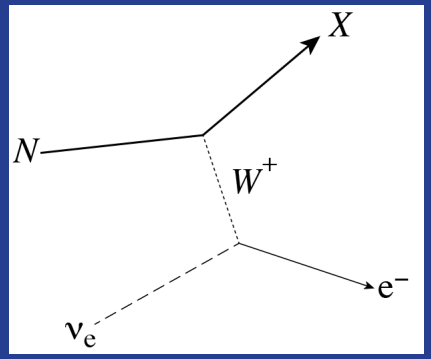
$(\nu_\mu N \to \mu^- X)$

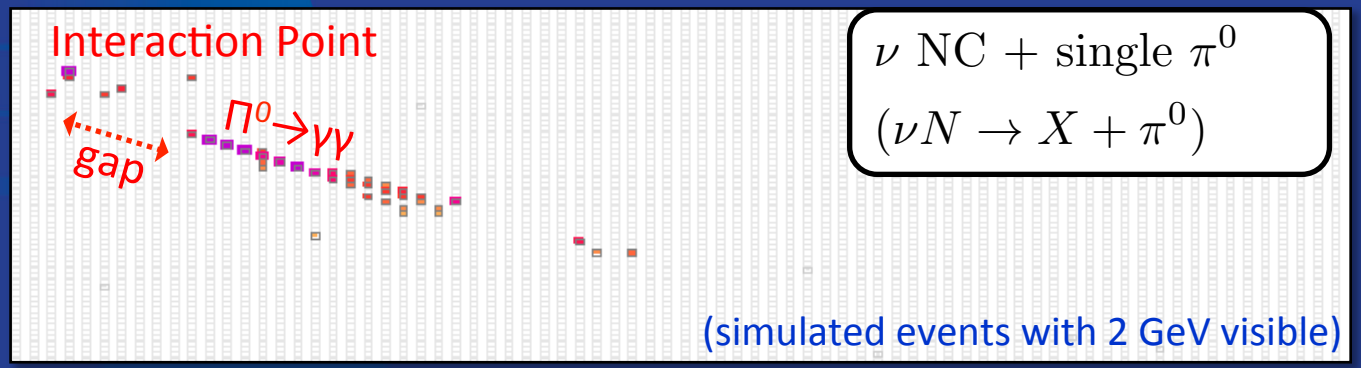




ν_e CC (EM shower)

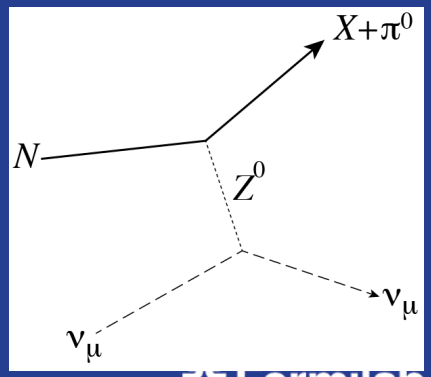
$(\nu_e N \to e^- X)$



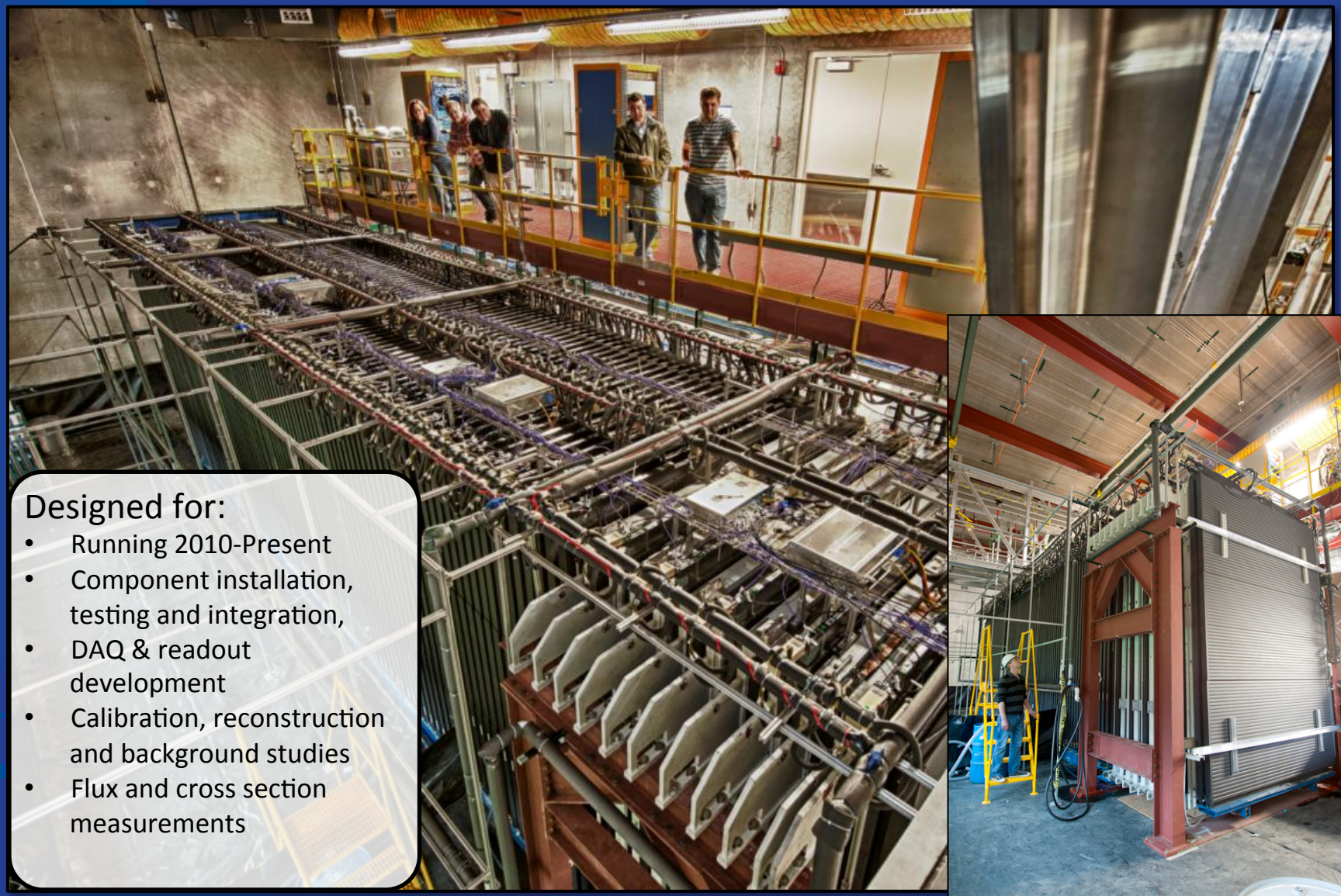


ν NC + single π^0

$(\nu N \to X + \pi^0)$



Prototype Near Detector (2010-2012)



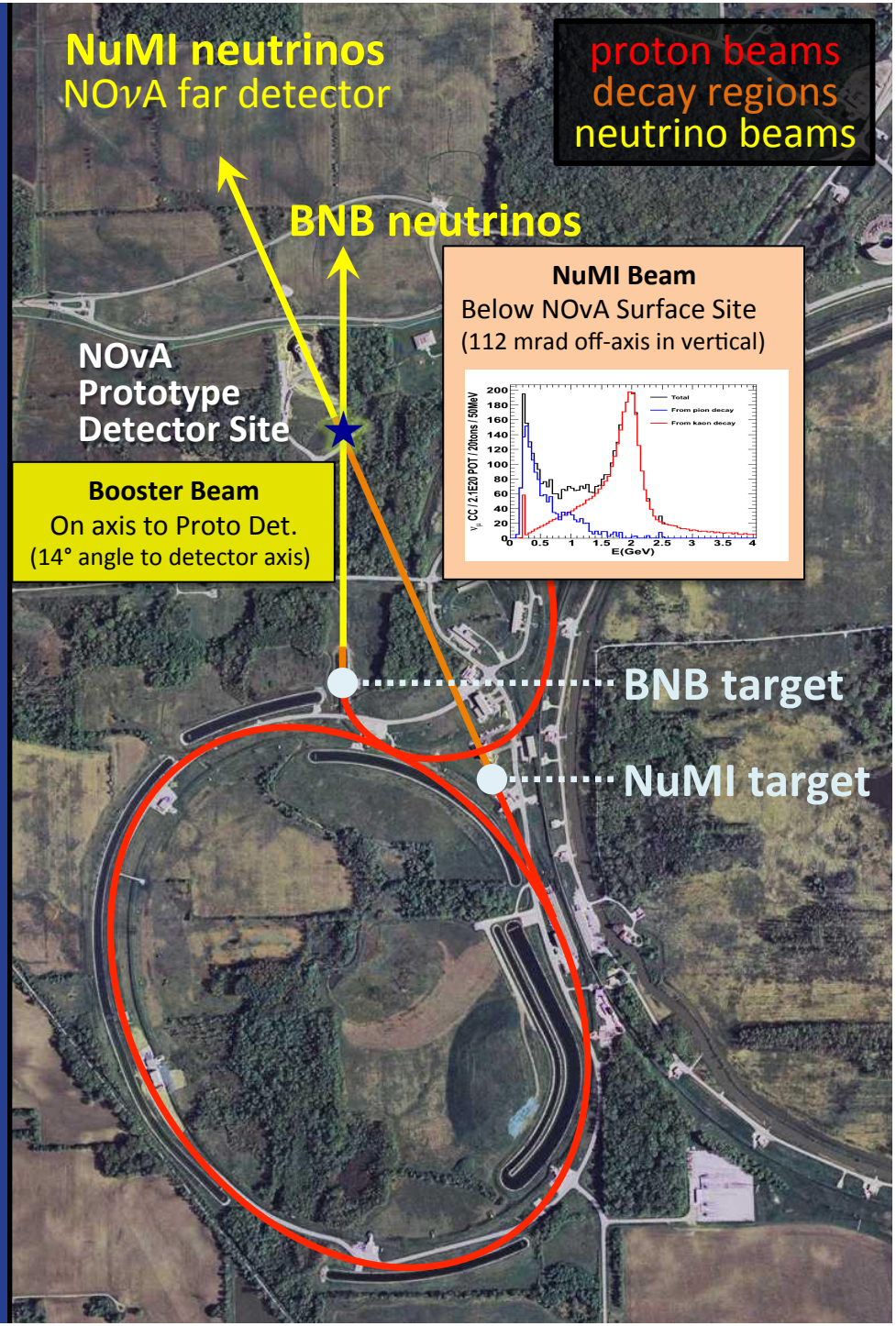
Designed for:

- Running 2010-Present
- Component installation, testing and integration,
- DAQ & readout development
- Calibration, reconstruction and background studies
- Flux and cross section measurements

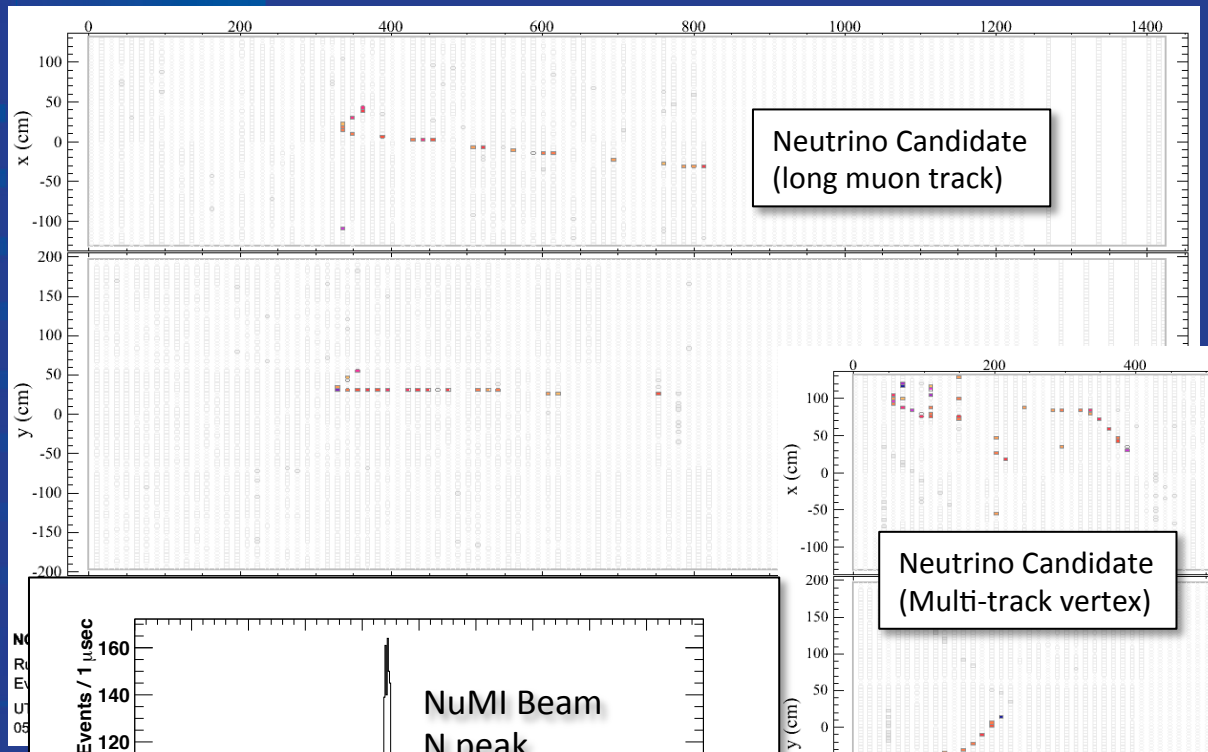
Prototype Near Detector Site & Beams

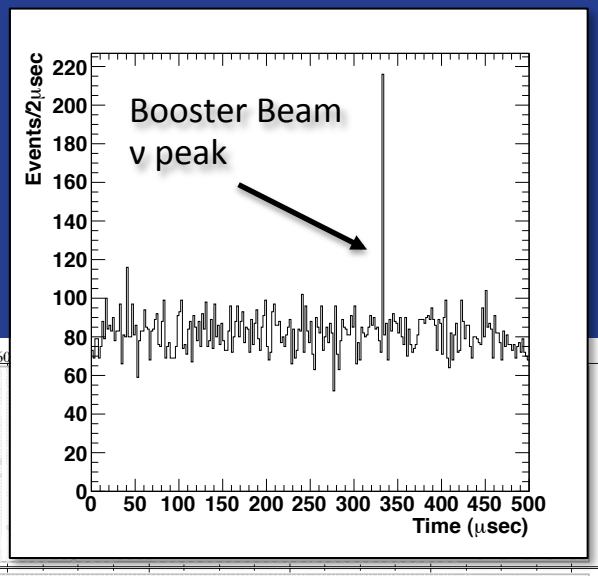
- The prototype near detector site was chosen at a unique location where it can see significant flux from both:
  - the 120 GeV NuMI ν beam
  - the 8 GeV booster ν beams
- This allows for a "neutrino test beam"
  - Can measure different fluxes
  - Beam time structures
  - Low energy detector response

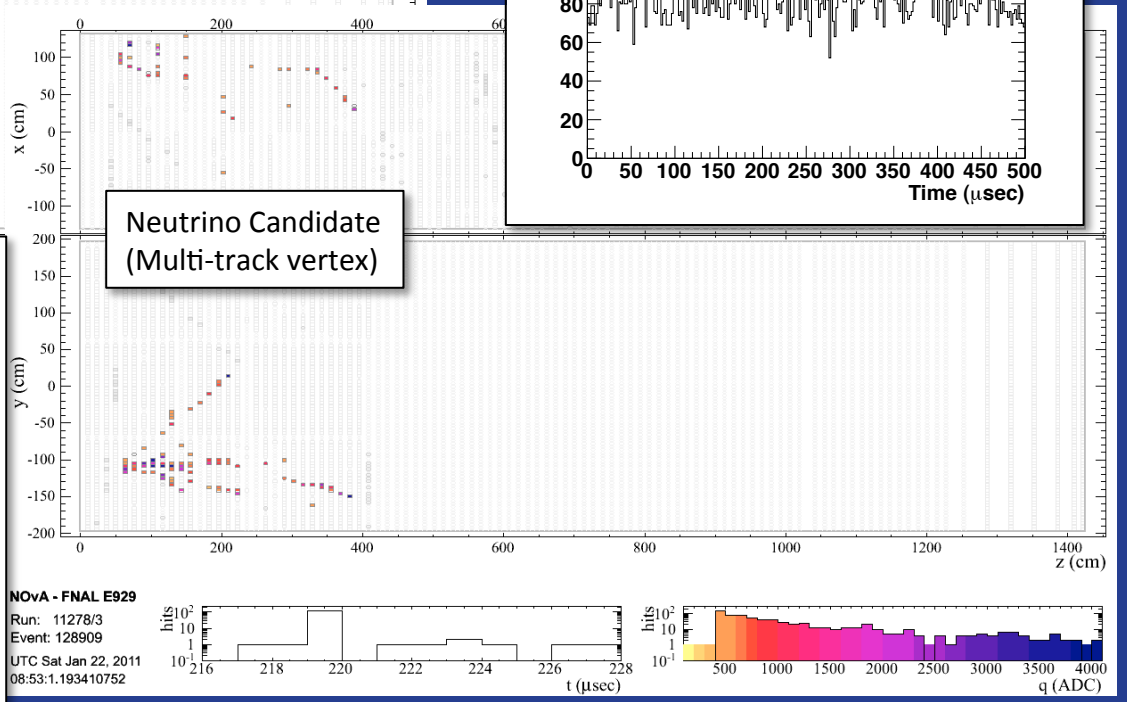
Prototype Near Detector Building

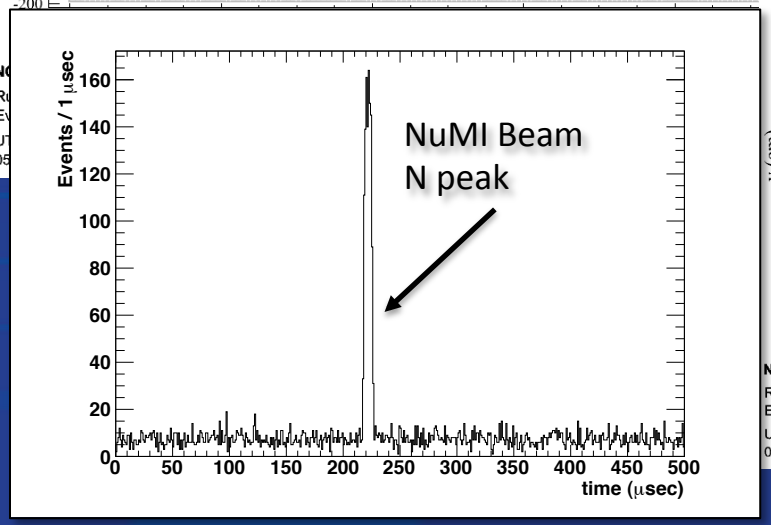


Prototype Detector Data

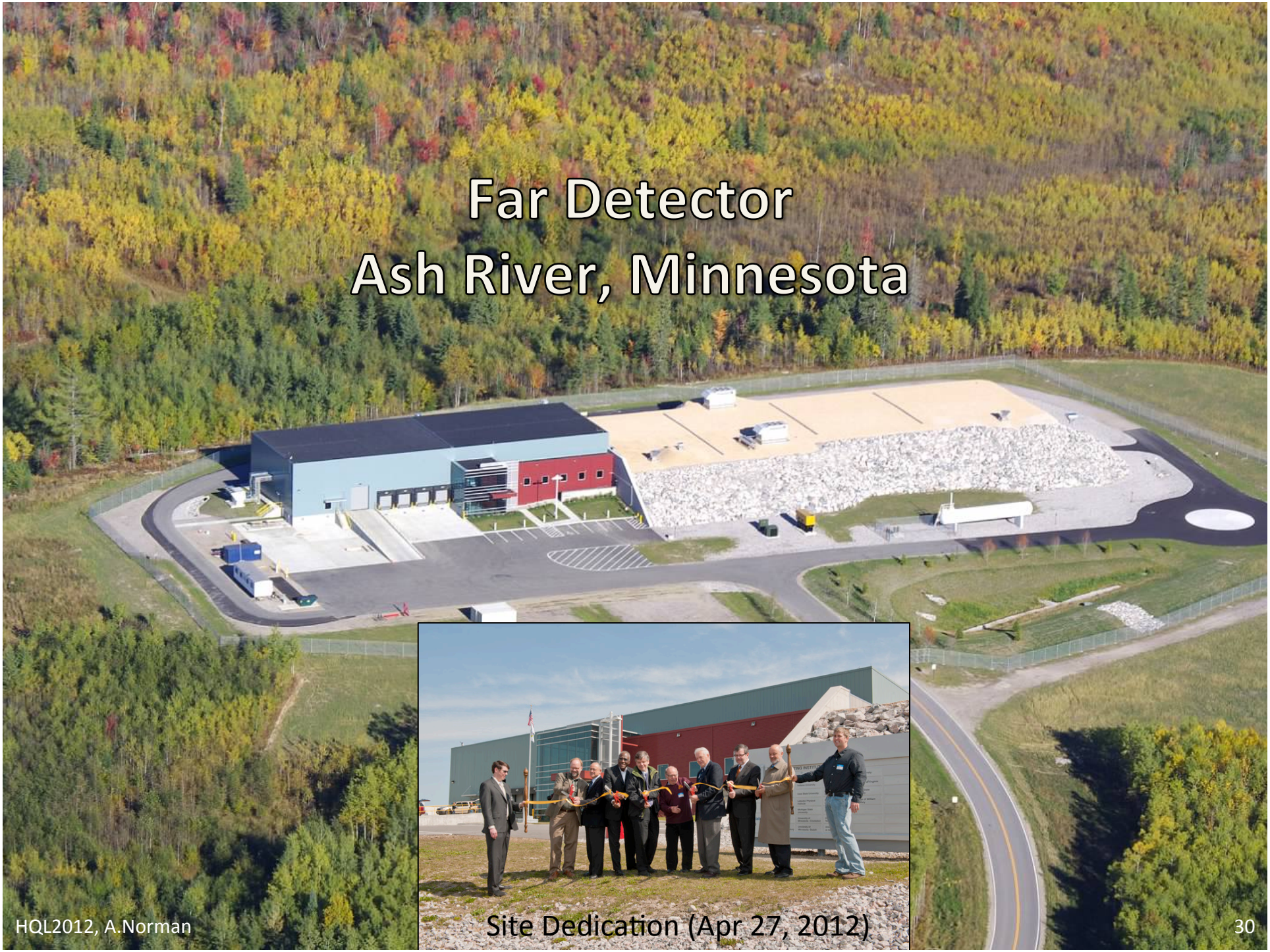








Far Detector
Ash River, Minnesota



Site Dedication (Apr 27, 2012)

Far Detector Hall

Far Detector Hall

Detector Construction Slide 3

U. Minnesota Module Factory (200+ students)

Ash River Detector Construction

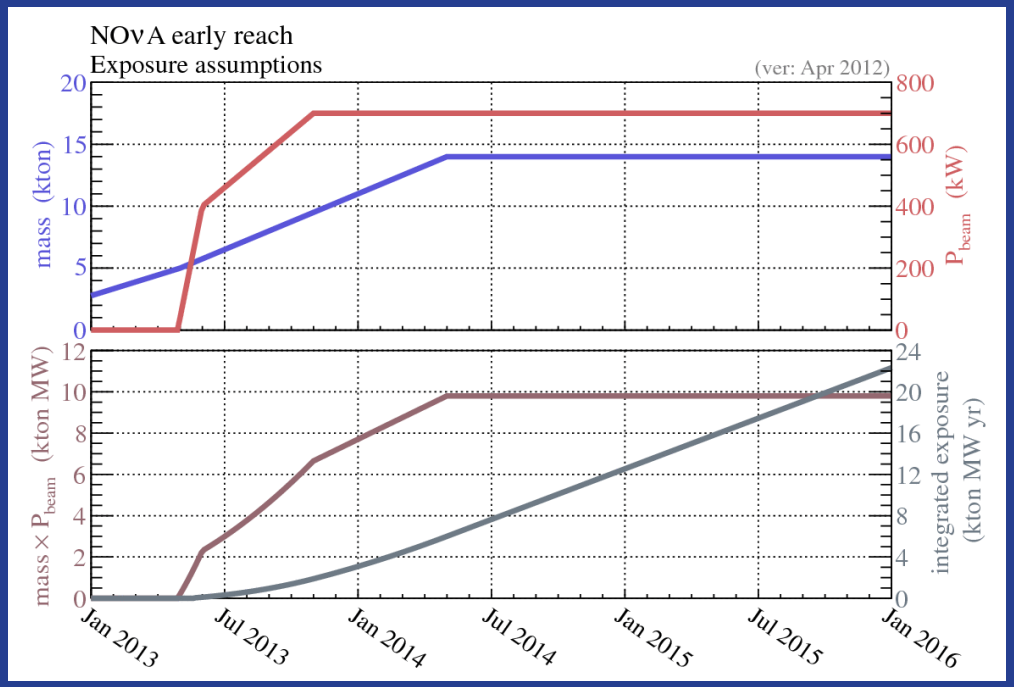
Accelerator Upgrades

Upgrading the FNAL accelerator complex to double the beam power

- NuMI (Neutrinos at the Main Injector) beam power increase from 350 kW to 700 kW
- Year-long FNAL accelerator shutdown started May 1, 2012
- Converts Recycler from antiproton to proton ring
- Shortens Main Injector spill cycle from 2.2 s to 1.33 s
- Upgrades NuMI target station for 700 kW running

Beam returns April/May 2013

- 5kT of detector mass operational
- Beam power ramps to full 700kW over 6 months
- Integrated exposure of 1 (kT MW yr) reached in first six months



The Future

- The latest values for θ_{13} will allow the NOvA program to make precision that will expand our understanding of the neutrino sector.
- The FNAL accelerator upgrade is underway
- The NOvA detectors are under construction
- We will see our first neutrino events in the Far Det. next spring
- We are exploring new analysis and reconstruction methods allow the first NOvA analysis to surpass the sensitivities shown today.

5/15/2012: Detector plane 1 dry stack

NOvA

ADDITIONAL MATERIAL