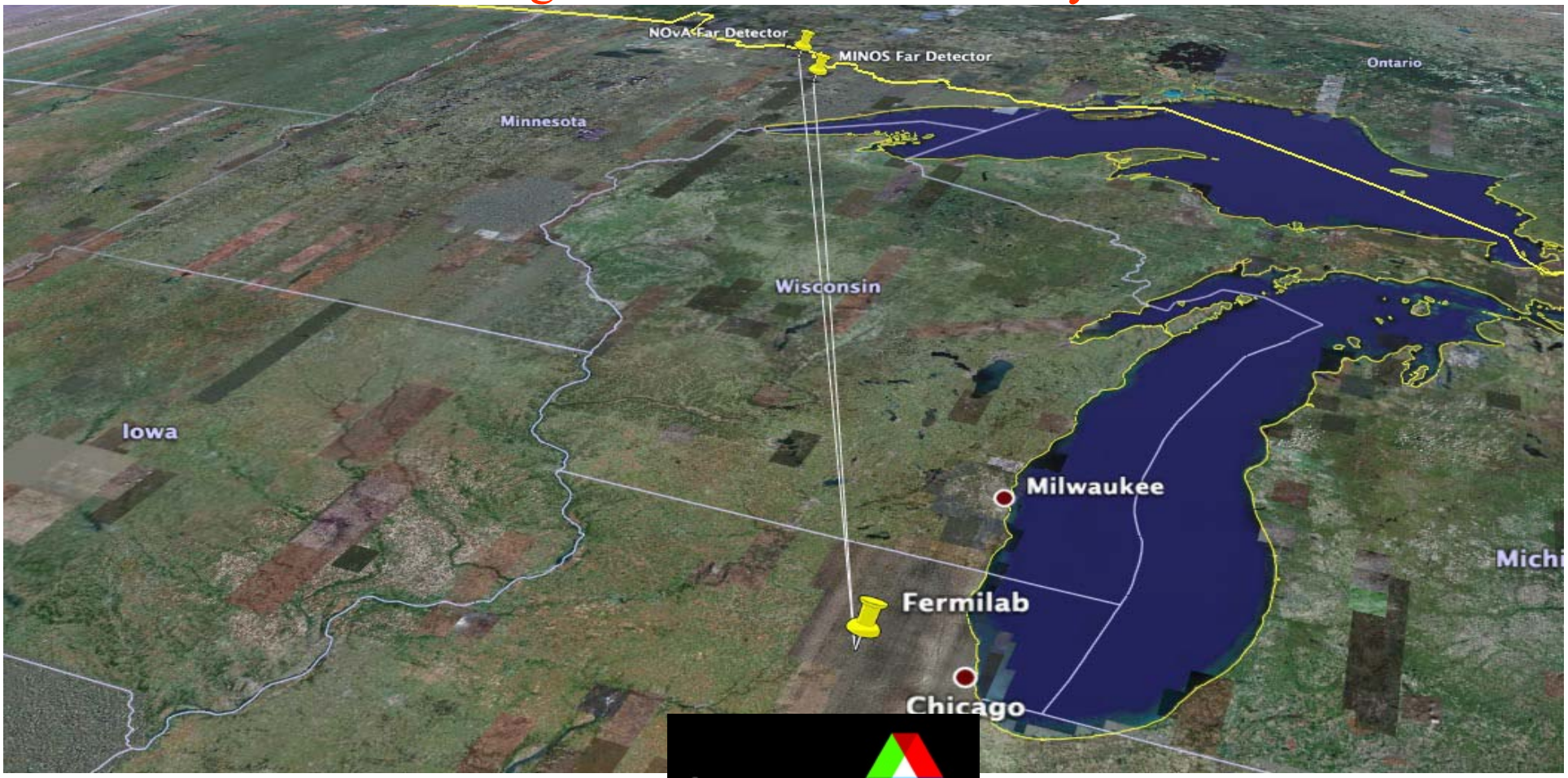
Status of the NOνA Experiment

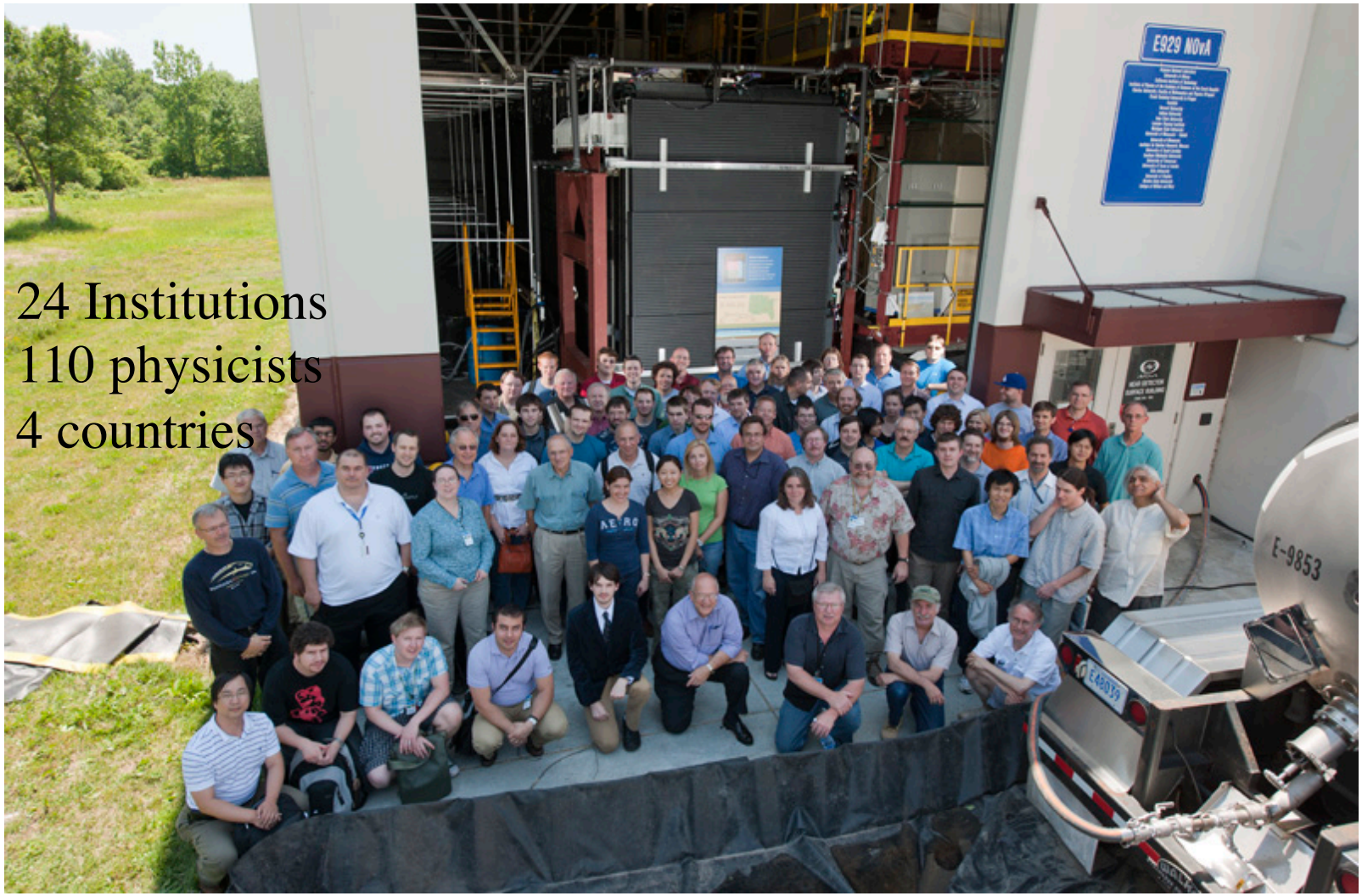
Zelimir Djurcic
Argonne National Laboratory



Argonne NATIONAL LABORATORY

15th Lomonosov Conference on Elementary Particle Physics, August 18 – 24, Moscow, Russia

The NOvA Collaboration



24 Institutions
110 physicists
4 countries

Argonne, Athens, Caltech, Institute of Physics of the Czech Republic, Charles University, Czech Technical University, FNAL, Harvard, Indiana, Iowa State, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/Twin Cities, INR Moscow, South Carolina, SMU, Stanford, Tennessee, Texas/Austin, Tufts, Virginia, WSU, William and Mary.

Neutrino Oscillations: Standard 3-Flavor Picture

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small\,? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

What is the value of θ_{13},δ_{CP} ?

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

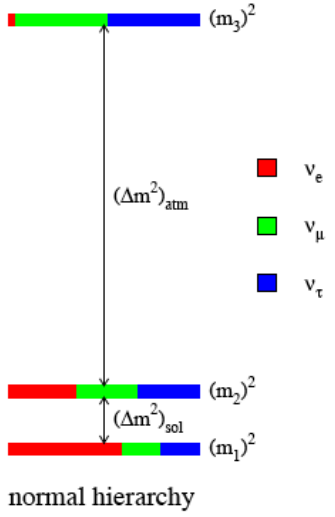
$\theta_{12} \sim 30°$ $\quad \sin^2 2\theta_{13} < 0.11$ at 90% CL $\quad \theta_{23} \sim 45°$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)^2}\Delta_{31}^{\,2}$$

$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^{\,2}$$

$$+ \cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$

$$+ \sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)$$



normal hierarchy

-NOνA is NuMI Off-Axis ν_e Appearance Experiment.

-Physics Goals:

- Search for oscillations $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

  -Measure θ_{13}

  -Constrain δ_{CP}

  -Determine neutrino mass hierarchy

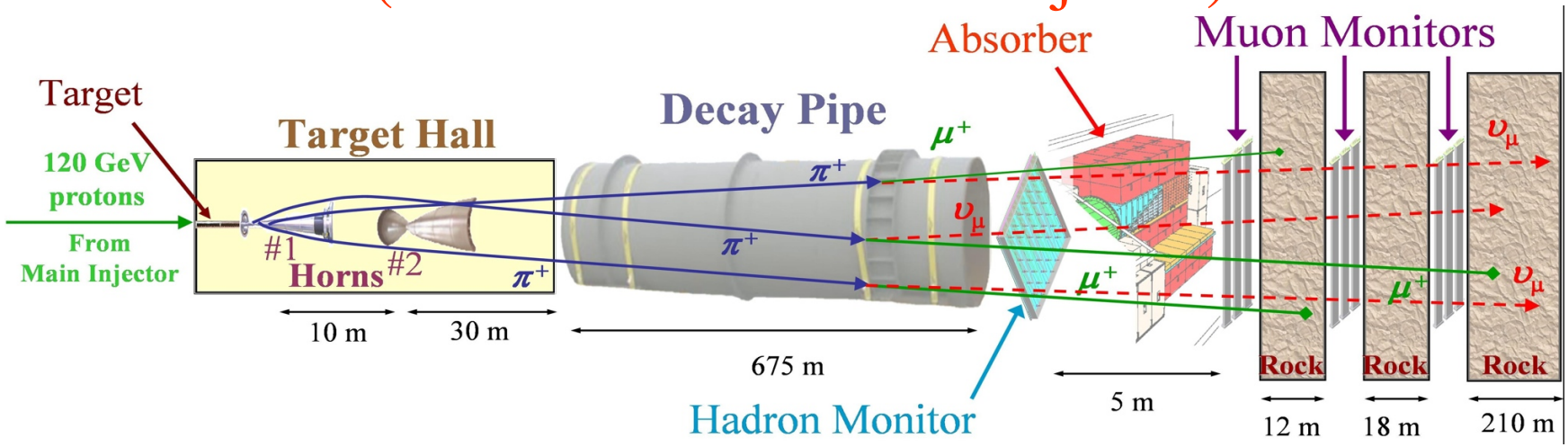
- Precision measurements of Δm^2_{32}, θ_{23}.

-NOνA will be using NuMI neutrino beam from Fermilab to Ash River in Minnesota (810km baseline).

-NOνA is two detector experiment where near detector is used to predict events in far detector.

-Near and Far detector functionally identical.

NuMI (Neutrinos at the Main Injector) Beam



-Beam spectrum tunable by horn currents, relative placement of target and horns.

-Can select ν or $\bar{\nu}$ predominant beam depending on horn current polarity.

-10μs beam spill (every 2.2 sec).

-Operating since 2005 (MINOS, MINERvA, ArgoNEUT)

-Routinely delivers 280-300kW beam power.

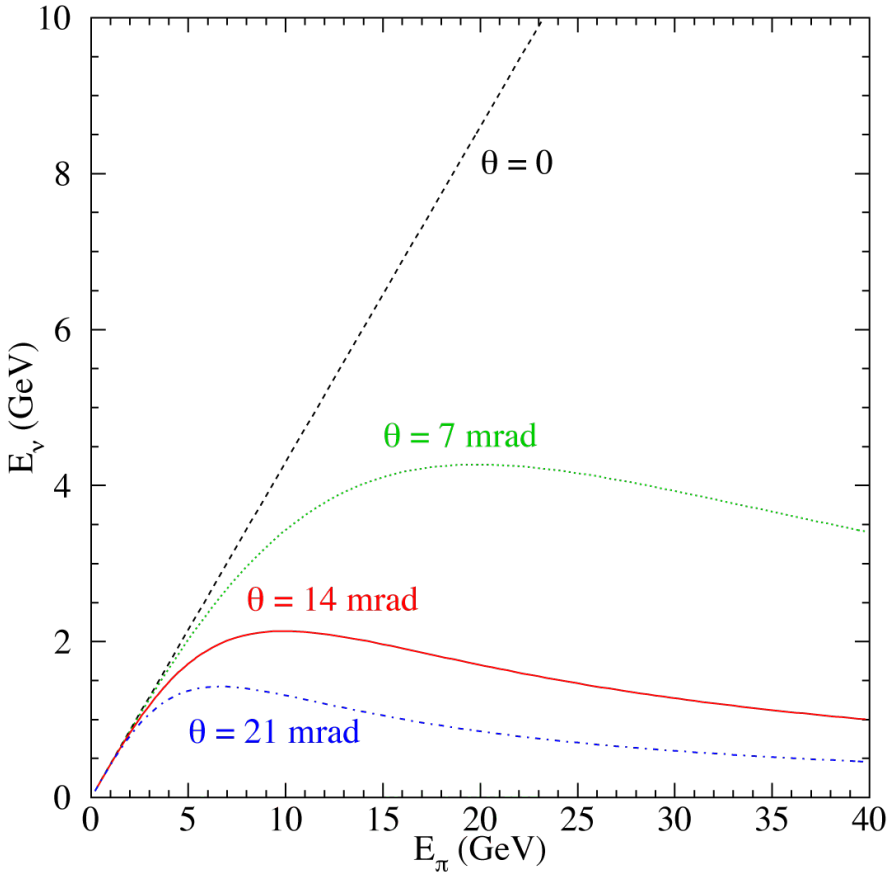
-Most operations to-date in "Low Energy" mode optimized for MINOS on-axis location.

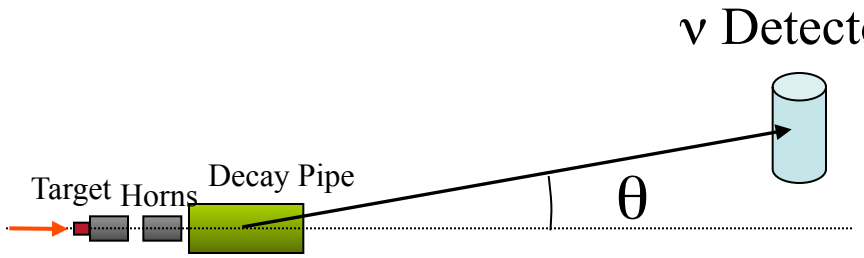
Future: -700 kW power to NuMI using existing accelerator complex.
-Reduce cycle time from 2.2 to 1.33 seconds.

NOνA uses an Off-Axis Beam

-On-axis, neutrino energy more tightly related to hadron energy.
-Off-axis, neutrino spectrum is narrow-band and "softened".
-Easier to estimate flux correctly: all mesons decay to ≈ same E_ν.

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





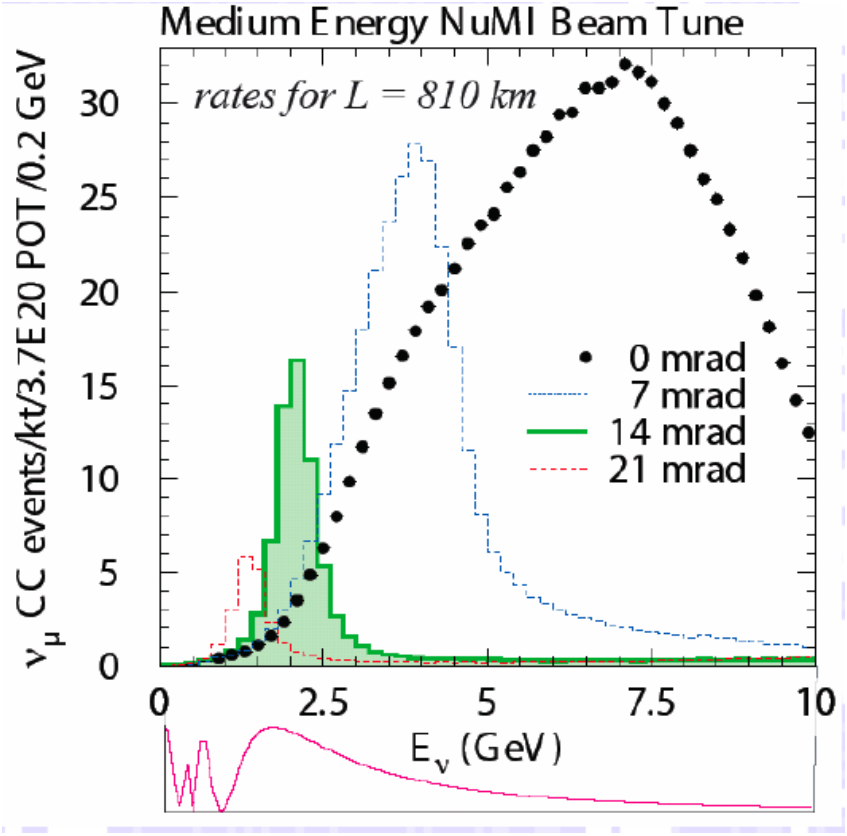
NOνA uses an Off-Axis Beam

-More flux near oscillation maximum

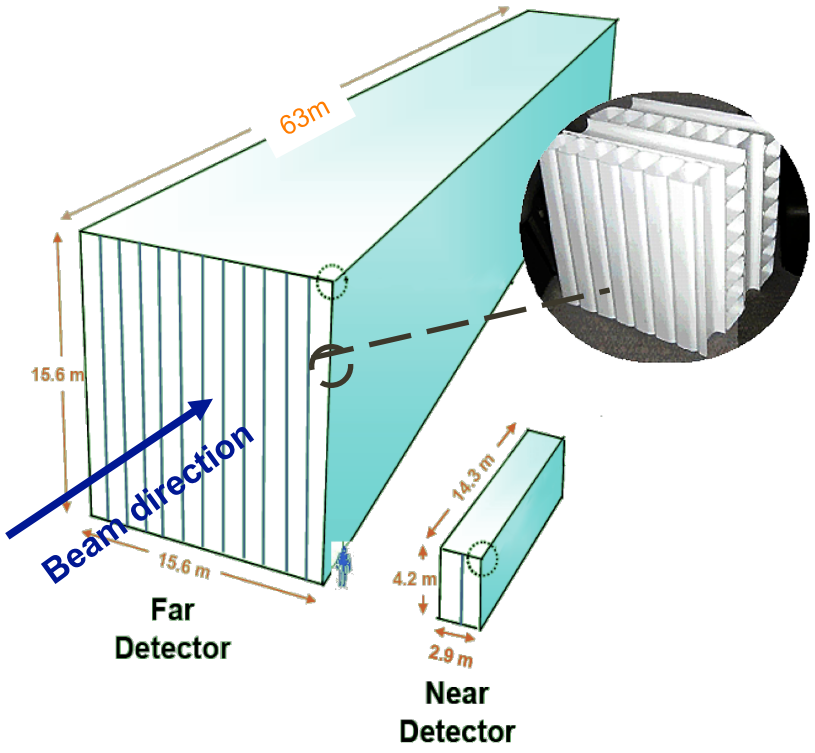
-Reduction of high energy tail reduces NC background.

-Concentration of ν_e from oscillation relative to intrinsic beam ν_e (from 3-body K and μ decay).

-NOνA will use Medium Energy NuMI Configuration (MINOS mostly used Low Energy mode).



NOνA Detectors



Far Detector

-928 Planes (15.6 m x 15.6 m)
-14kTon
-About 360000 cells
-Cosmic Ray Muon Rate:
~200 kHz (2-3 m overburden)
-Neutrino Rate:
1400 ν_e beam events/year

Near Detector

-196 Planes (2.9 m x 4.2 m)
+10 Steel/Scint Plane Pairs (μ-Catcher)
-220 Ton
-16000 cells
-Cosmic Ray Muon Rate: About 50 Hz
(105 m overburden)
-Neutrino Rate:
10 μs spill duration every 1.33 s
30 neutrino events/spill

Detector Technology

-16-cell PVC extrusions (15% TiO_2).

Each NOvA cell:

3.9 cm x 6.0 cm x 15.6 m (FarDet)

~90% reflectivity at 430 nm

8 reflections on average

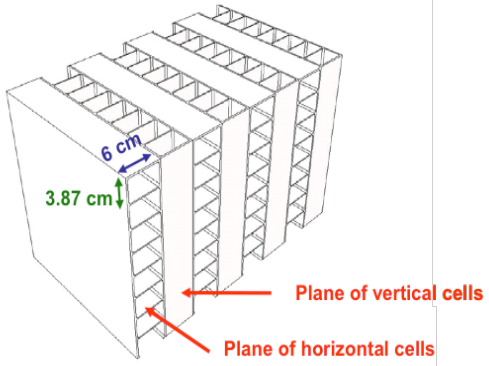
-About 360,000 cells (Far), ~16,000 (Near).

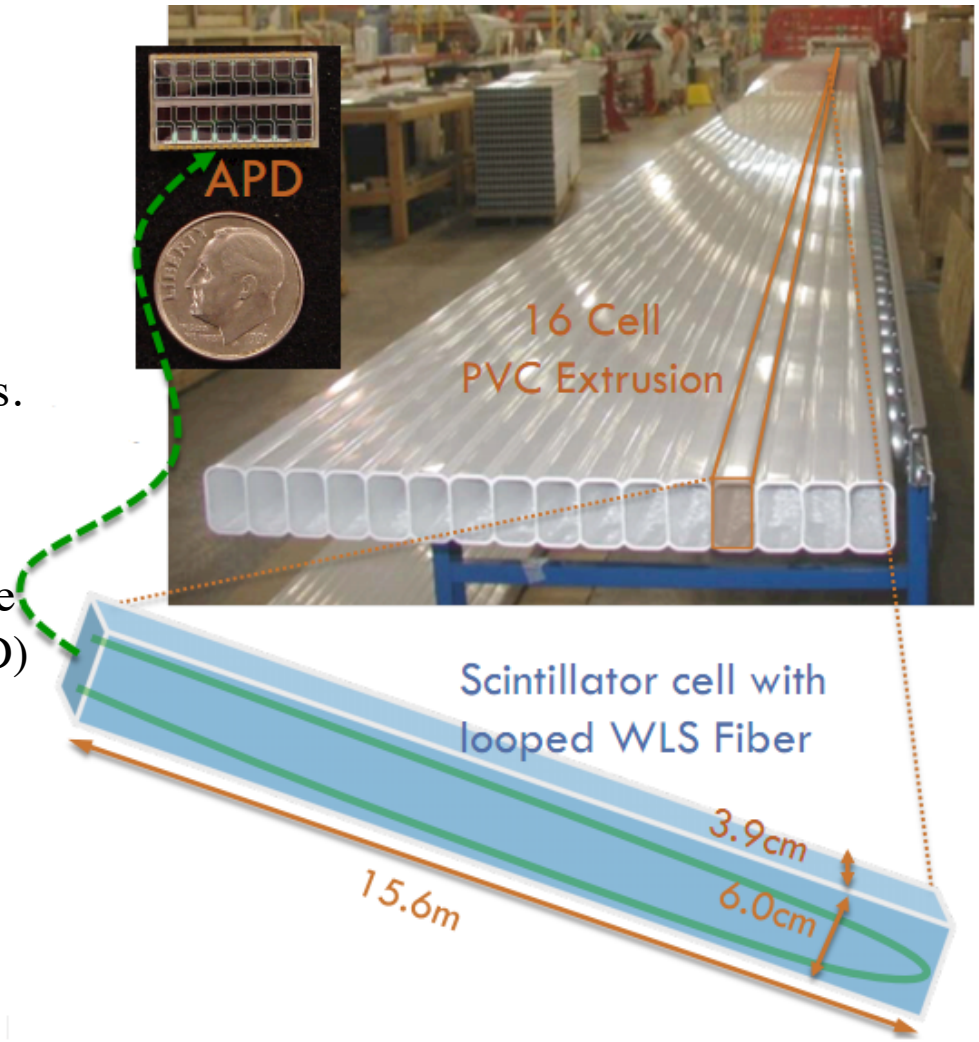
-32 in a sealed module. Alternating X/Y planes.

-Filled with liquid scintillator

mineral oil + ~5% pseudocumene

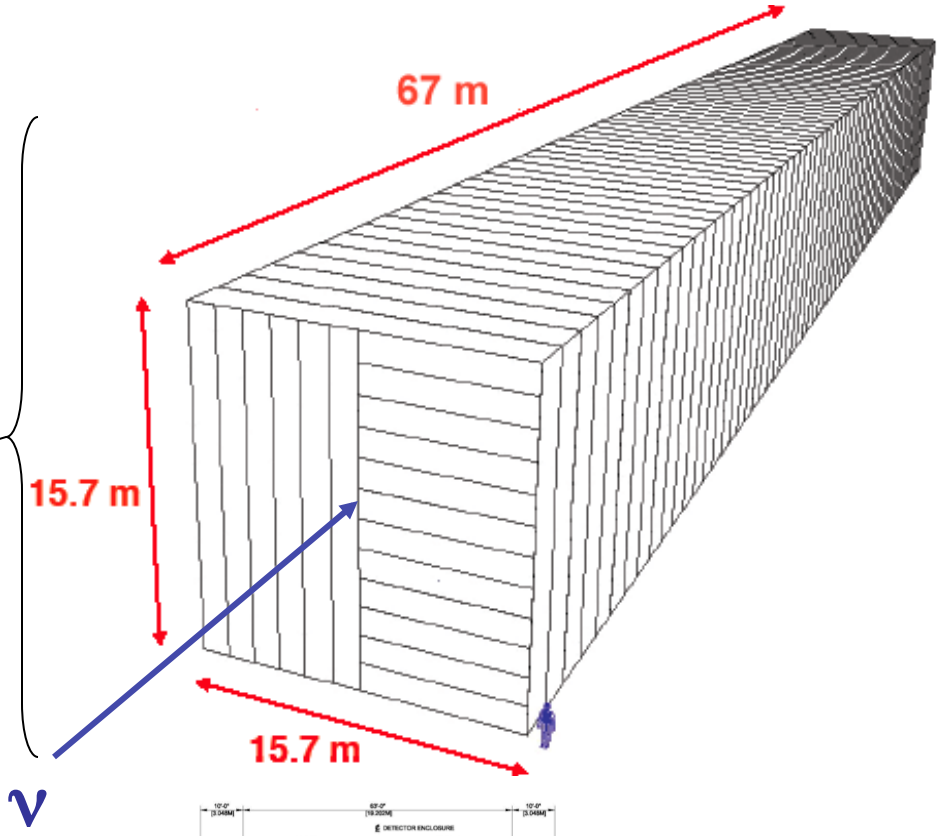
-Read out by wavelength-shifting fiber into one pixel of a 32-pixel avalanche photodiode (APD)

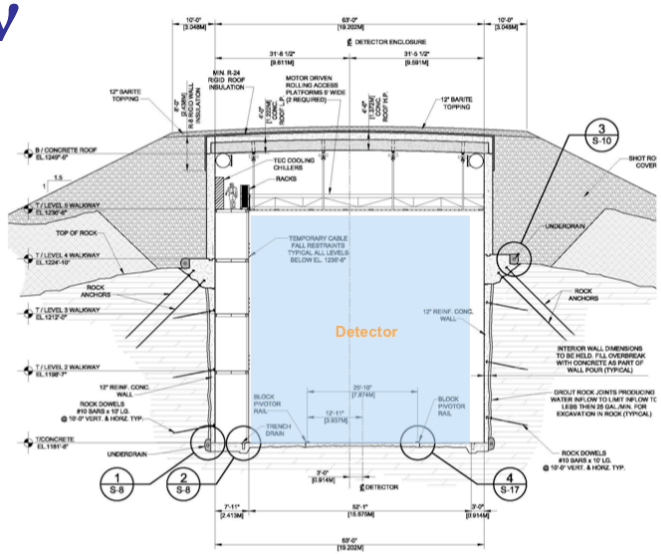




NOνA Far Detector Location

-810 km from Fermilab.
-14.6 mrad off-axis.

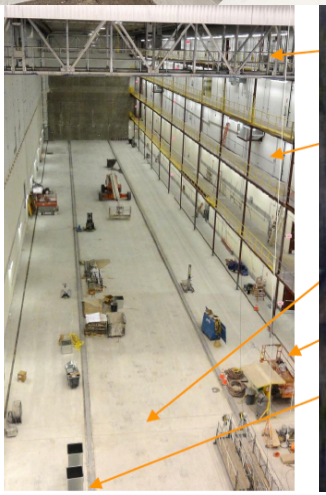




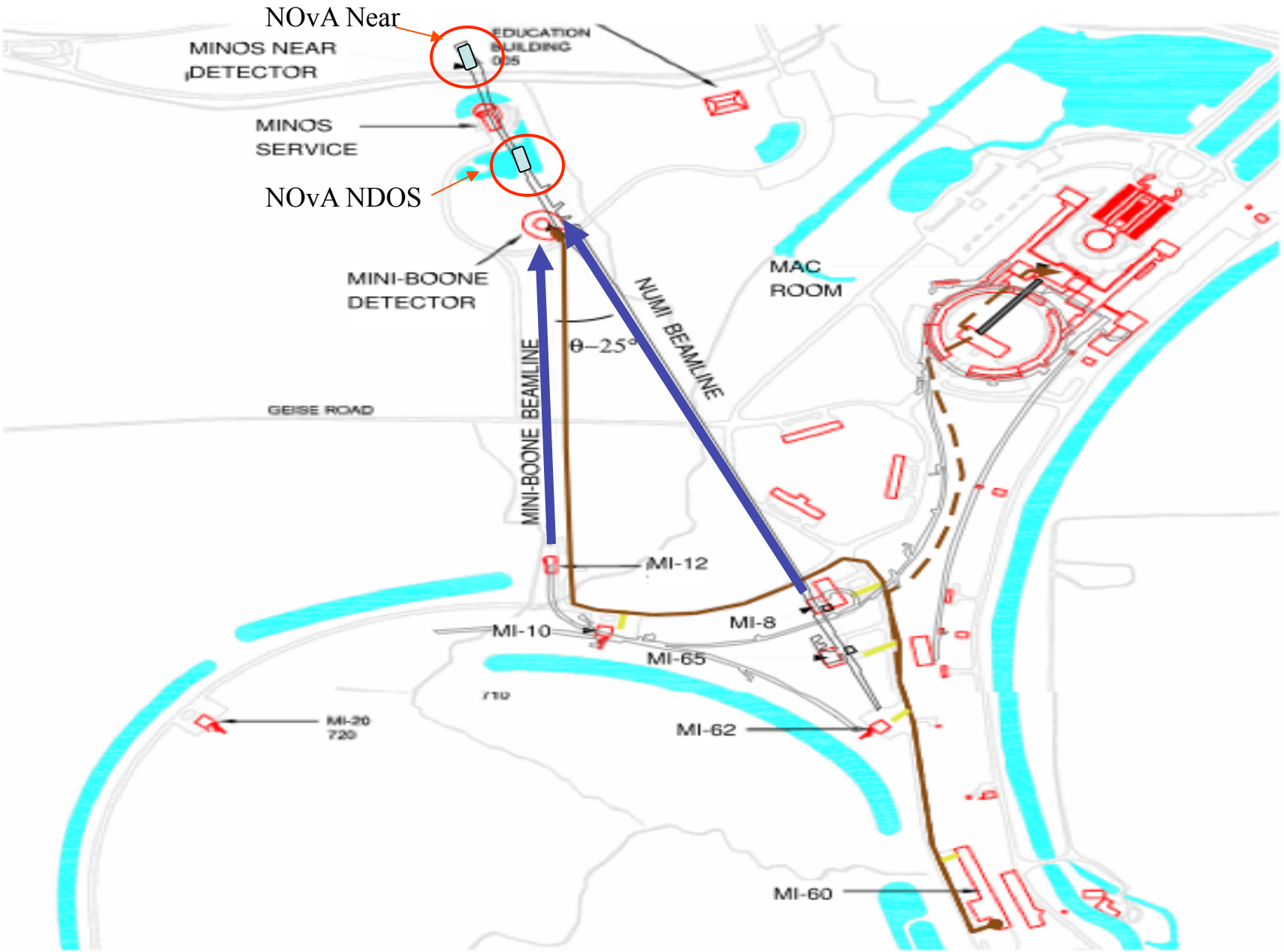
NOνA Far Detector Lab

-Far Detector laboratory is complete.

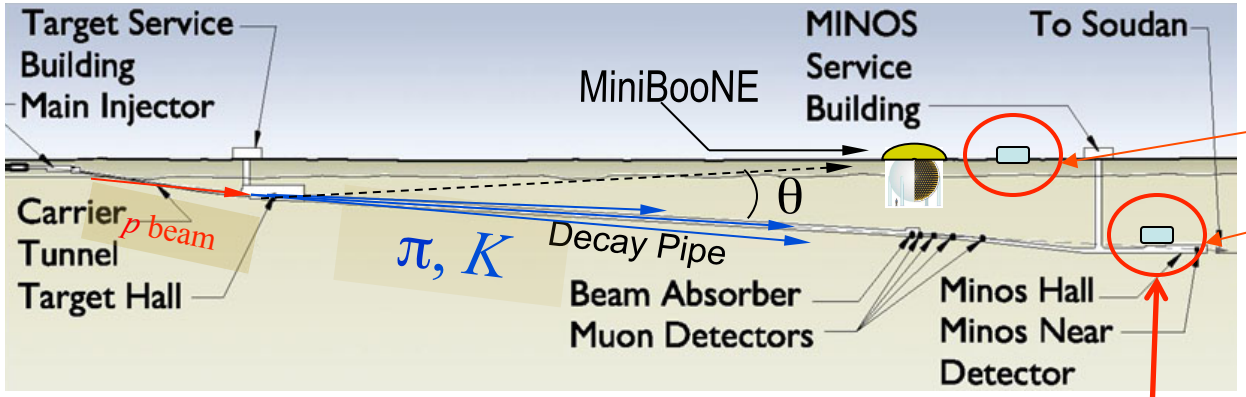
-Beneficial occupancy of Ash River laboratory: April 13th 2011.



NOvA near detector(s) and Fermilab Neutrino Beams

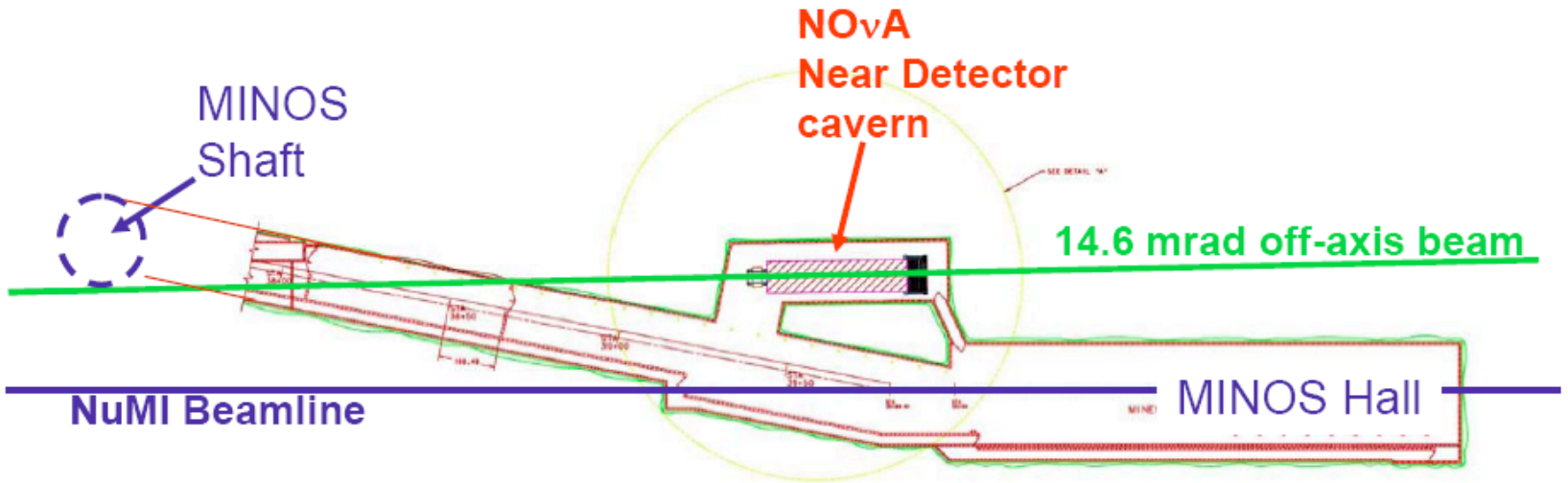


NOνA Near Detector

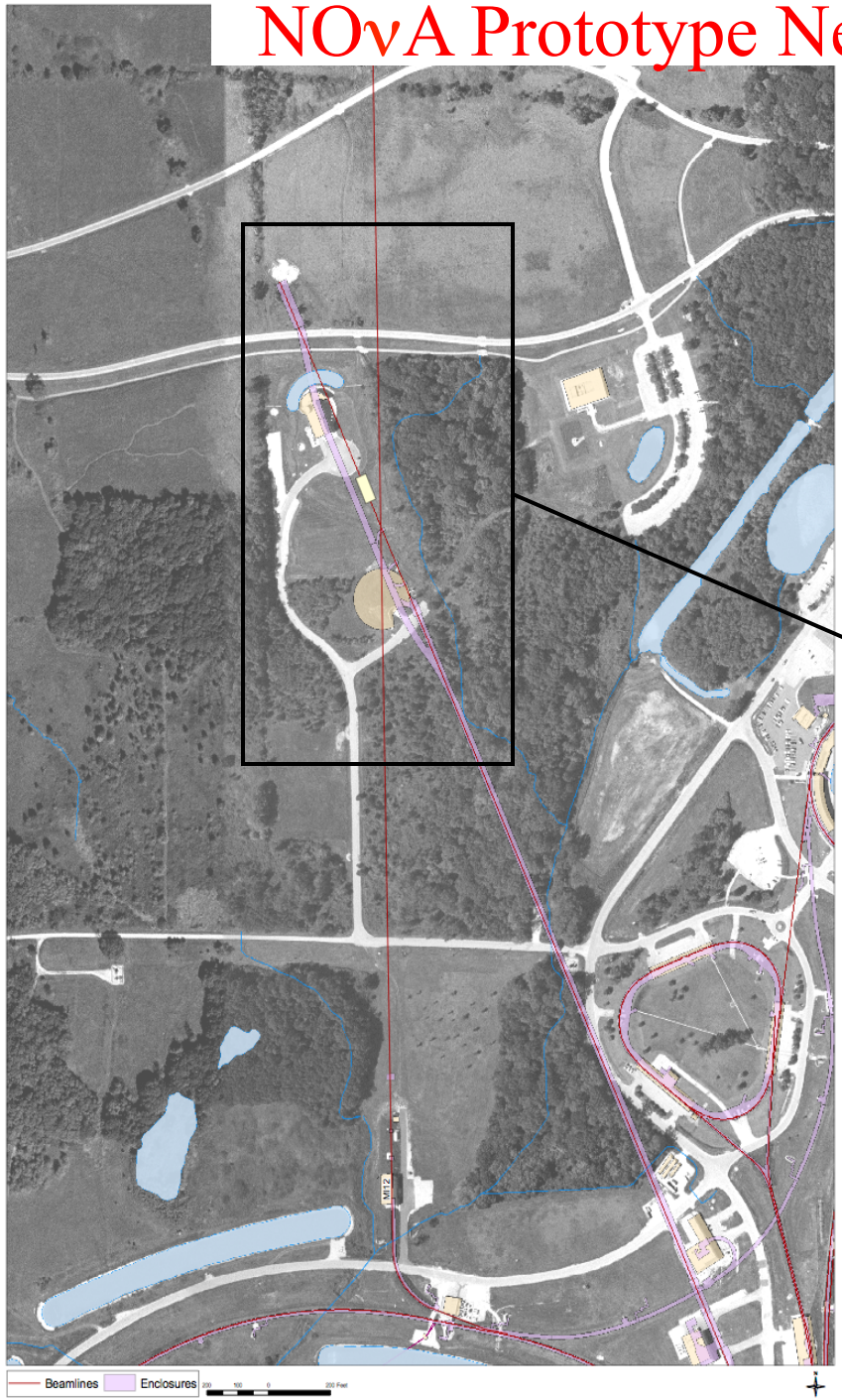


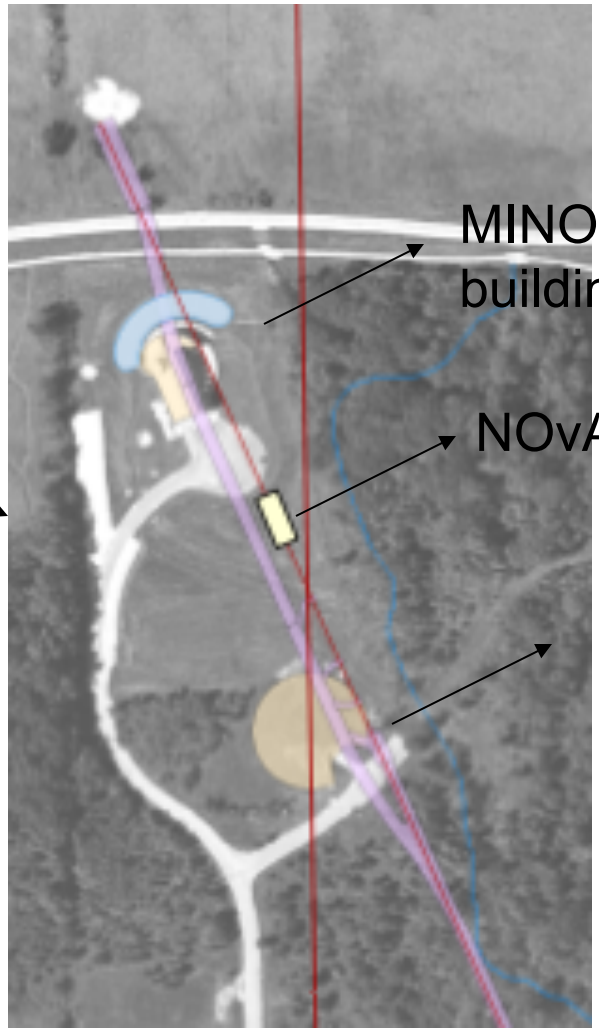
-Cavern for Near Detector to be excavated near MINOS Near Detector Hall.

-1km from NuMI target.



NOvA Prototype Near Detector On Surface (NDOS)





NOνA Prototype Near Detector On Surface (NDOS)

-Main goals are:

-Test detector design and prepare for far detector production.

-Develop DAQ system on custom design hardware.

-Tune calibration procedures.

-NDOS collects data from NuMI and BNB beams

-Show electron neutrino selection and e/π^0 separation.

-Verify cosmic background suppression.

-Study nuclear hadronization models and multi-nucleon production.

-Quasi-elastic cross section at 2 GeV.

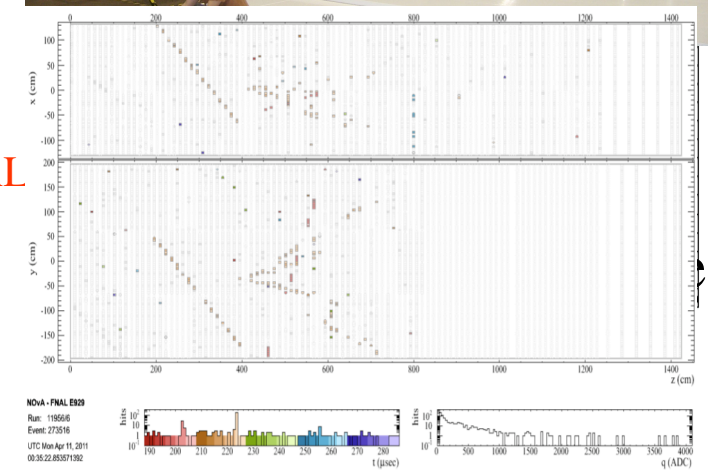
NOνA NDOS Construction

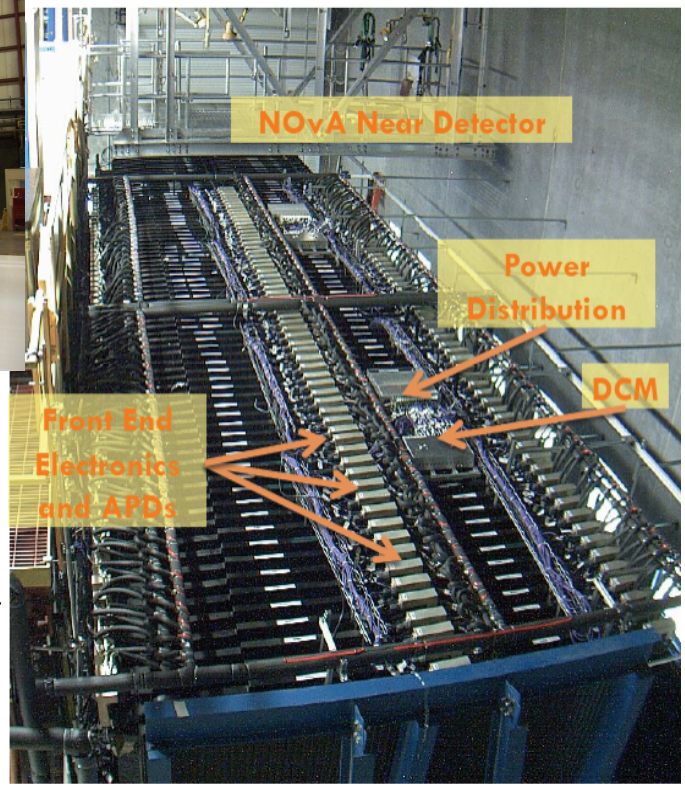
Module Stacks & Leak Test Station

Placing Module in NDOS Block

NDOS Block Shipped to FNAL

Unique Gluing technique and technology developed at ANL





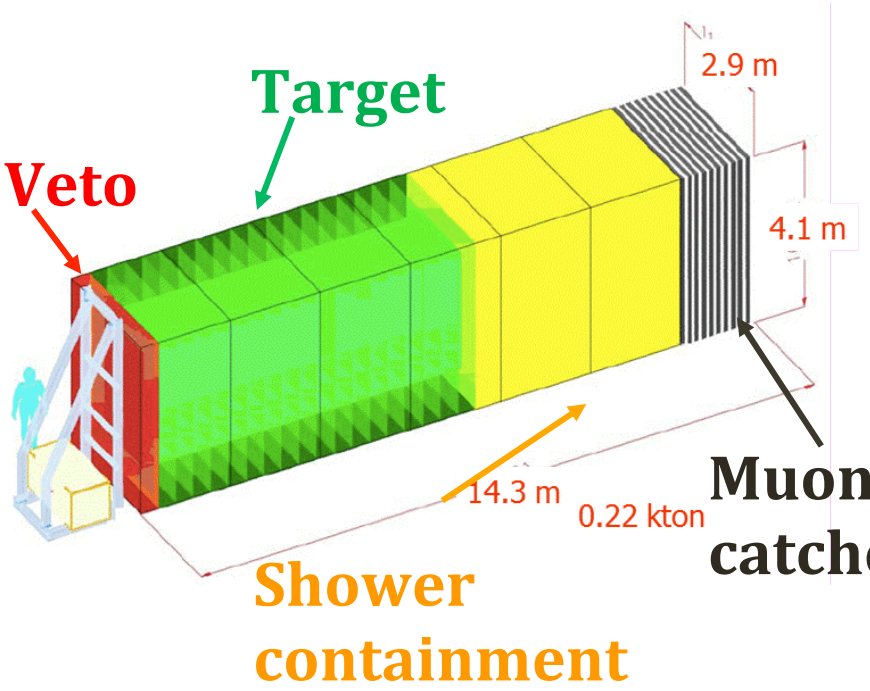
NOνA NDOS Operation

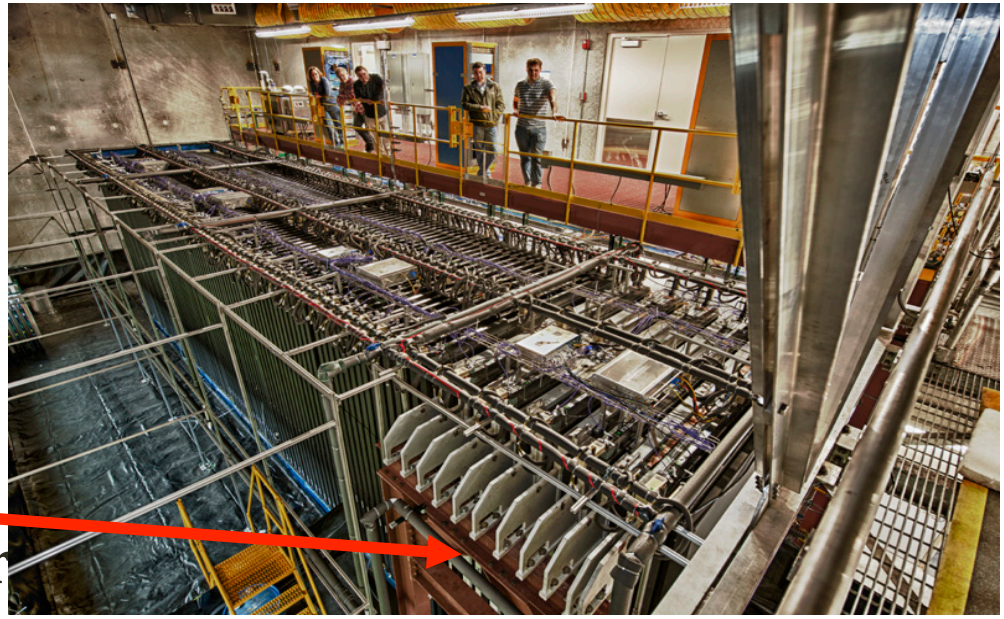
-Prototype Near Detector collecting data since October 2010.

-Six blocks of 31 alternating orthogonal planes and a muon catcher are installed and filled with scintillator.

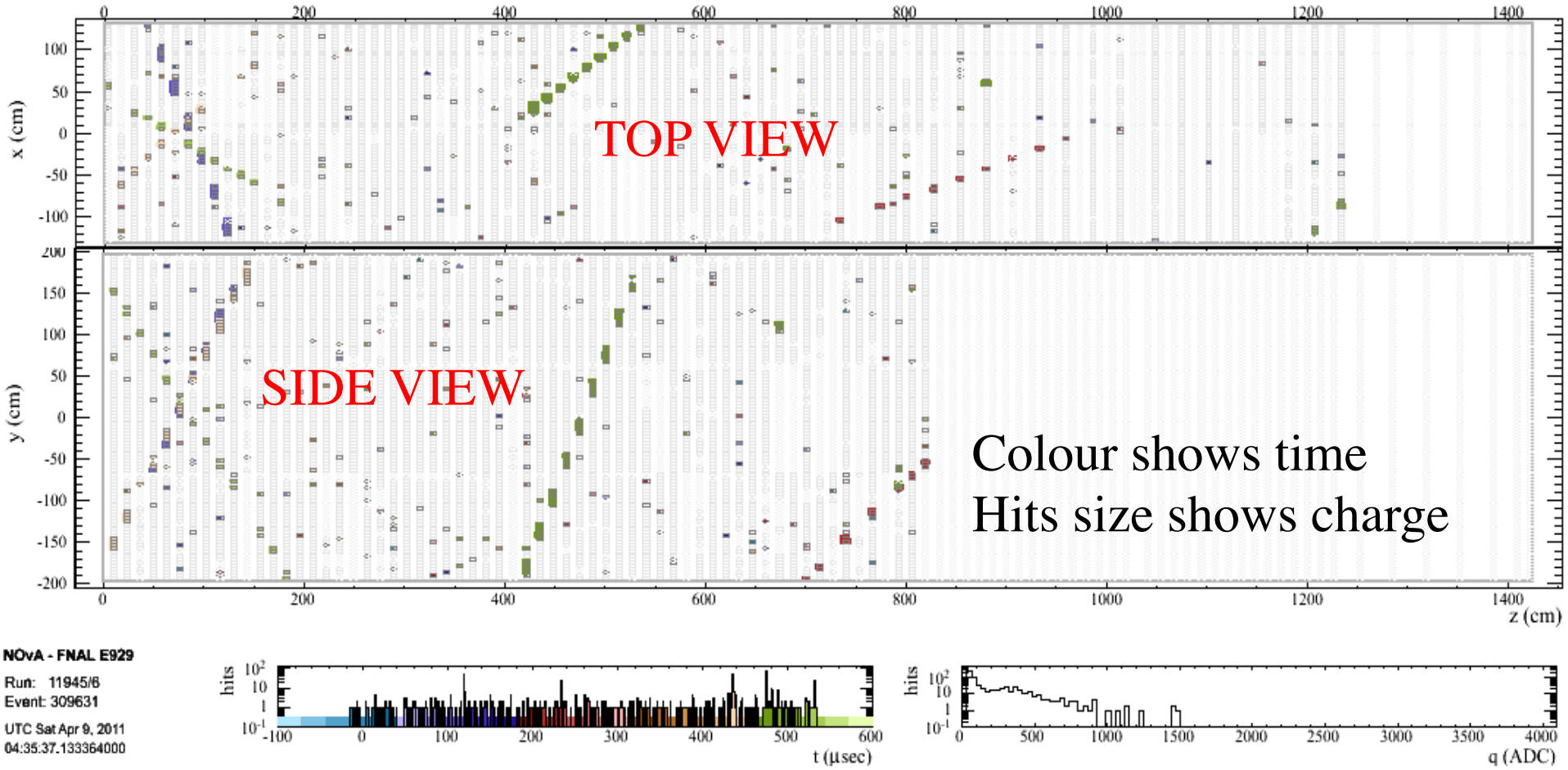
-About 50% of the detector is instrumented with electronics

-Triggers (500 μs wide) obtained from NuMI (6.4° off-axis) and Booster (~on-axis) beams, plus 10 Hz pulser.

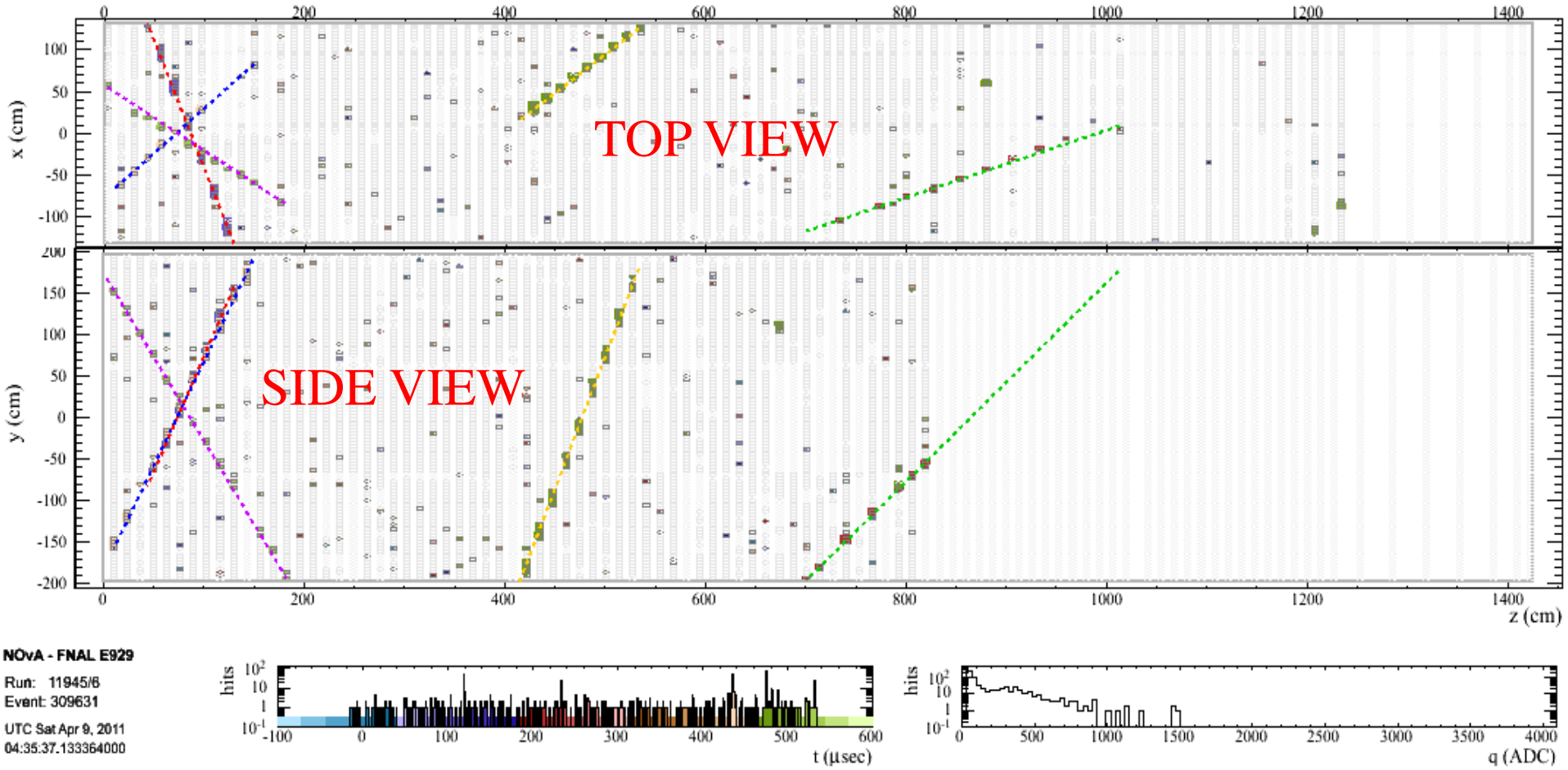




NOvA NDOS Operation: Cosmic Rays

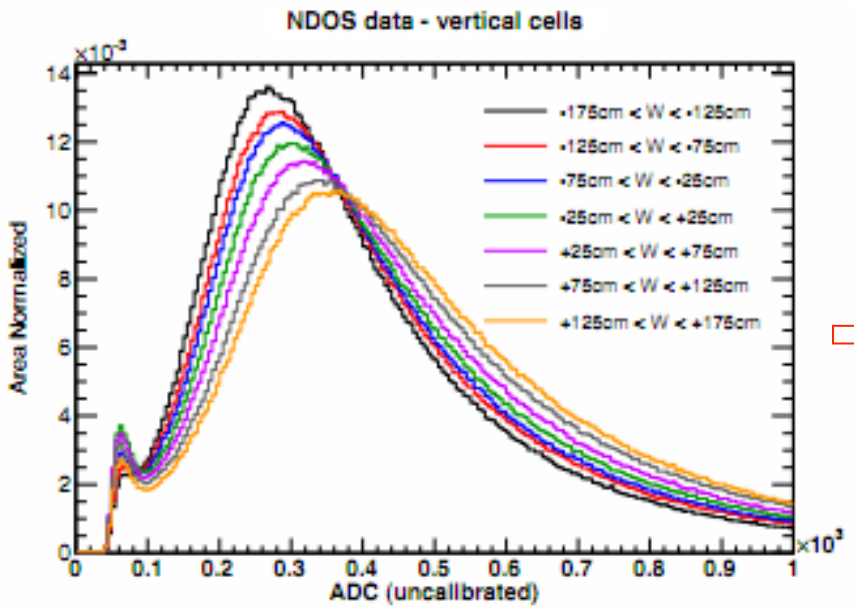


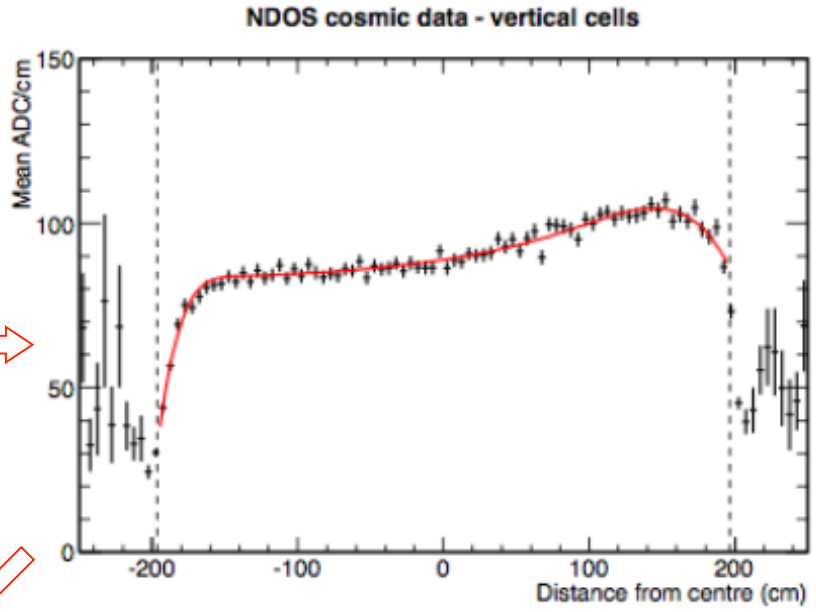
NOνA NDOS Operation: Cosmic Rays

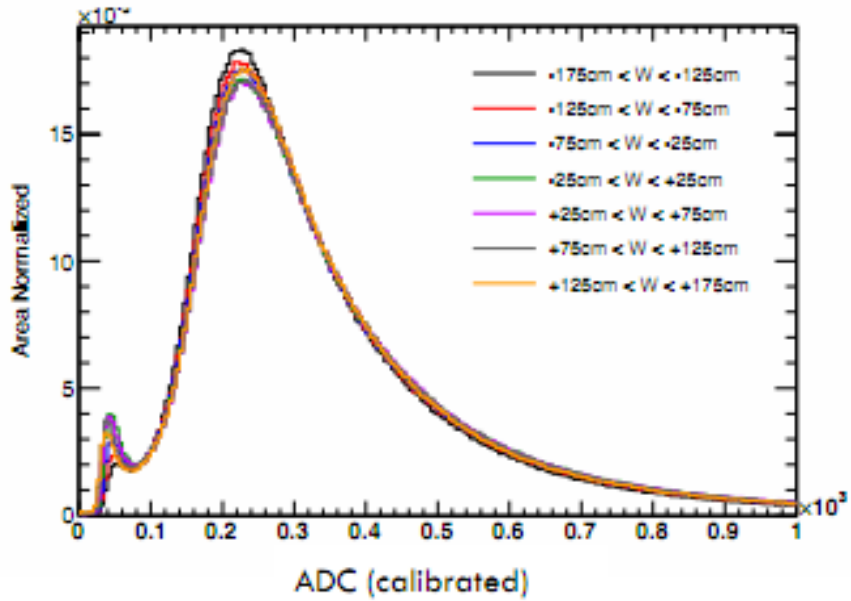


NOνA NDOS Operation: Calibration

-Use of cosmic muons as an intra-detector calibration source: cell-by-cell calibration.





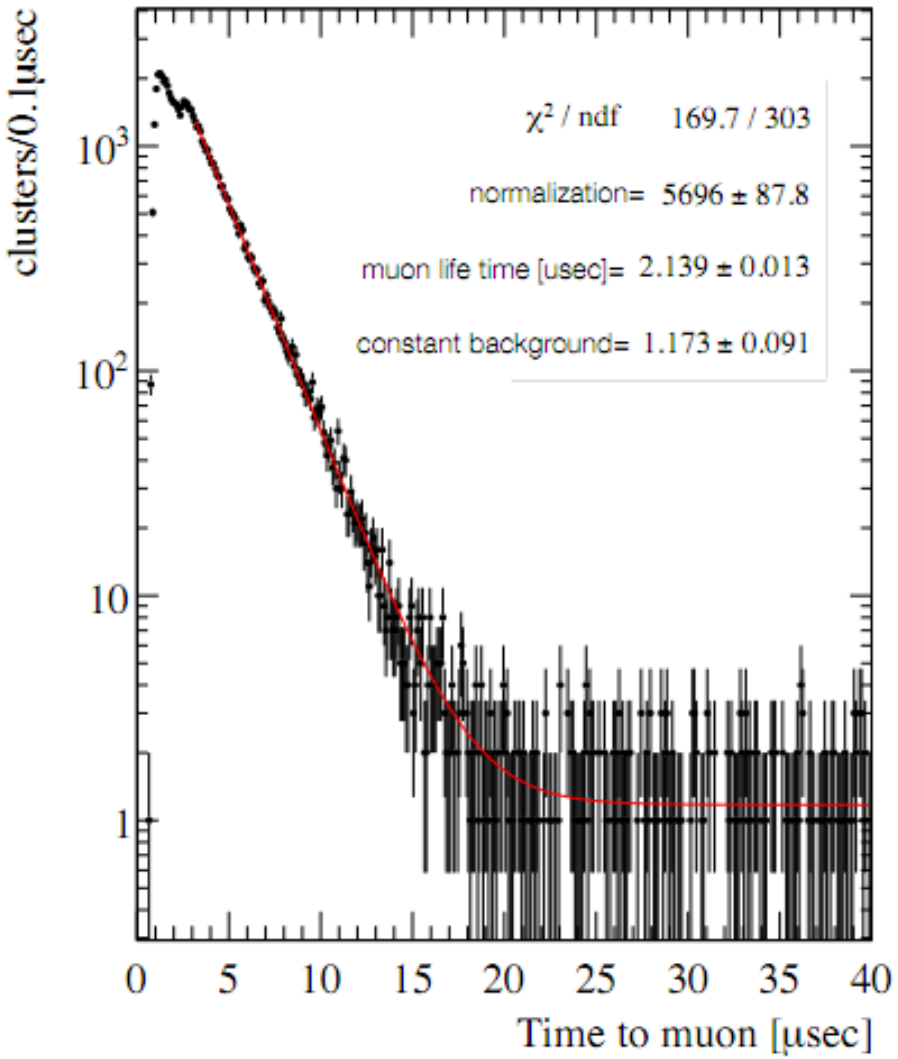


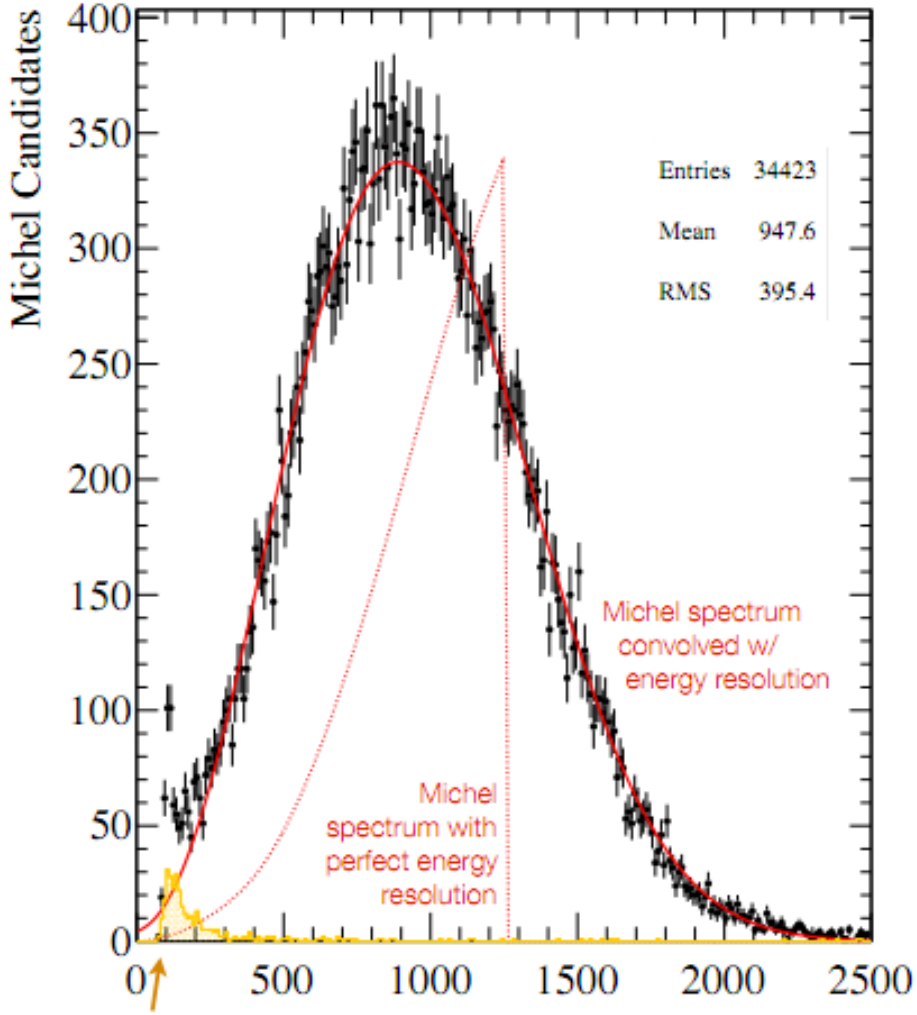
Top left: Path length-corrected response to μ for different distances from fiber end for a single example cell.

Above: Measured and fitted fiber attenuation for the example cell.

Bottom left: Response to μ after att. length corrections.

NOvA NDOS Operation: Michel Electron Calibration

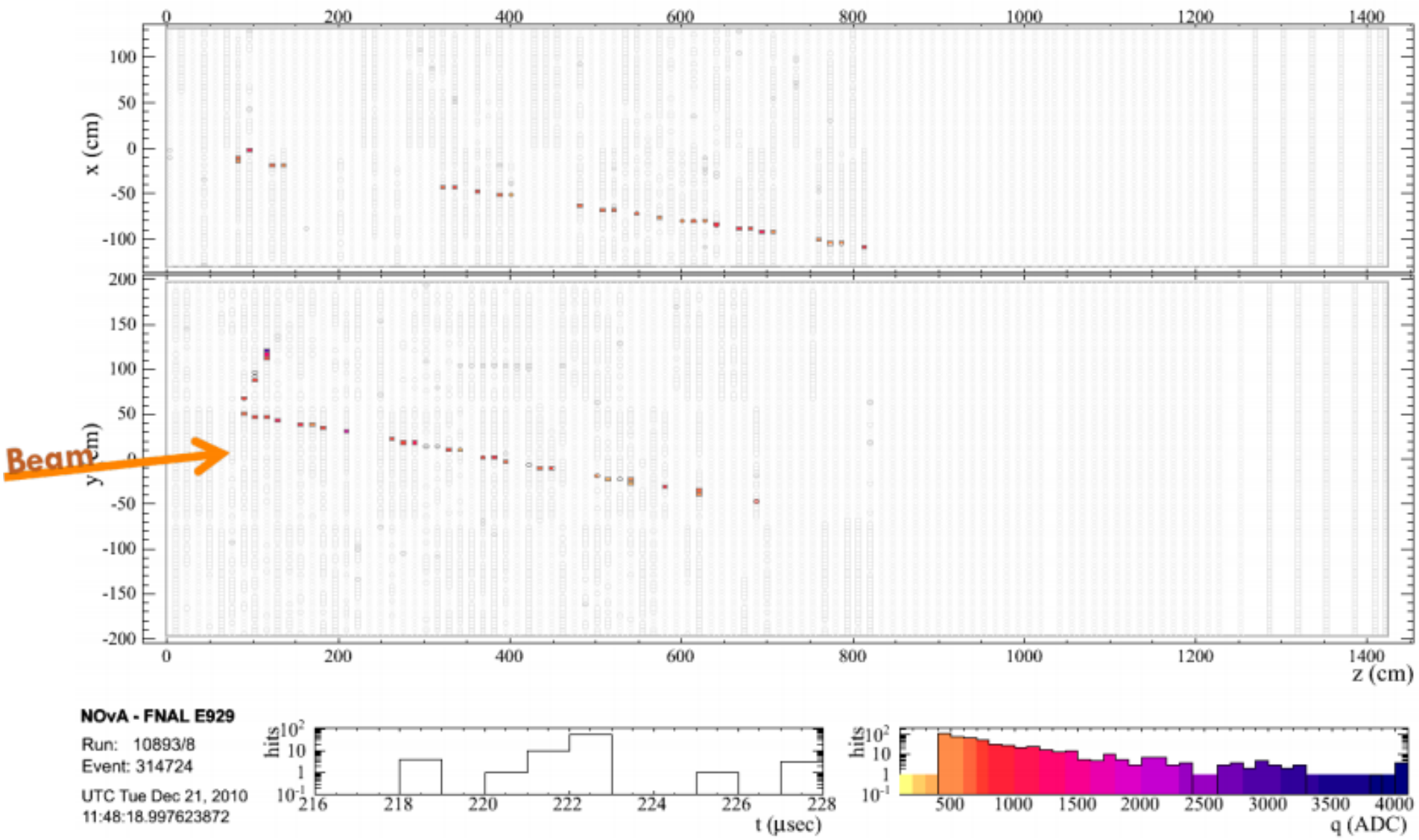




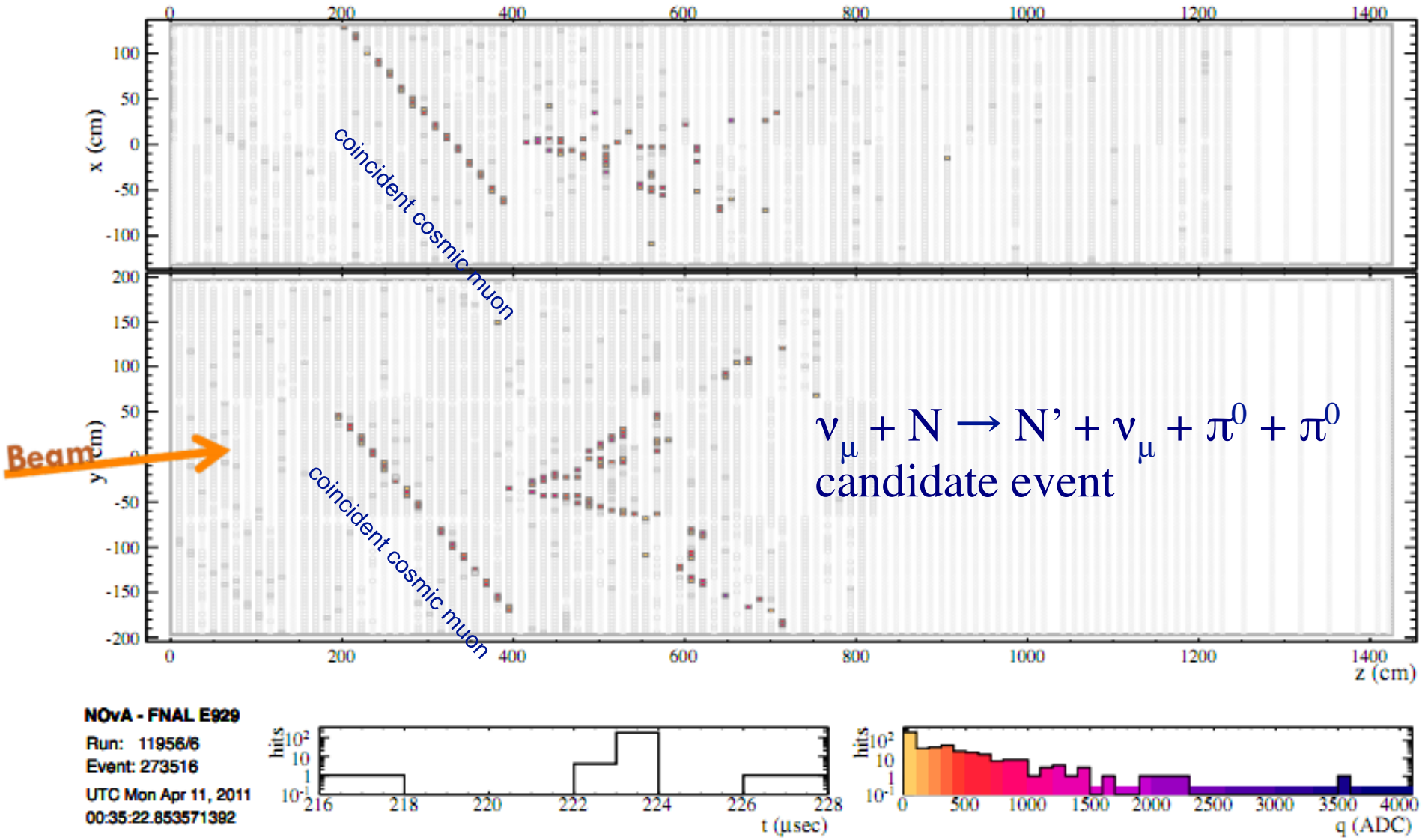
Random coincidences

These are clusters that are matched to muons recorded 20 seconds prior to event

NOvA NDOS Operation: Neutrino Data



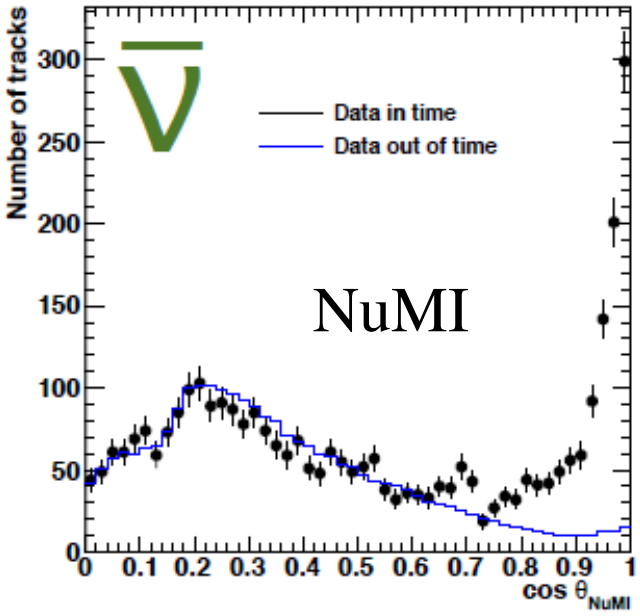
NOνA NDOS Operation: Neutrino Data



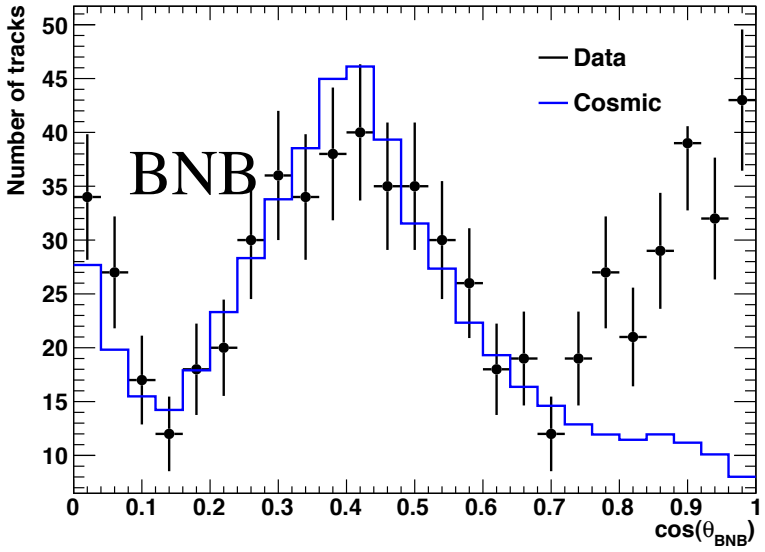
Neutrino candidates

-NDOS collects data from NuMI and BNB beams.

110 mrad off NuMI axis.



NDOS nearly on Booster axis, but detector rotated wrt axis.



NOνA Status and Timeline

NuMI Beam

-Upgrade from 320 kW to 700 kW.
-Accelerator shutdown planed for March 2012: perform upgrade.
-Beam returns at 700 kW, with ~1/2 of Far Detector ready – Feb. 2013.

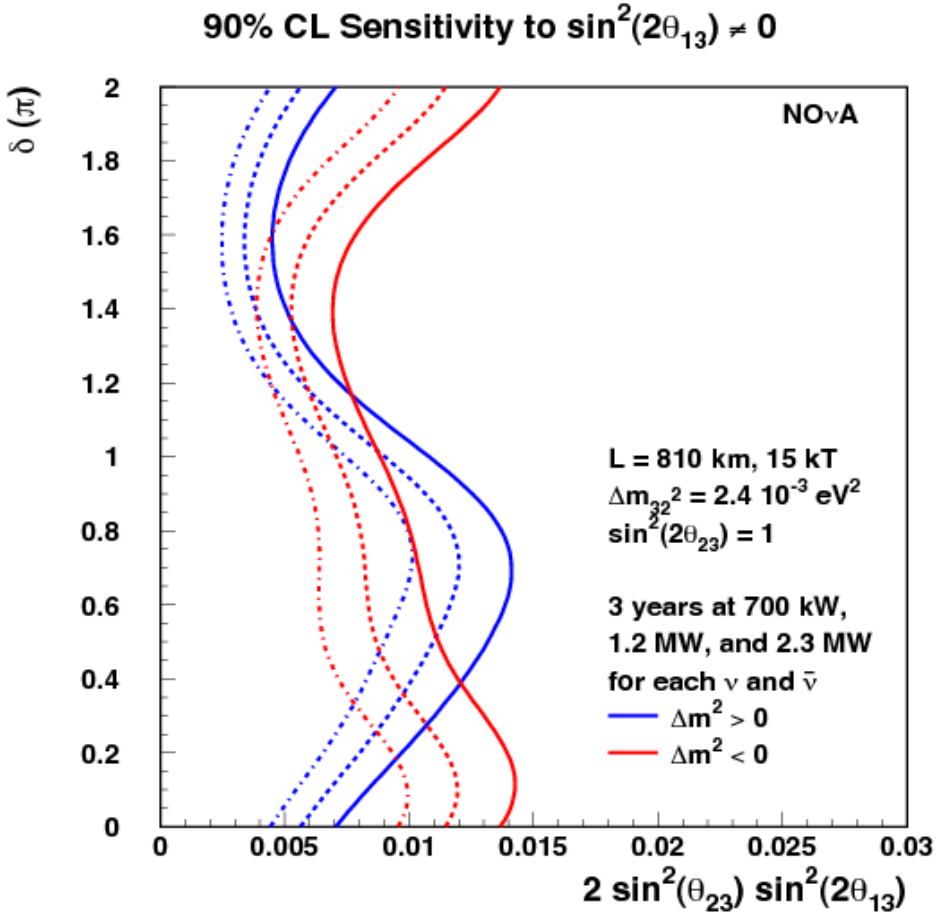
Far Detector

-Far detector building complete.
-Detector construction starting January 2012.
-50% completion by end of shutdown.
-Detector complete by early 2014.

Near Detector

-Cavern excavation during shutdown.
-NDOS (Prototype Near Detector on Surface) is operational, taking data since 10/2010
    -Extremely valuable preparation for construction at Ash River.
    -Early look at real cosmic rays and neutrinos.
    -Headstart on calibration techniques and physics analyses.

NOνA Sensitivity to θ_{13}

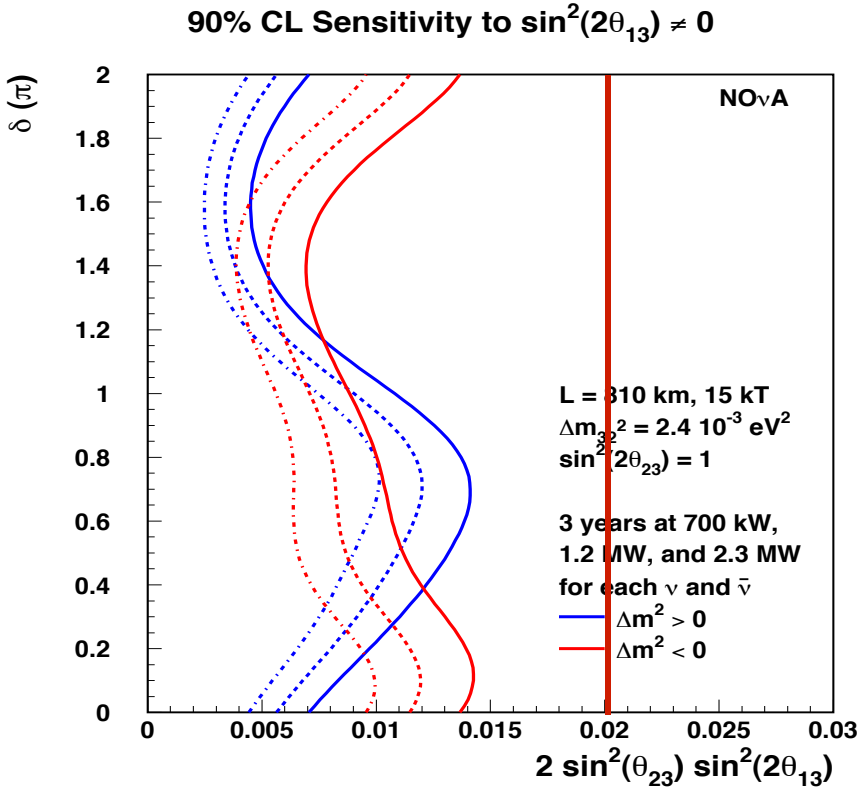


-Sensitivity to $\sin^2(2\theta_{13})$ after 3 years in each neutrino beam and antineutrino beam in case of **normal** and **inverted** hierarchy.

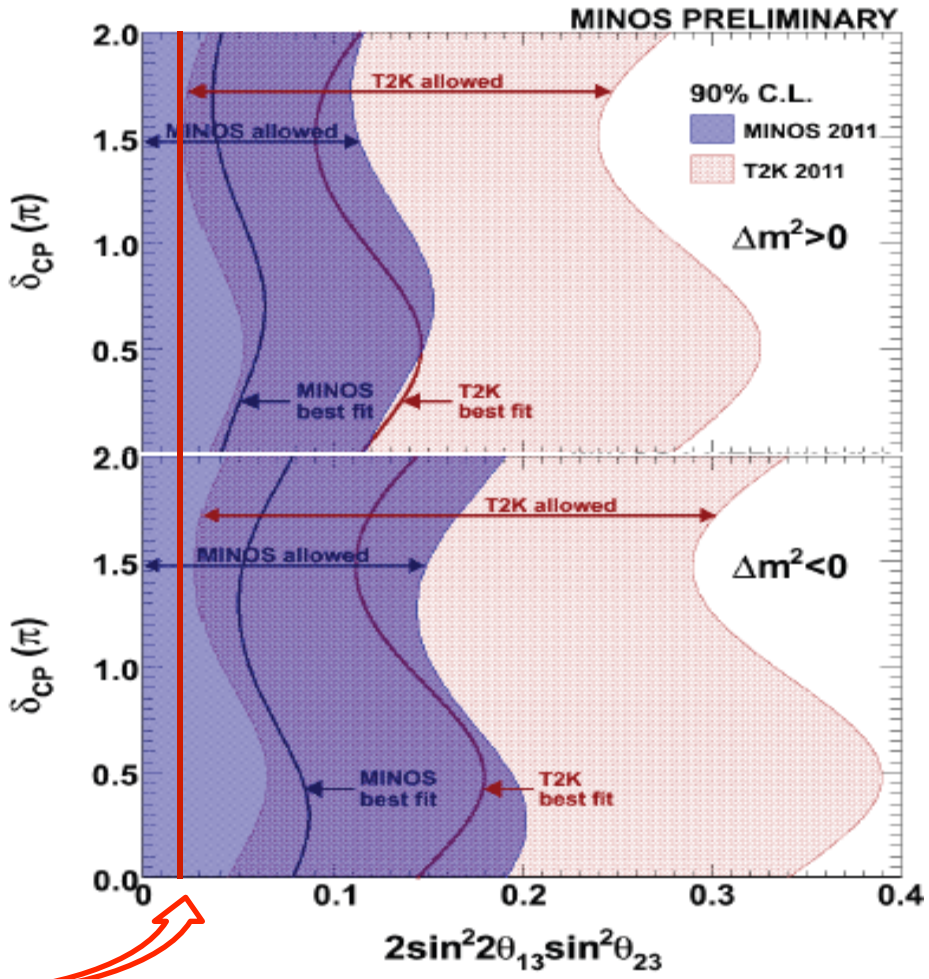
-Assume 18 x 10^{20} POT in each neutrino and antineutrino mode.

-Contours for different beam upgrades also shown.

NOνA Sensitivity to θ_{13} compared to recent results

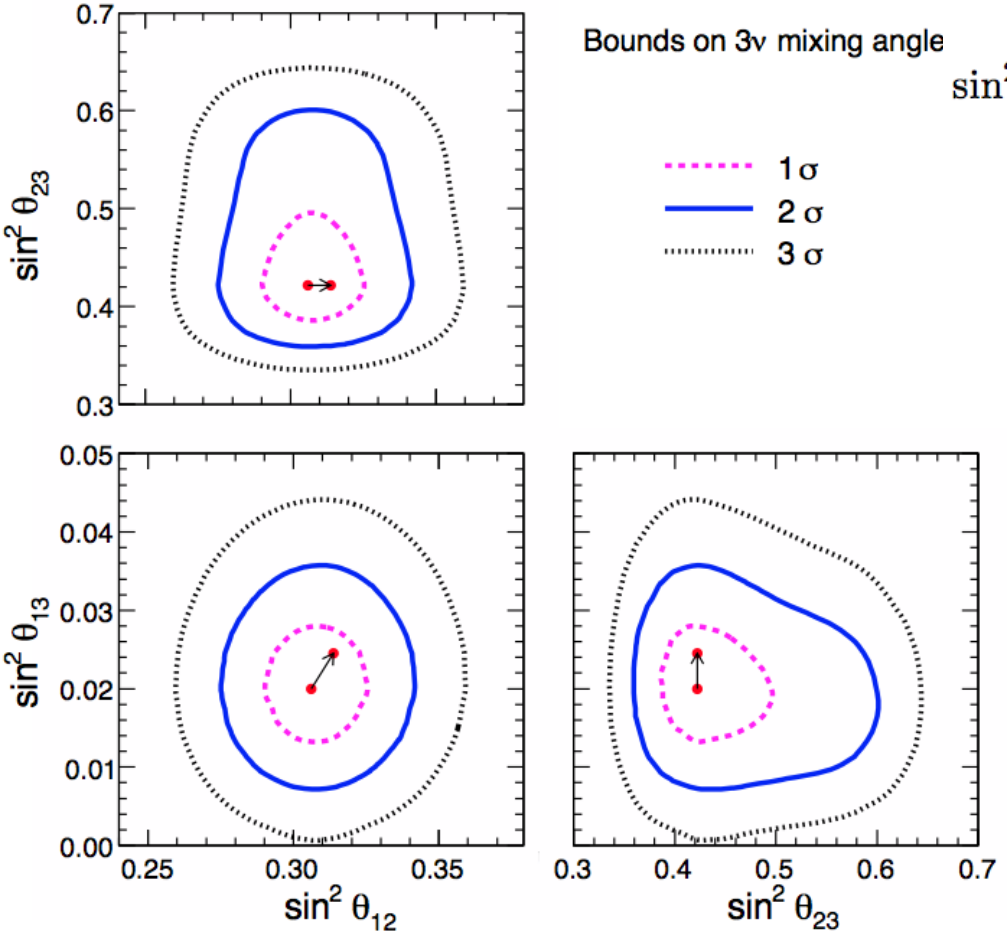


Overlay of MINOS and T2K allowed regions:



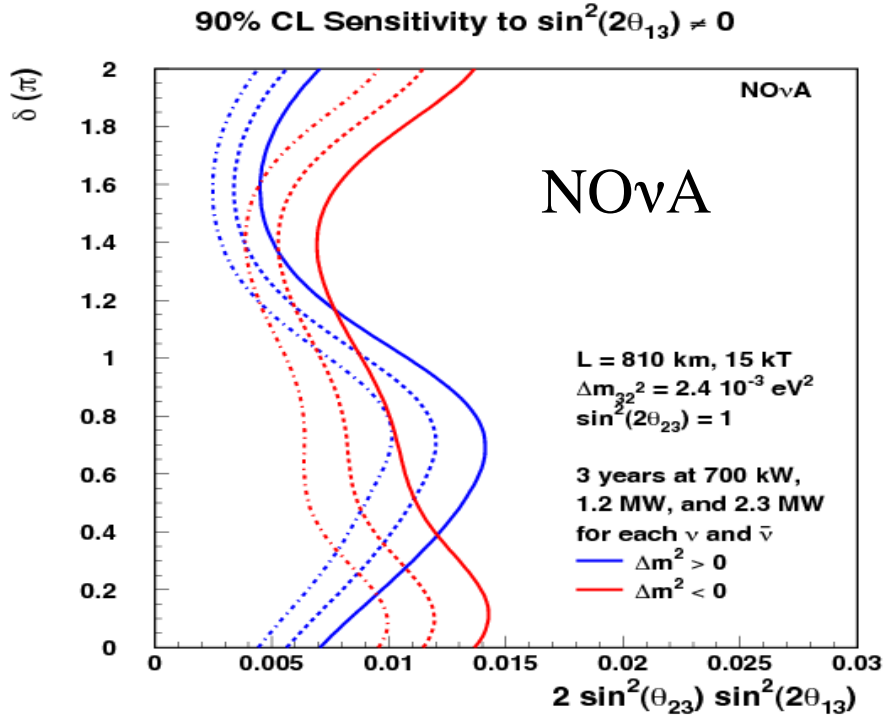
NOνA and Non-zero θ_{13} Evidence

Recent global analysis fit for $\sin^2\theta_{13}$ vs $\sin^2\theta_{12}$ (Fogli et al. arXiv:1106.6028[hep-ph])



$$\sin^2\theta_{13} = \begin{cases} 0.021 \pm 0.007\,, & \text{old reactor fluxes} \\ 0.025 \pm 0.007\,, & \text{new reactor fluxes} \end{cases} \quad (1\sigma)$$

$$\sin^2 2\theta_{13} = \begin{cases} 0.082 \pm 0.028 \\ 0.098 \pm 0.028 \end{cases}$$



Is θ_{13} non-zero and within a reach?

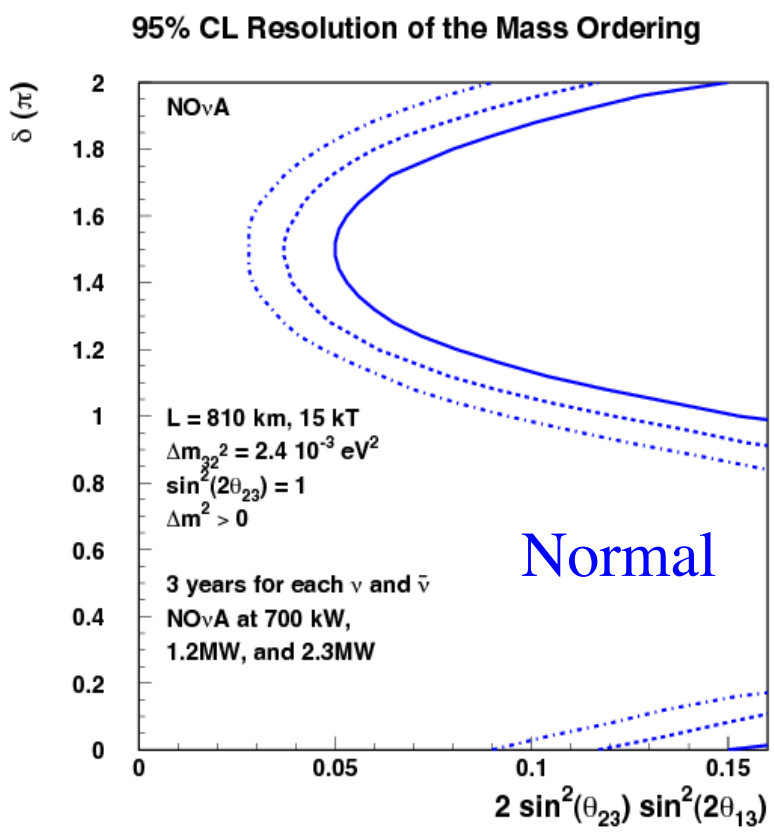
→Need new sensitive experiments to confirm

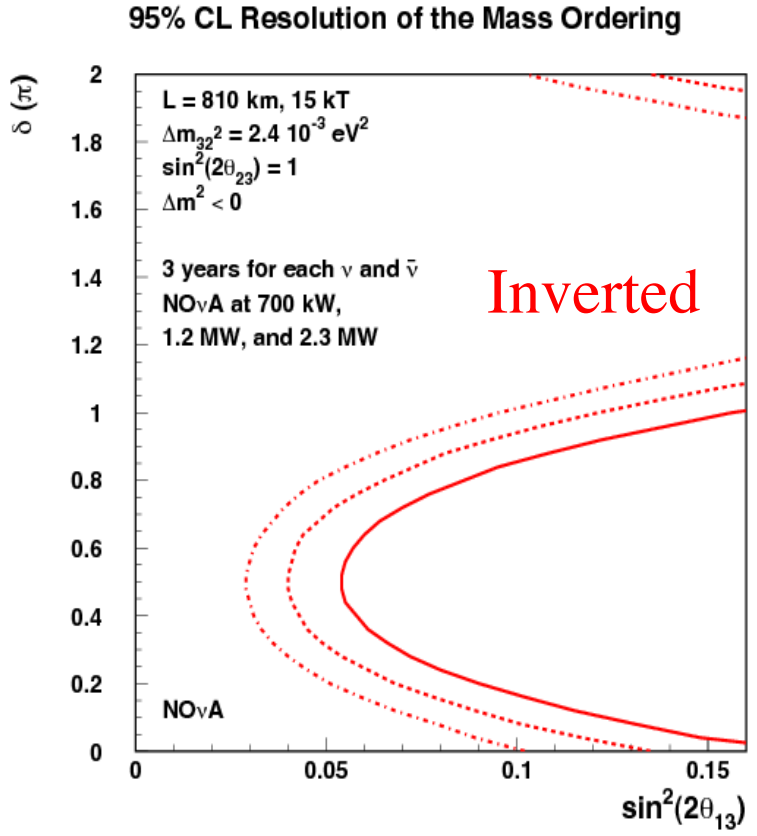
NOνA has an order of magnitude better sensitivity.

Resolving the mass hierarchy with NOνA

-Given matter–induced effects NOνA's 810 km long baseline makes oscillation probability change by ~30%.

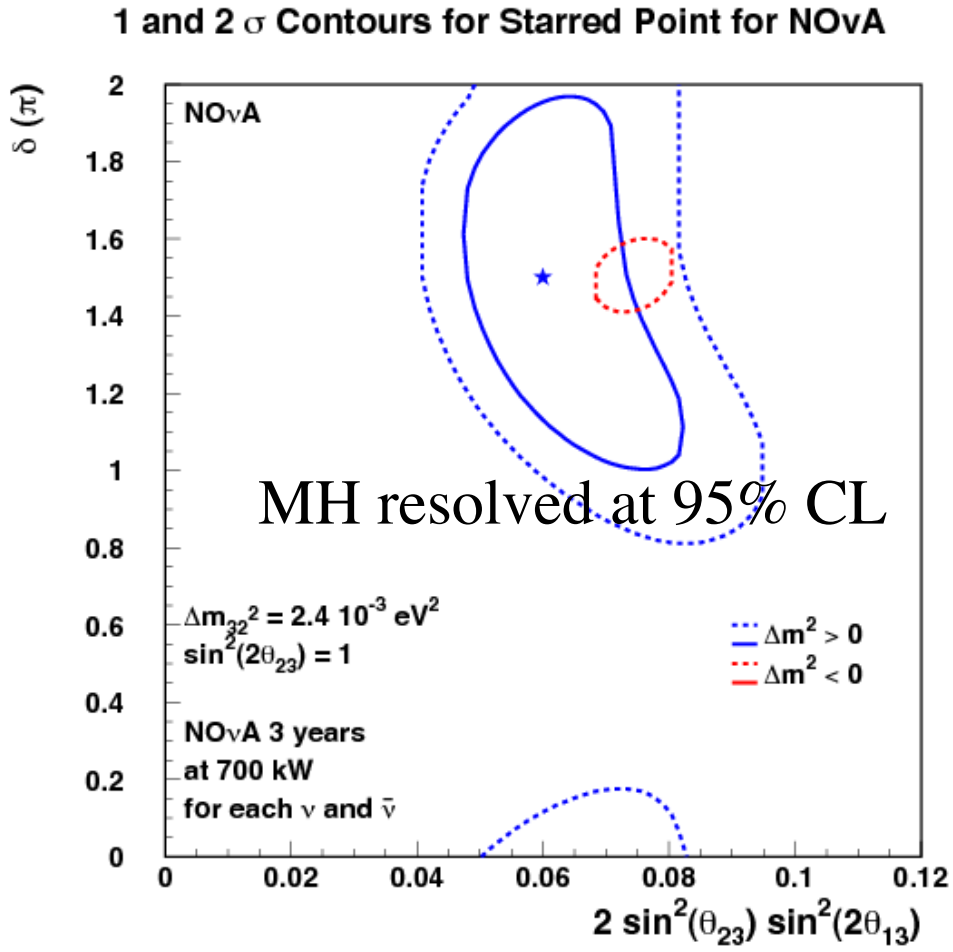
-Matter effects depend on the mass hierarchy and change $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ differently.

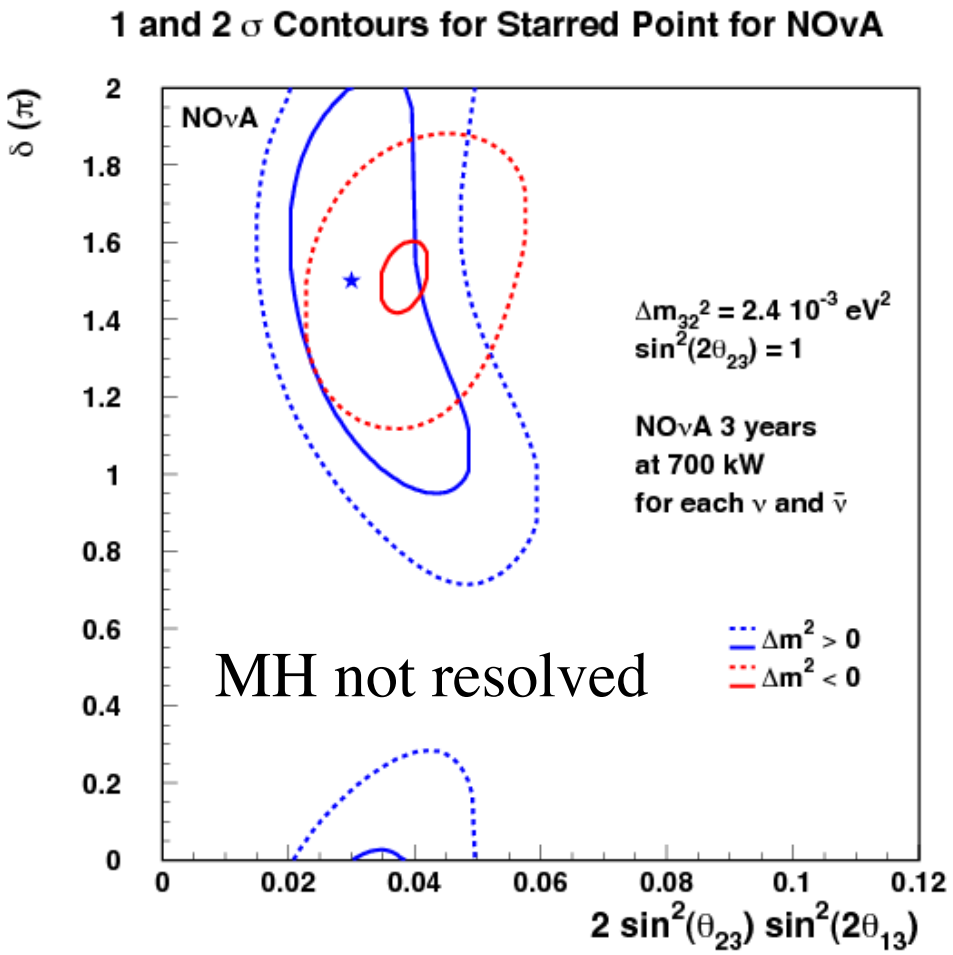




-Running NOνA for 3 (neutrinos) + 3 years (antineutrinos) may resolve the mass hierarchy if θ_{13} is large enough.

Constraining δ_{CP} with NOνA





-Plots show 1 and 2σ contours for 700 kW beam with chosen point.

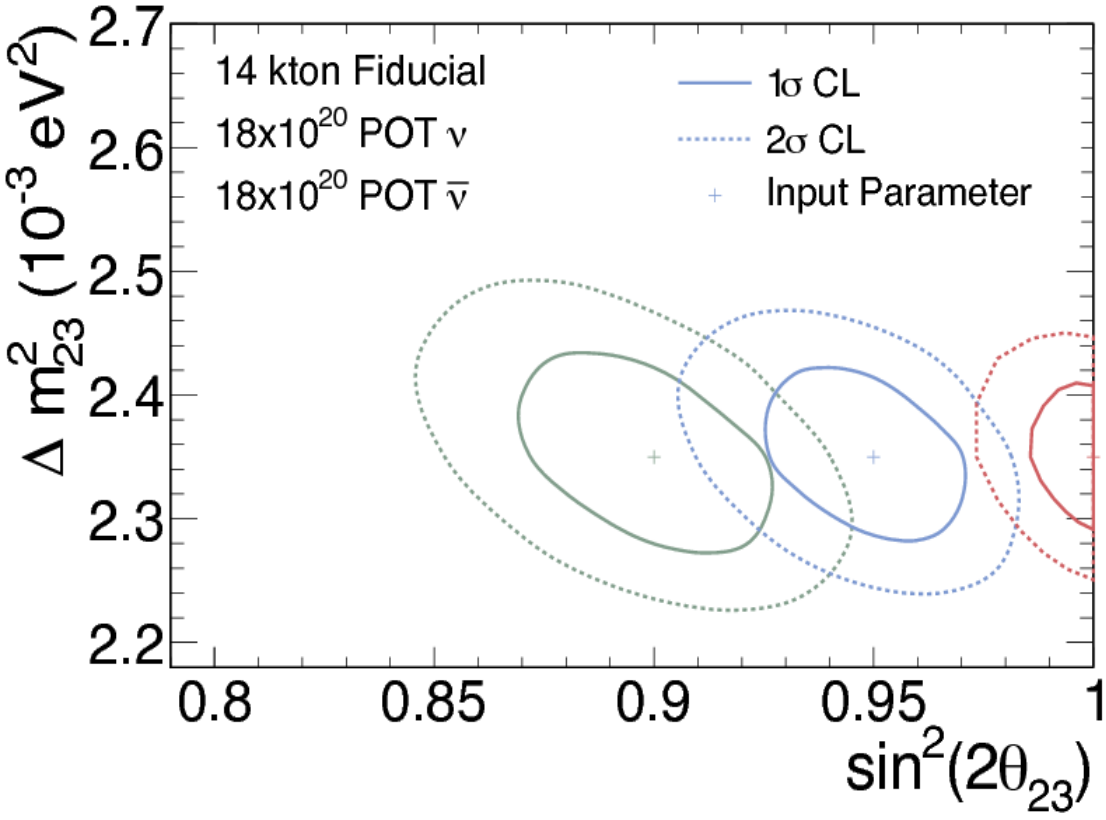
Precision measurements of Δm^2_{32}, θ_{23}

-Sensitivity to Δm^2_{32}, θ_{23} after 3 years each of neutrino and antineutrino beam.

-Contours for Δm^2_{32} at the fit value of 2.35×10^{-3} eV^2 and different values for $\sin^2(2\theta_{23})$

-NOνA will improve on the MINOS measurement of Δm^2_{32} and can measure $\sin^2(2\theta_{23})$ to better than 2% due to large detector mass and excellent energy resolution of charged current events $(\nu_\mu + n \rightarrow \mu + p)$.

-More precise test whether $\sin^2(2\theta_{23})$ is maximal



ν and $\bar{\nu}$ disappearance parameters

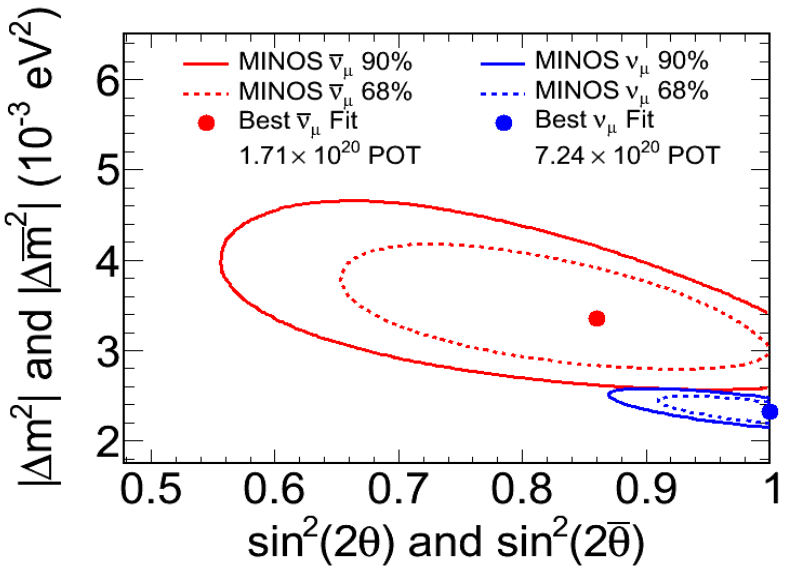
-MINOS reported a ~2σ evidence for difference between best fit values for ν and $\bar{\nu}$ disappearance parameters (arXiV:1103.0340)

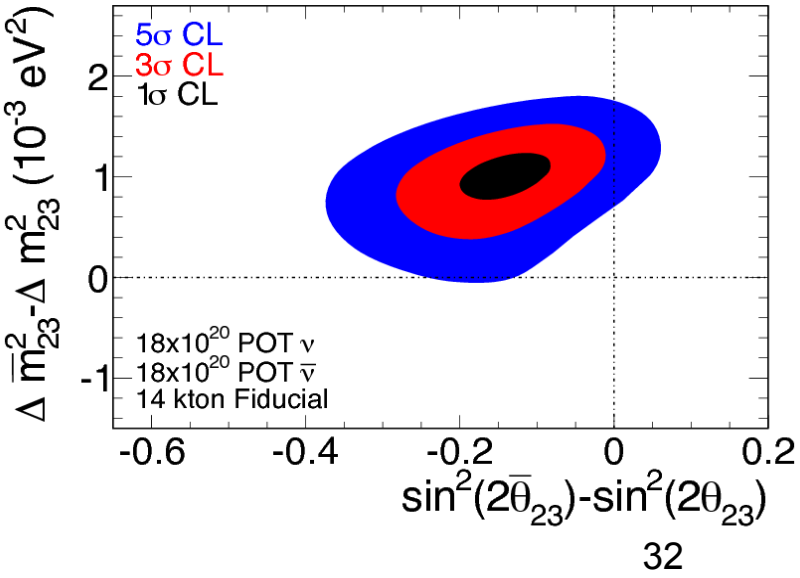
-NOνA intends to run for 3 years in neutrino mode and 3 years antineutrino mode.

-Top plot: MINOS result for anti-neutrino (red) neutrino (blue) disapperance. The solid (dashed) curves give the 90% (68%) contours.

-If MINOS central values are correct, NOνA would establish the difference with 3σ significance in 2 years, 5σ in 6 years.

-Bottom Plot: NOνA results after full 6 year run, 3(neutrinos) +3(antineutrino) years.





Summary

-NOνA is NuMI Off-Axis ν_e Appearance Experiment.
-NOνA will be using NuMI neutrino beam from Fermilab to Ash River in Minnesota (810km baseline).
-NOνA is two detector experiment where near detector is used to predict events in far detector.
  -Near and Far detector functionally identical.

-NOνA is on track to make many important contributions to neutrino physics, including:
  -Measurement of $\theta_{13.}$
  -Determination of mass hierarchy.
  -More precise measurements of Δm^2_{32}, $\sin^2(2\theta_{23})$.
-Far detector construction coming soon.
-NuMI beam upgrade to be done during the accelerator shutdown.
-Near detector on the surface taking neutrino data now.

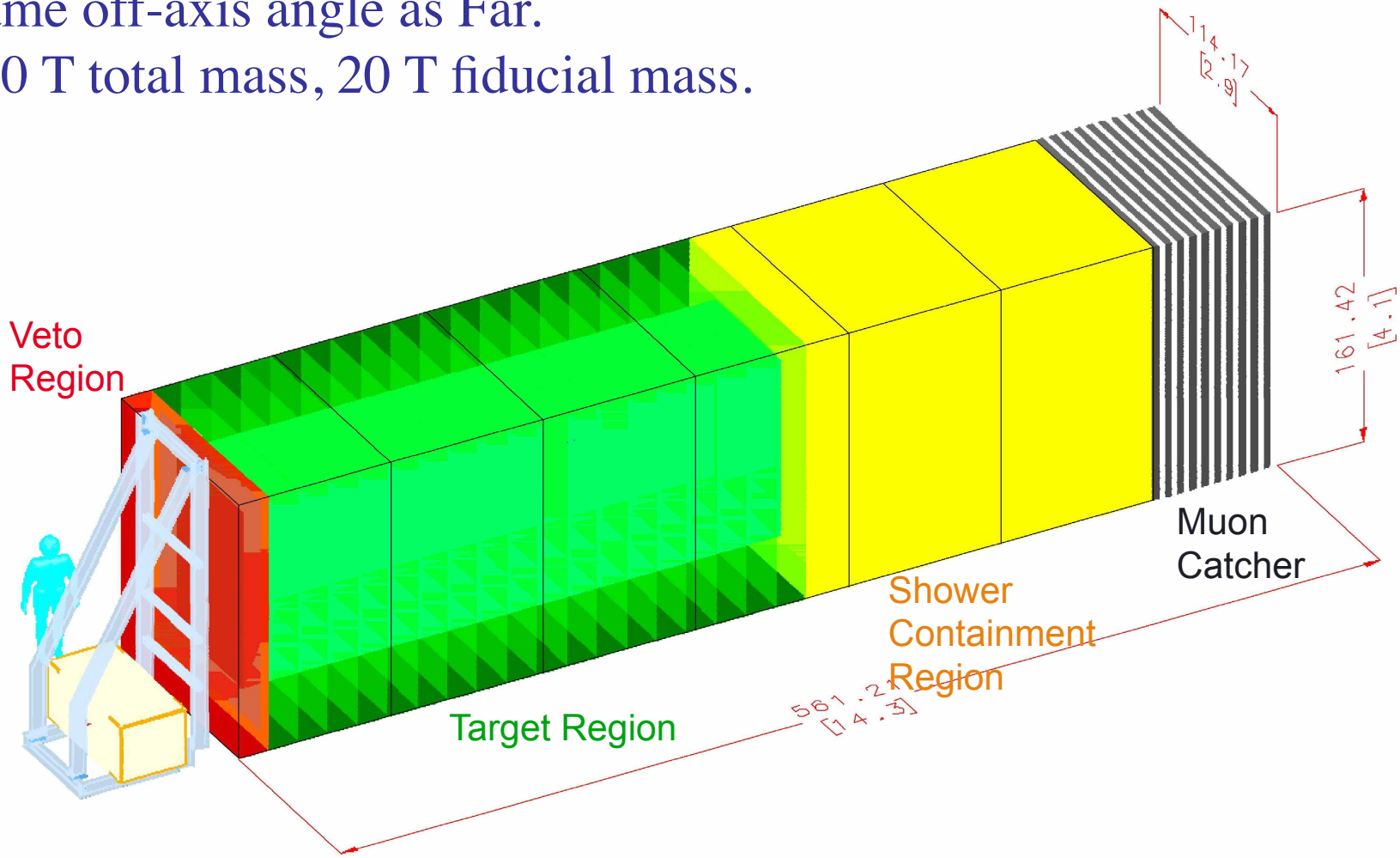
Backups

NOνA Near Detector

-Identical to Far Detector (in material, segmentation, and orientation), except smaller, with muon catcher.

-Same off-axis angle as Far.

-220 T total mass, 20 T fiducial mass.

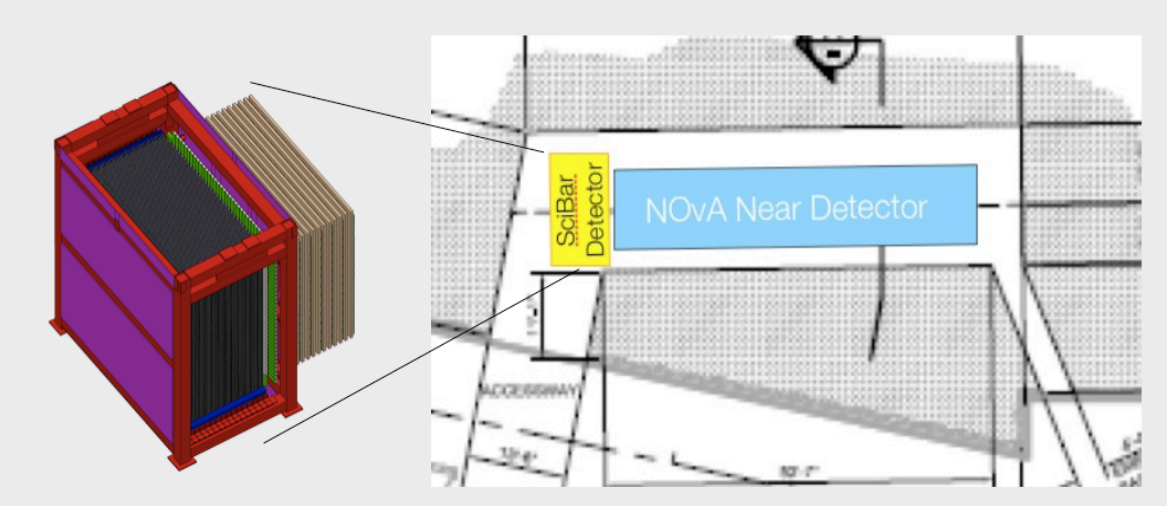


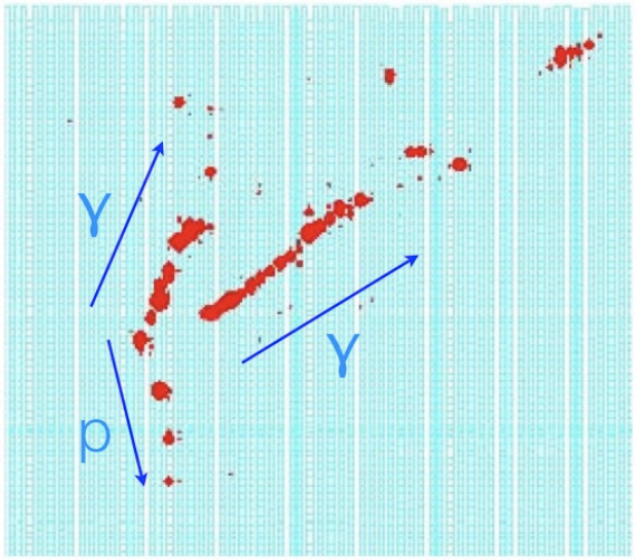
Proposed SciNOνA Project

-Place fine-grained detector (scint. strips, SciBar-like) in front of NOvA Near.

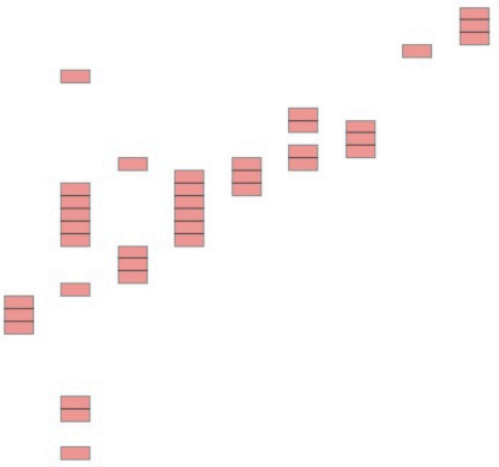
-Measurement of ν-nucleaus scattering in narrow-band beam.

-Enhance NOνA program by precise measurements of NC background.





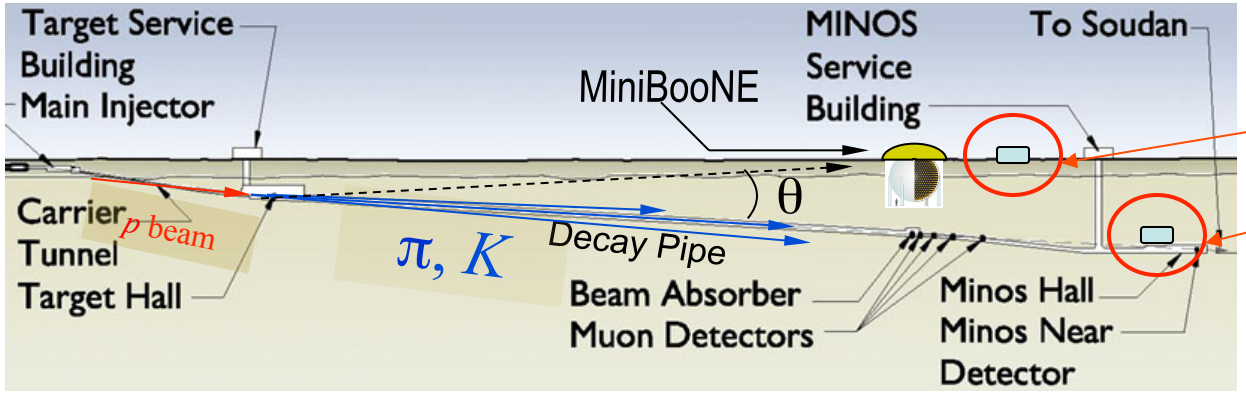
p + π⁰ in SciBar



Same event resampled in NOvA

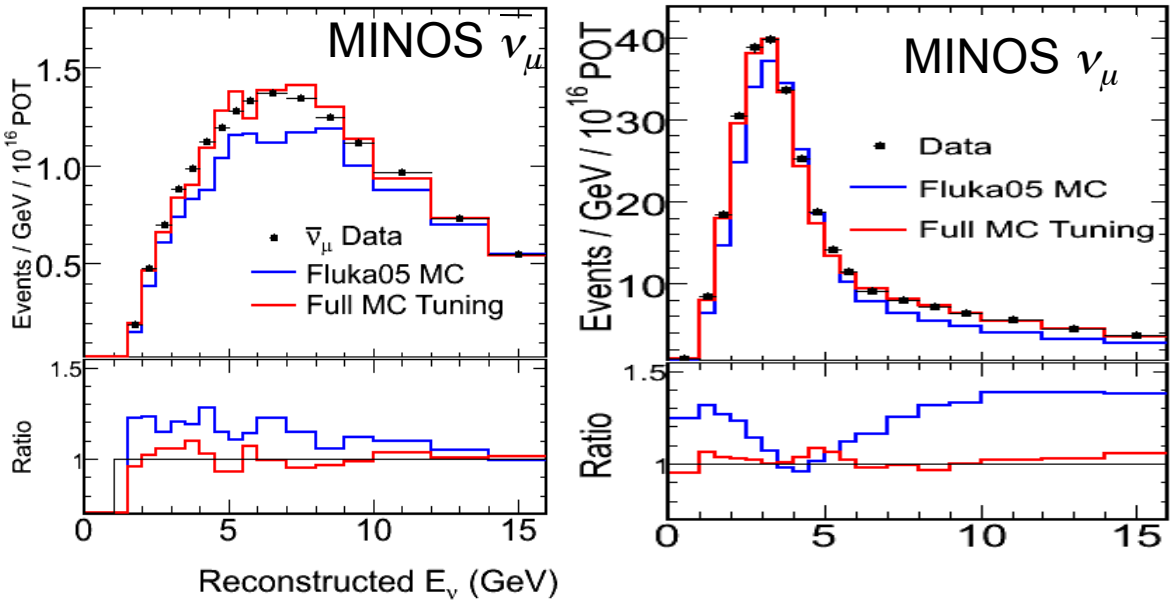
More fine-grained detector would enable a data-driven check of NCπ^0 background (i.e. efficiency).

NuMI Neutrino Beam



NuMI spectrum is "calibrated".

Extensive experience with MINOS data.
MINOS acquired datasets in variety of NuMI configurations.
Tuned kaon and pion production (x_F,p_T) to MINOS data.



Same parent hadrons produce neutrinos seen by NDOS (MiniBooNE).

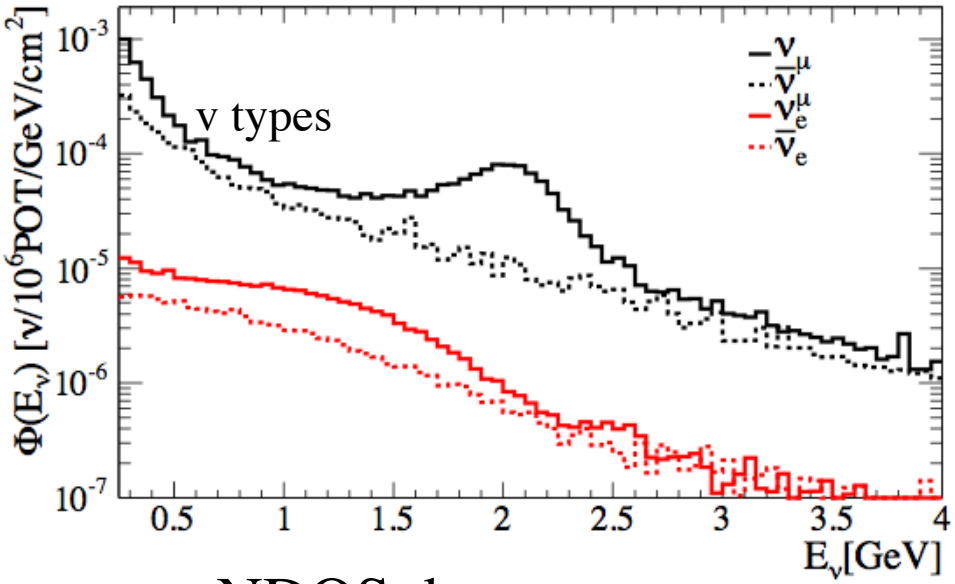
Flux at NDOS (MiniBooNE) should be well-described by NuMI beam MC.

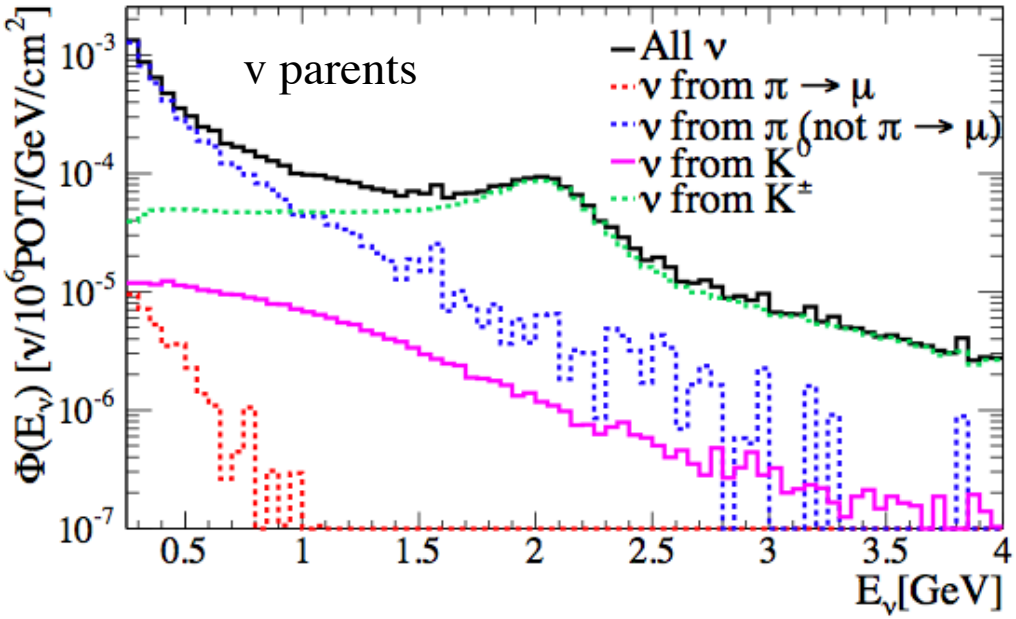
D.G. Michael et al, Phys. Rev. Lett. 97:191801 (2006)
D.G. Michael et al, arXiv:0708.1495 (2007)

NOνA Near Detector On Surface (NDOS)

-NuMI flux simulation for NDOS detector in Low Energy configuration.

-Neutrino mode.





-NDOS detector sees ν's from K's.

-This component well measured at NDOS.

-Used to tune K's at Near.

-Study reconstruction and particle ID (enhanced ν_e component).

-Will measure Booster ν's.

NOνA Near Detector On Surface (NDOS)

-NuMI beam currently operates in neutrino mode, expect anti-neutrino mode early next year.

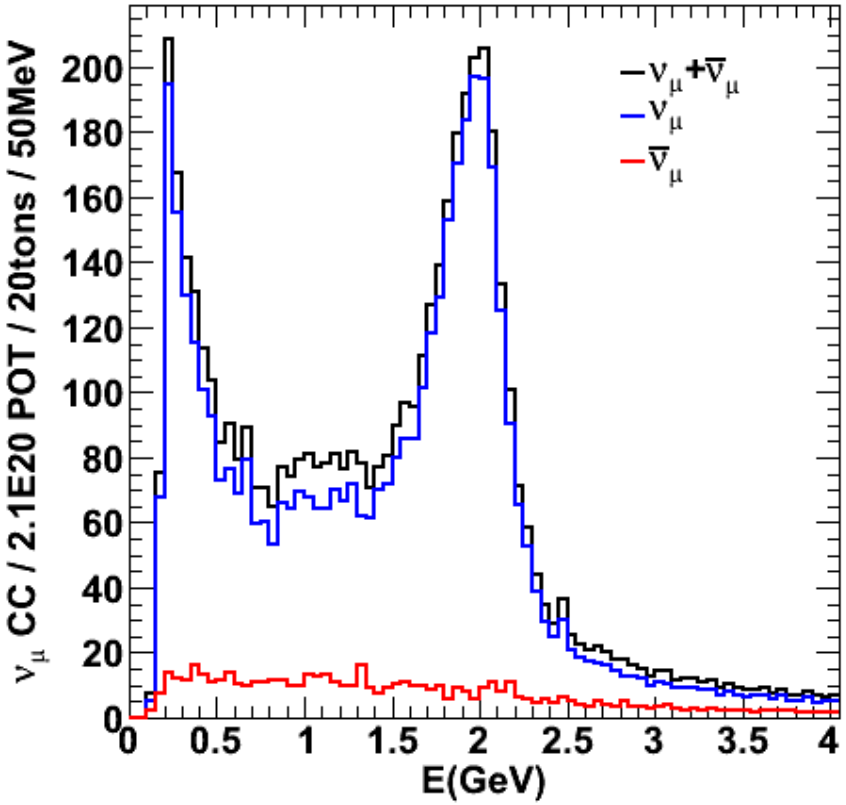
-NDOS may get measurement in both modes.

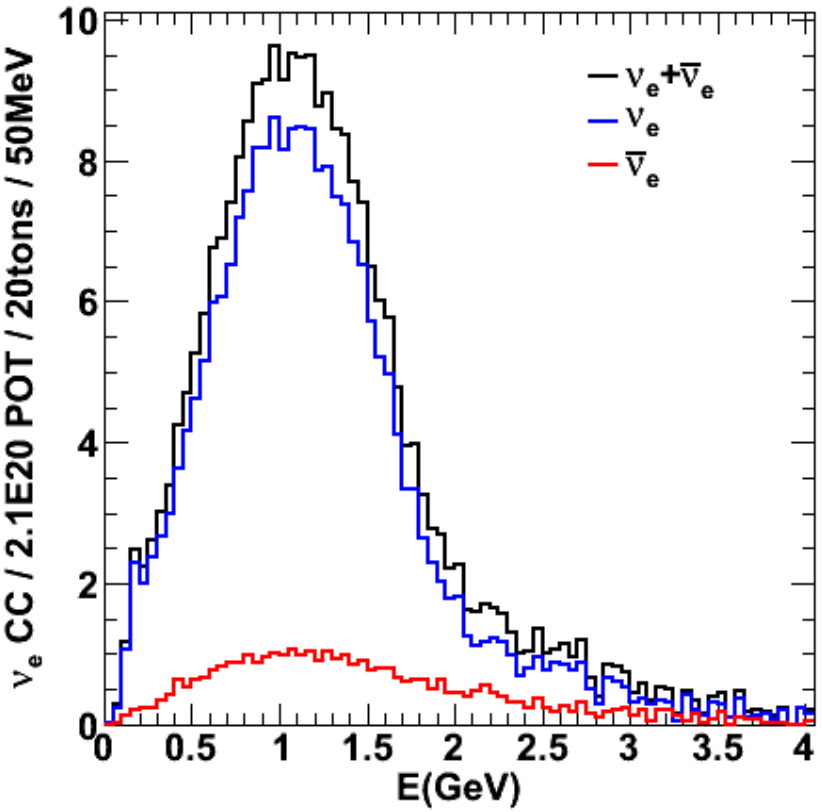
-Neutrino mode: 2.1×10^{20} POT.

GeV	Total CC	CC QE	CC RES	CC DIS	CC COH	NC
ν_μ Total 1.6-2.4	4751 1931	2288 559	1533 842	861 511	38 20	1911 699
ν_e Total	340	166	119	50		125
$\bar{\nu}_\mu$ Total 1.6-2.4	624 132	323 50	179 55	103 24	14	353 142
$\bar{\nu}_e$ Total	37	19	12	5		19

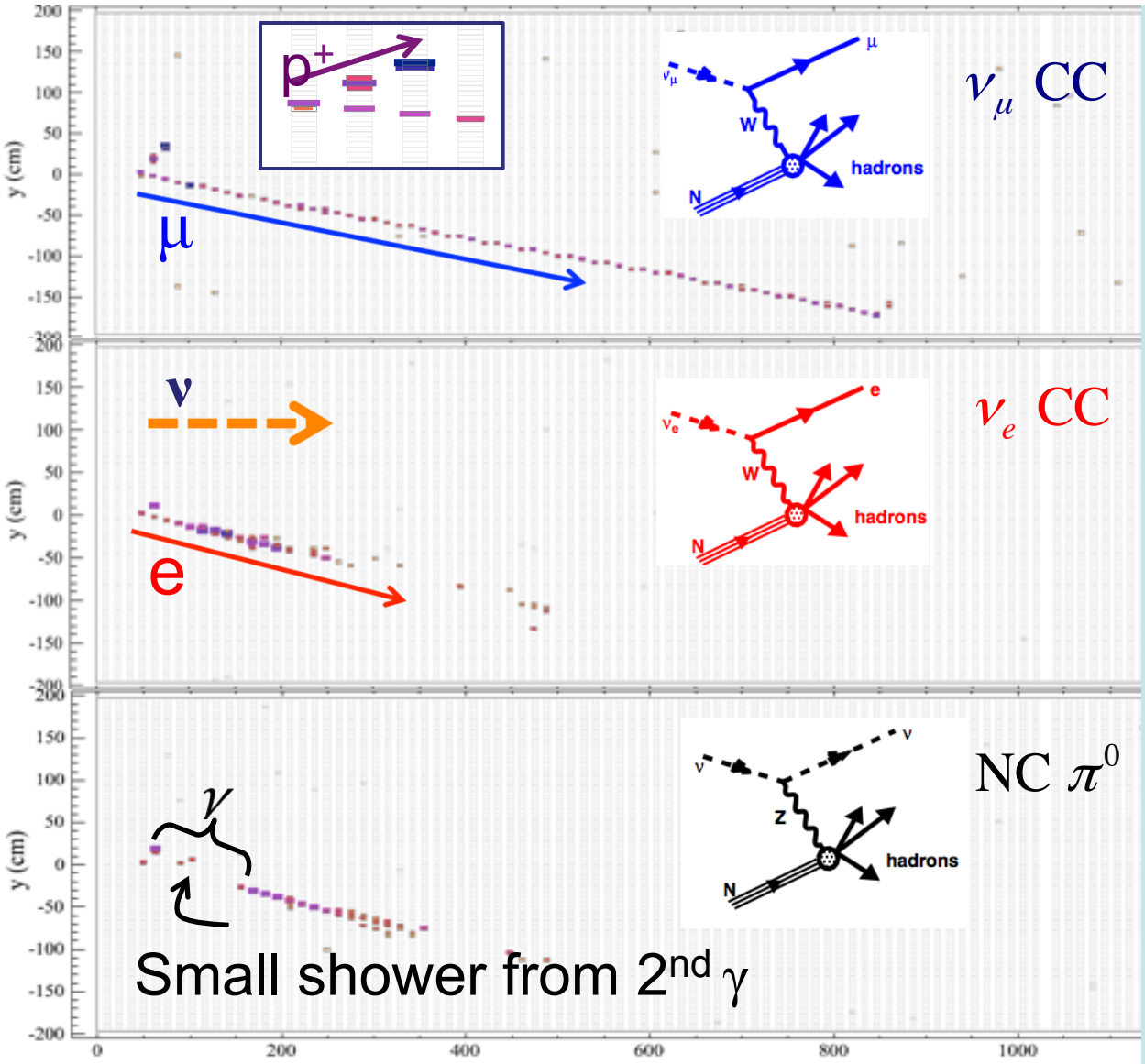
NOνA Near Detector On Surface (NDOS)

-Neutrino mode: 2.1×10^{20} POT.





Monte Carlo Events in NOνA



ν_μ Charged-current

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

ν_e Charged –current

Single shower with characteristic e-m shower development.

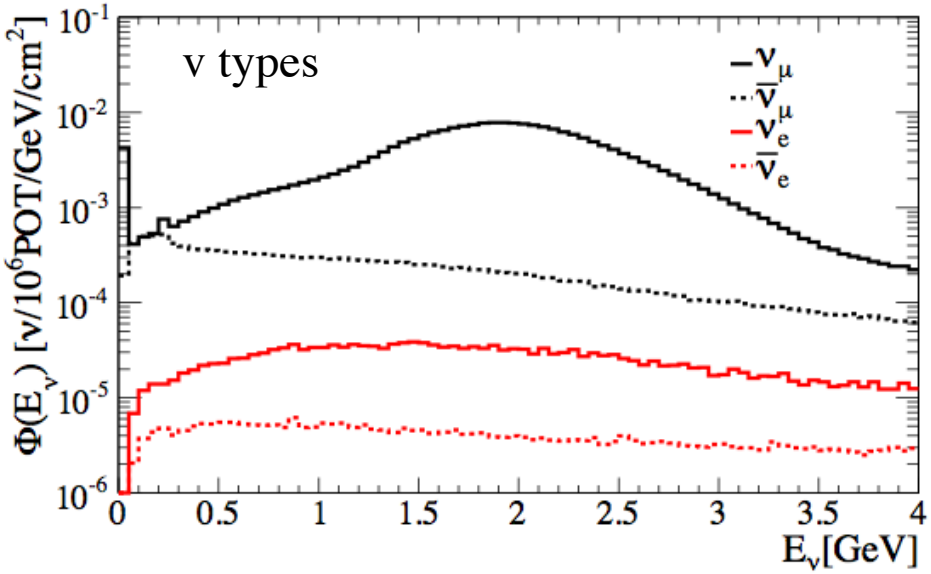
NC with π^0 in final state

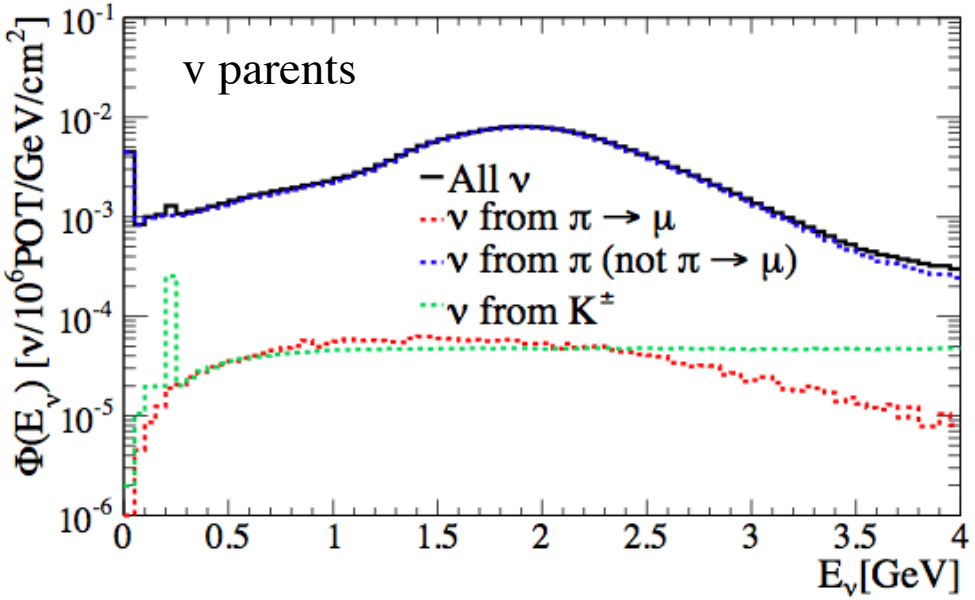
Possible gaps near event vertex, multiple displaced e-μ showers.

NOνA Near Detector

-NuMI flux simulation for Near detector in Medium Energy configuration.

-Neutrino mode.



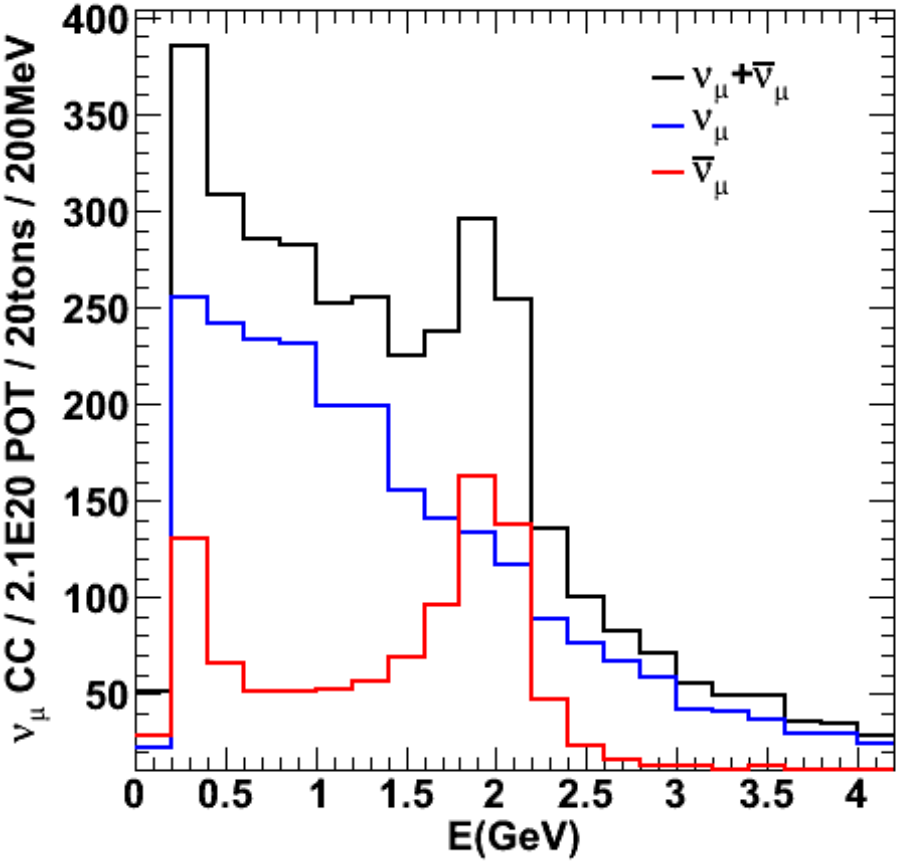


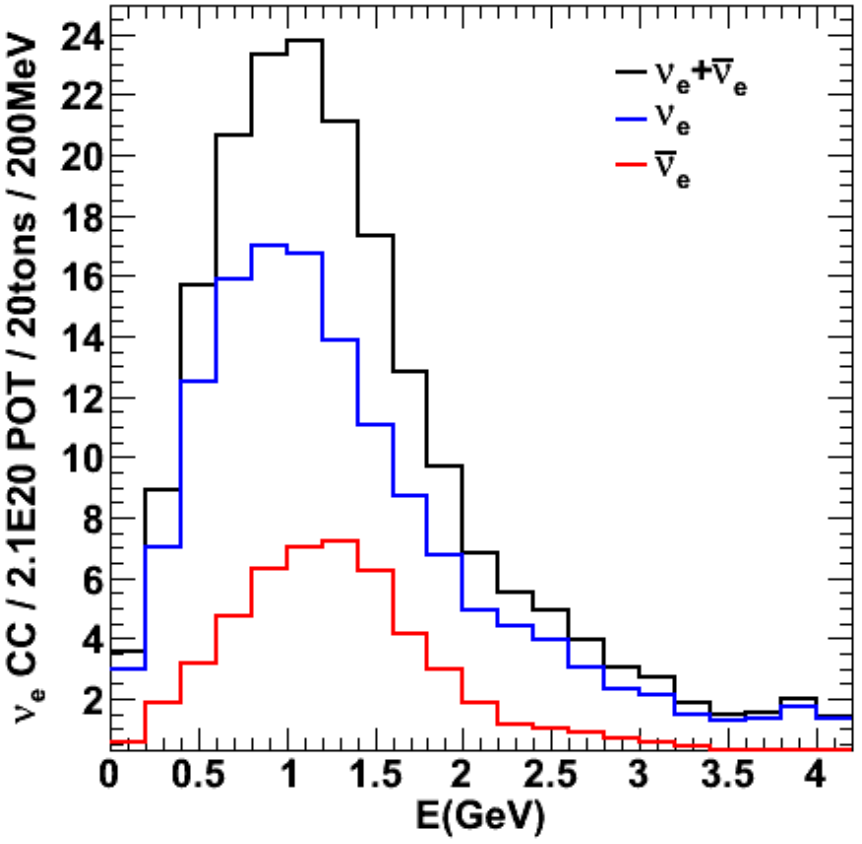
-Near detector sees ν's from π's.

-This component well measured at Near.

NOνA Near Detector On Surface (NDOS)

-Anti-neutrino mode: 2.1×10^{20} POT.





NOνA Near Detector On Surface (NDOS)

-NuMI beam currently operates in neutrino mode, expect anti-neutrino mode early next year.

-NDOS may get measurement in both modes.

-Anti-neutrino mode: 2.1×10^{20} POT.

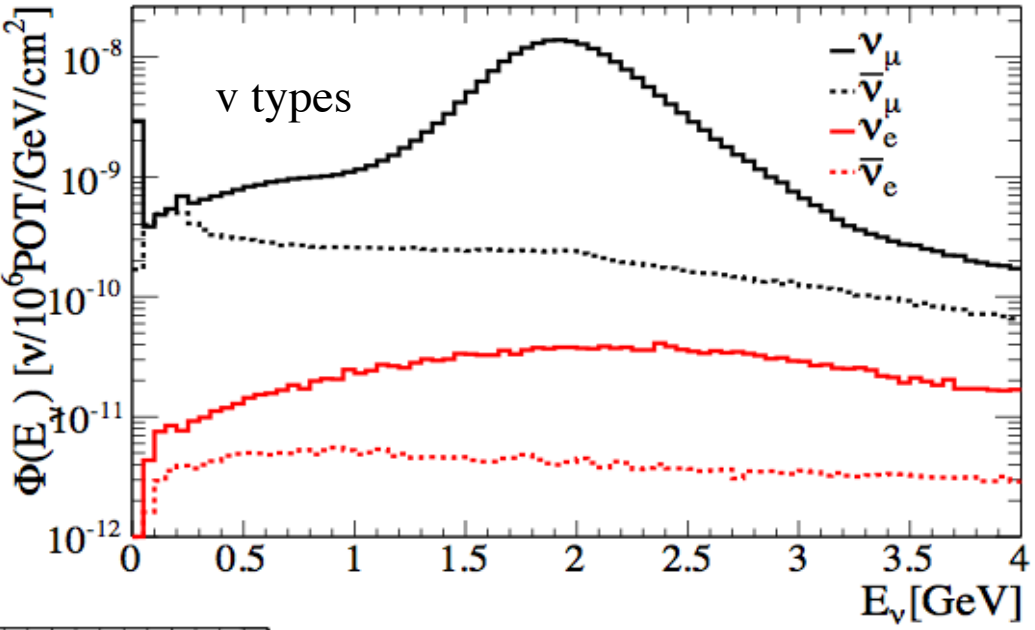
GeV	Total CC	CC QE	CC RES	CC DIS	CC COH	NC
ν_μ Total 1.6-2.4	2664 498	1259 143	789 216	505 134	21	1056 180
ν_e Total	306	148	106	48		113
$\bar{\nu}_\mu$ Total 1.6-2.4	873 363	471 139	262 151	119 65	19	507 170
$\bar{\nu}_e$ Total	52	28	17	6		28

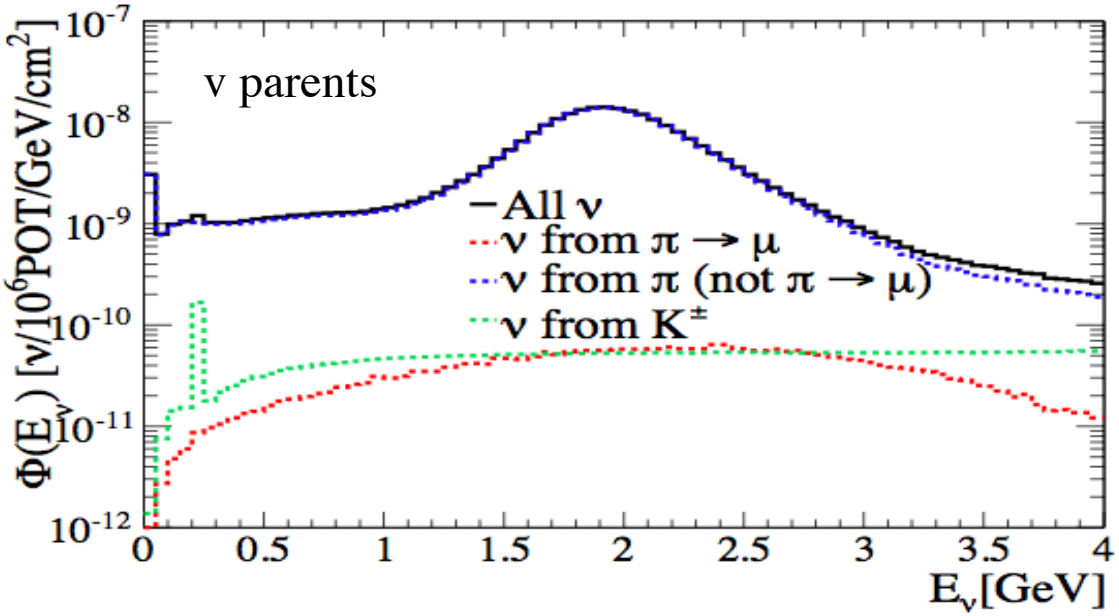
NOνA Far Detector

-NuMI flux simulation for Far detector in Medium Energy configuration.

-Neutrino mode.

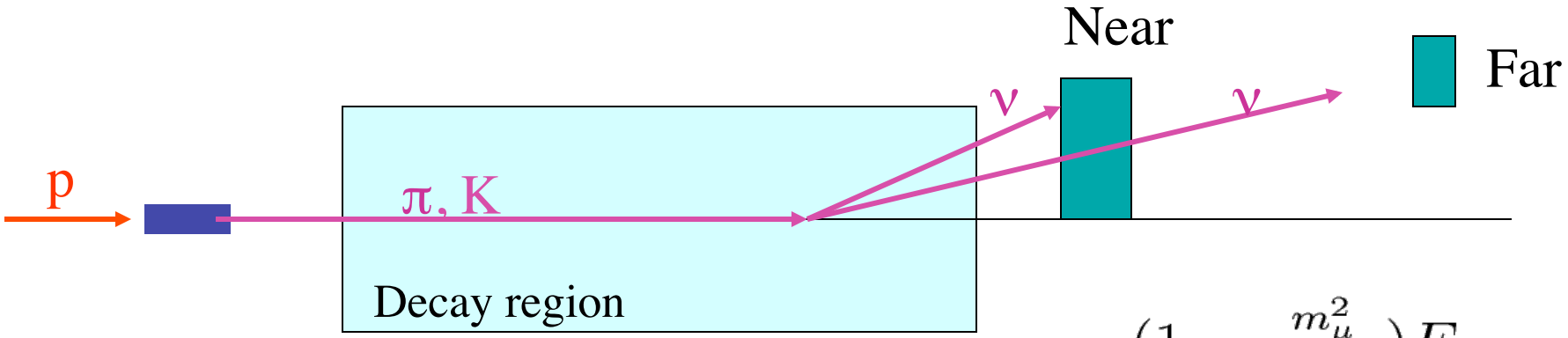
-Unoscillated spectra.





Near to Far Extrapolation

-Neutrino spectrum without oscillations at Far detector is similar but not identical to the Near spectrum.



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

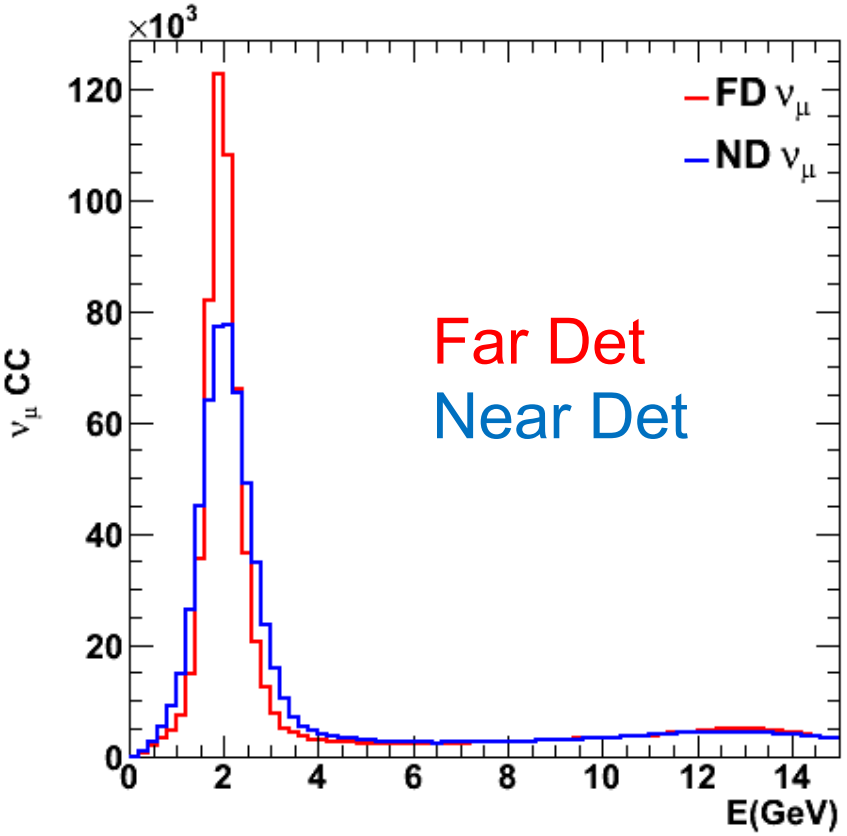
-Neutrino energy depends on angle wrt original meson direction and meson's energy.

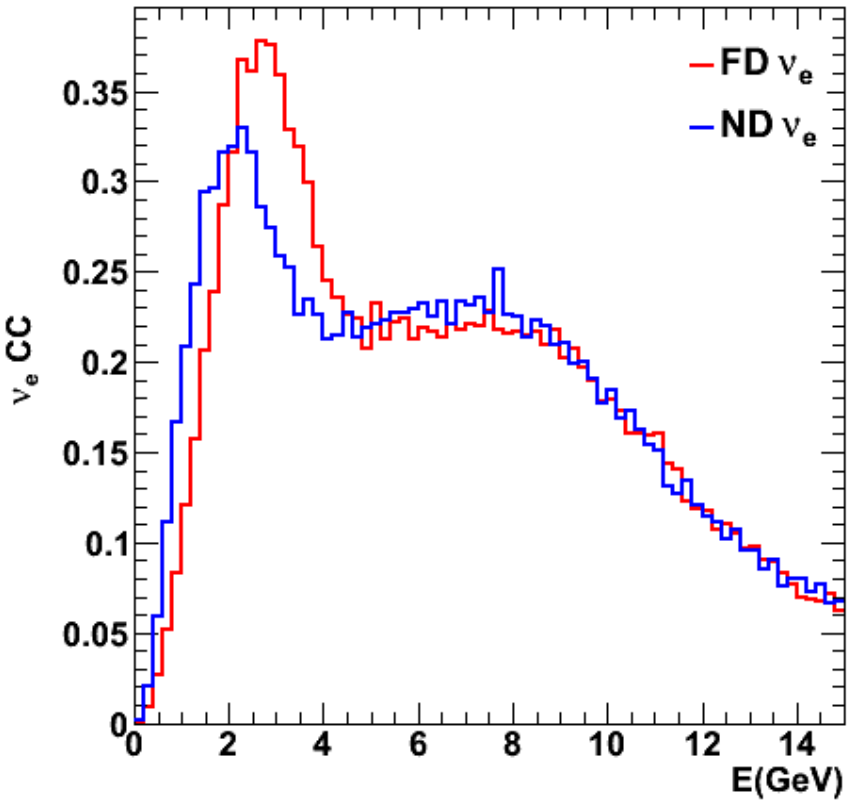
-Higher energy pions decay further along decay pipe.

-Angular distributions different between neutrinos seen at Near and Far detectors.

Near to Far Extrapolation

-Comparison of Neutrino spectra at Near and Far detectors
-Neutrino mode.

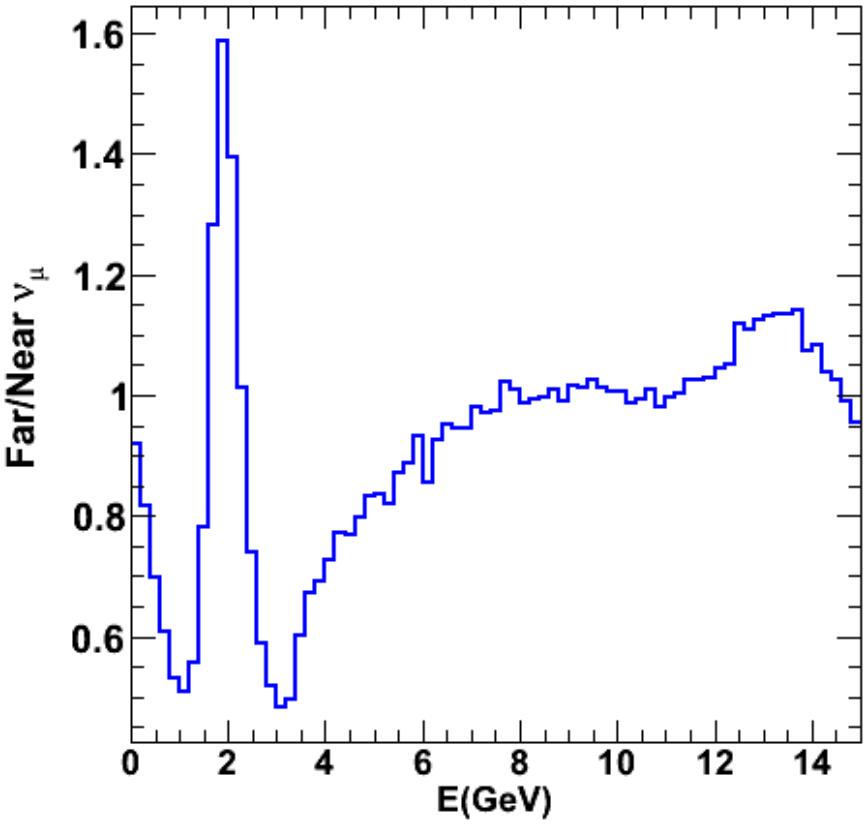


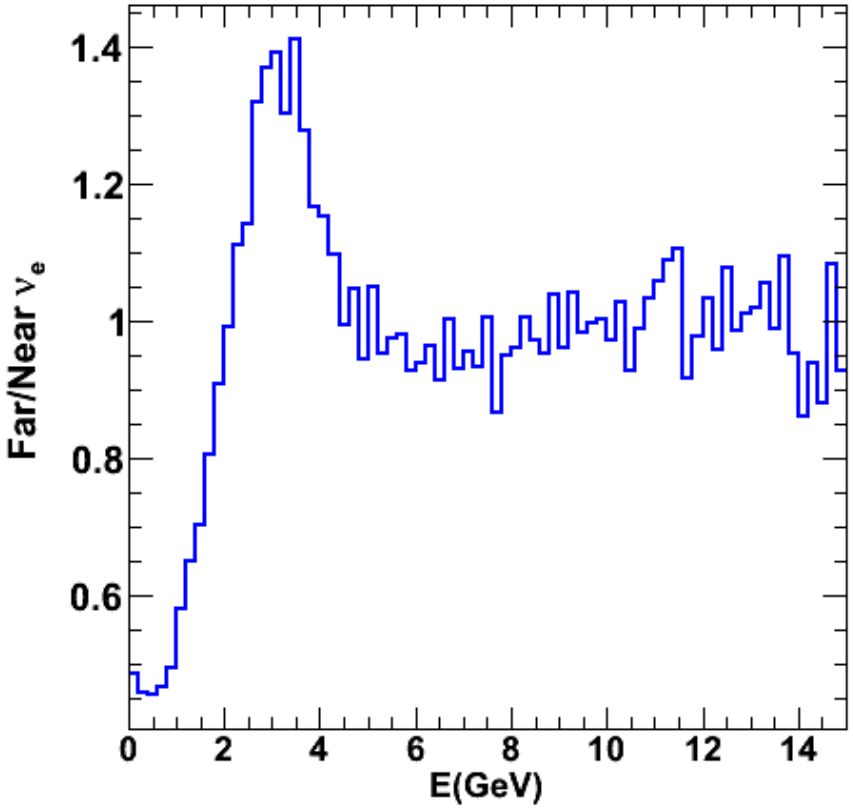


Normalized by area

Near to Far Extrapolation

-Ratio of Neutrino spectra at Near and Far detectors
-Neutrino mode.

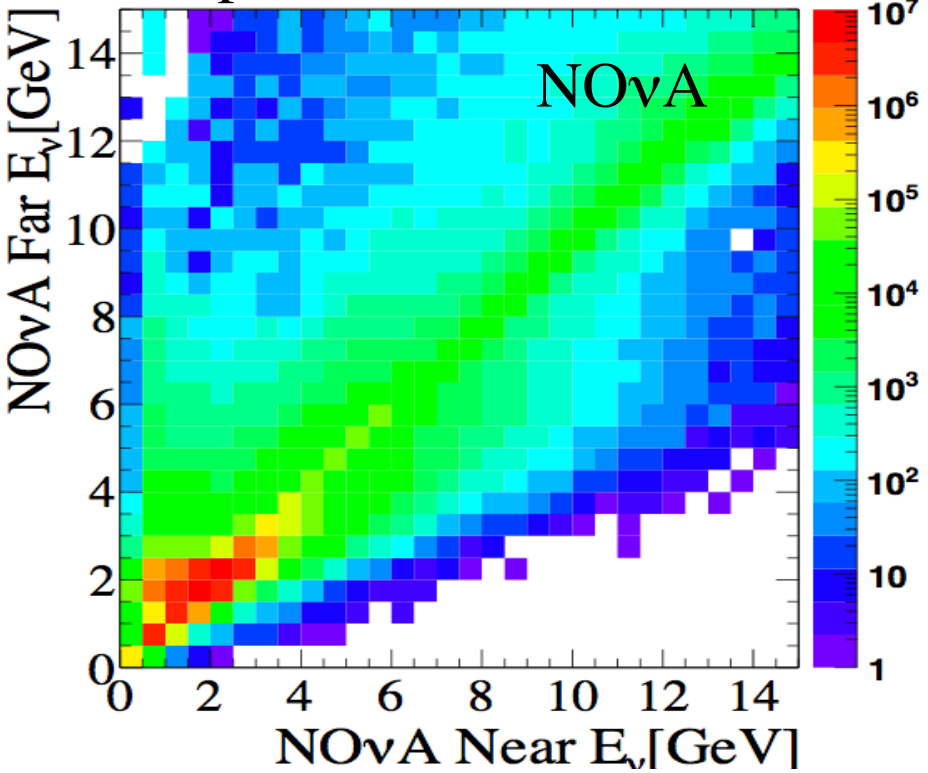


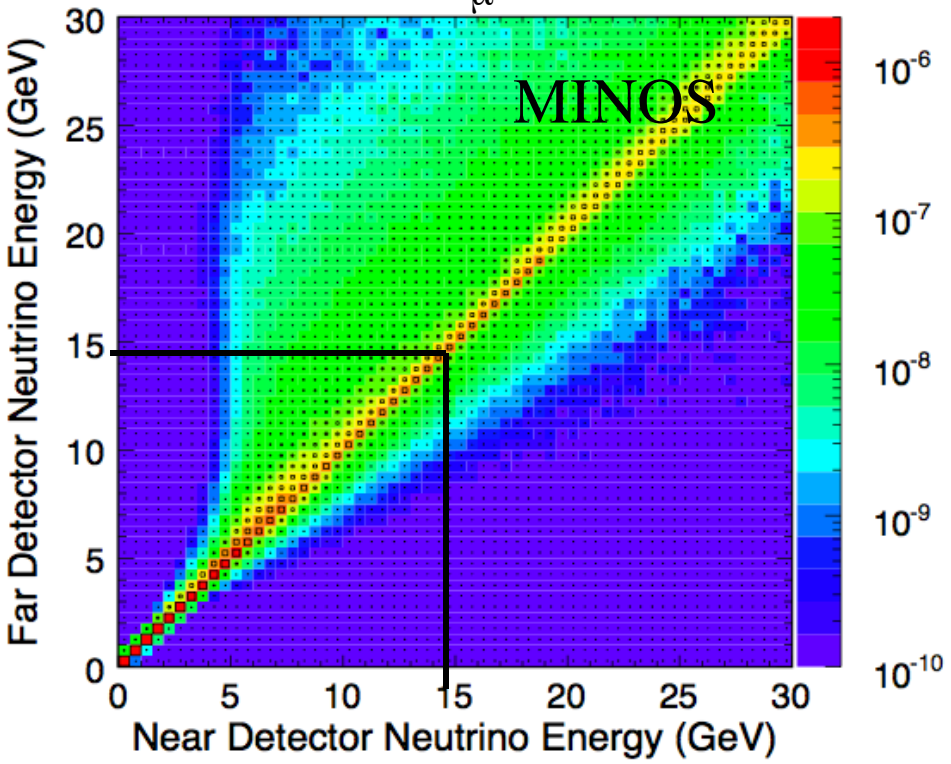


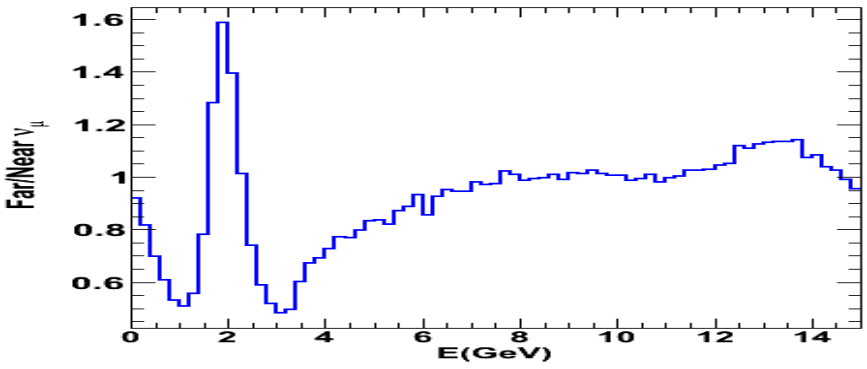
Near to Far Extrapolation

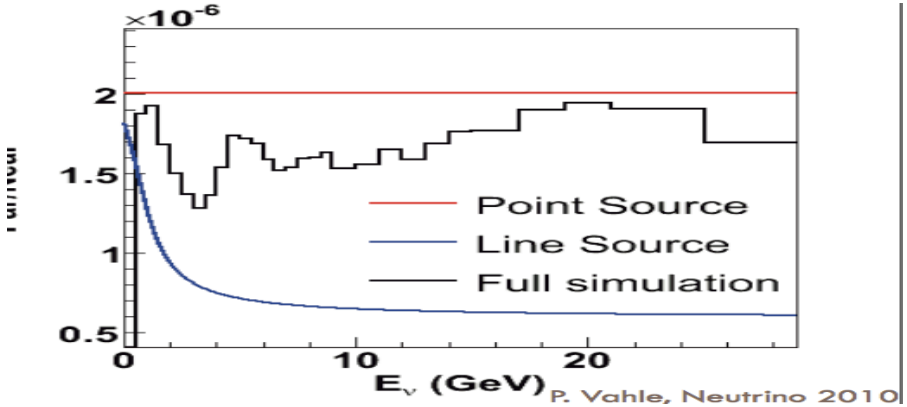
-Covariance Matrix correlating fluxes at Near and Far detectors.

-Compare NOνA beam matrix/ratio vs MINOS for ν_μ 's:



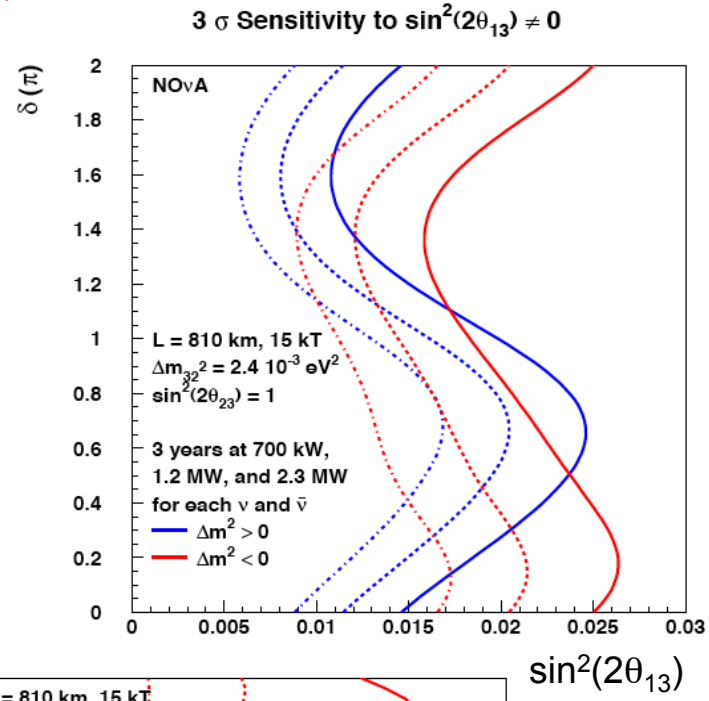




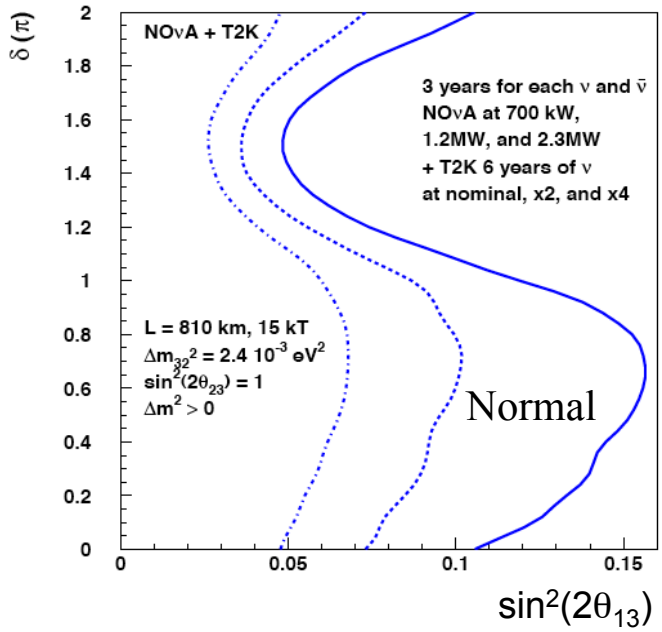


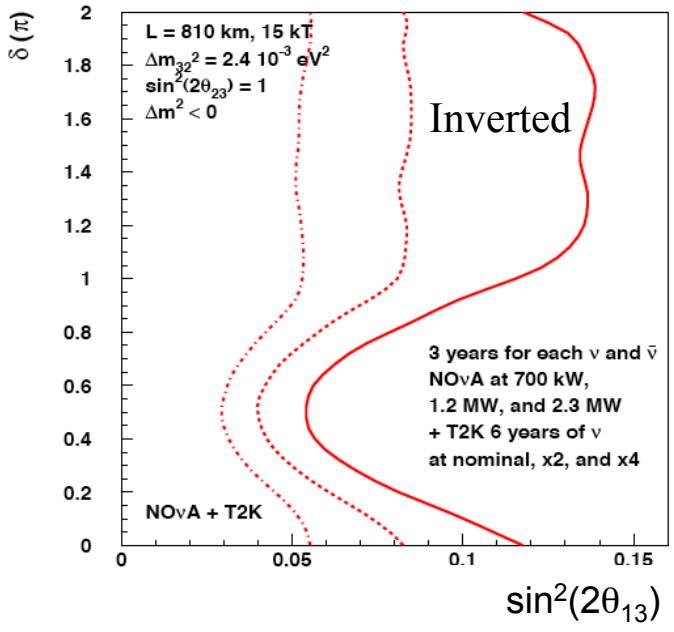
Near to Far Extrapolation

-Sensitivity calculations performed assuming a systematic uncertainty in the background extrapolation from the near to far detector of 10%.



95% CL Resolution of the Mass Ordering

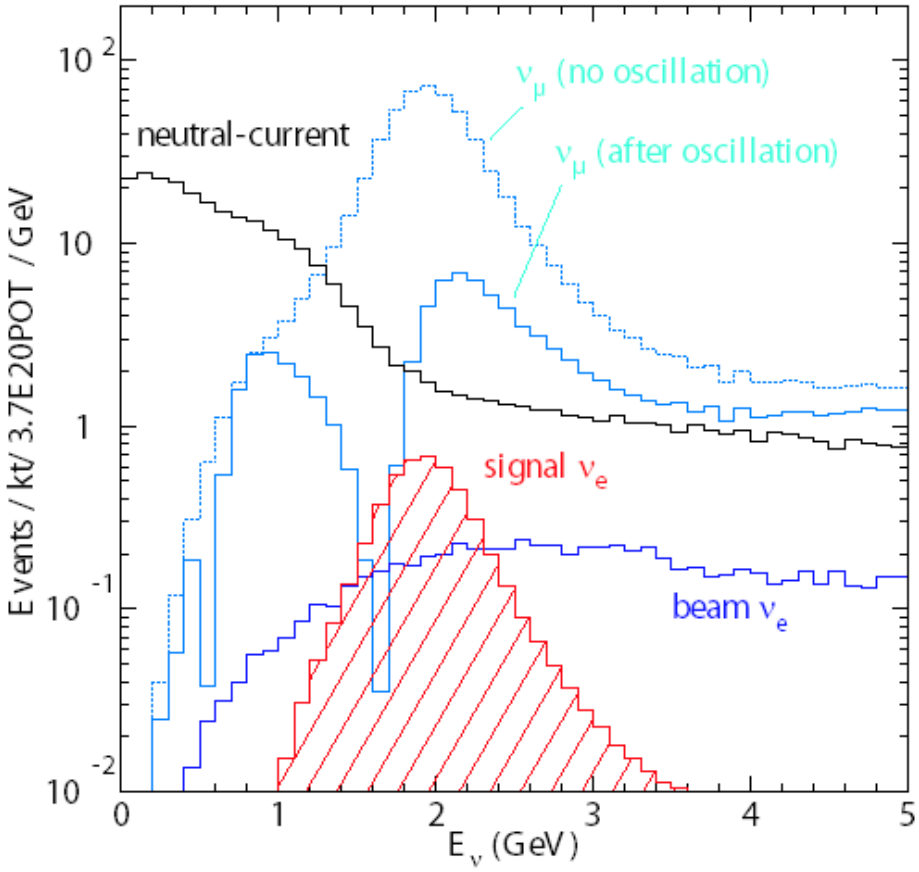




Near to Far Extrapolation

-For ν_e appearance analysis need extrapolation of backgrounds.

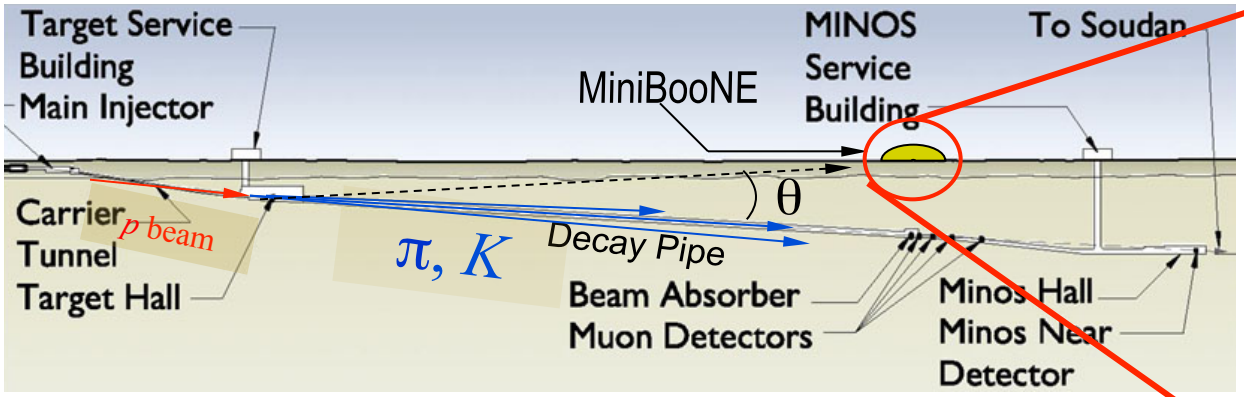
-Experience from MINOS:
- -used various beam configurations to enhance each background (NC, intrinsic ν_e 's, and ν_μ 's) in horn-off, HE, and LE configuration.
- -bkgd components decomposed and extrapolated independently.

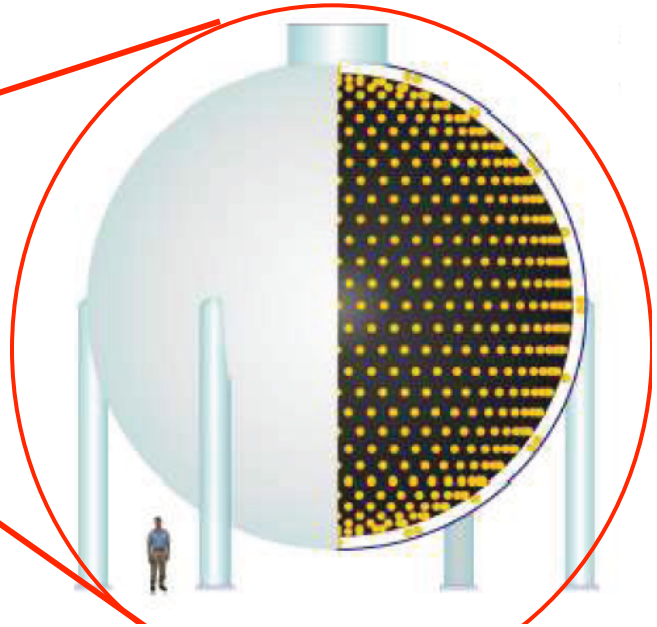


-However, off-axis beam more robust against change of beam configuration → less difference in bkgds.

-shower reconstruction for NOνA being developed.
-one option to consider for NOνA is MRCC (muon removed shower reconstruction), used in MINOS as well.

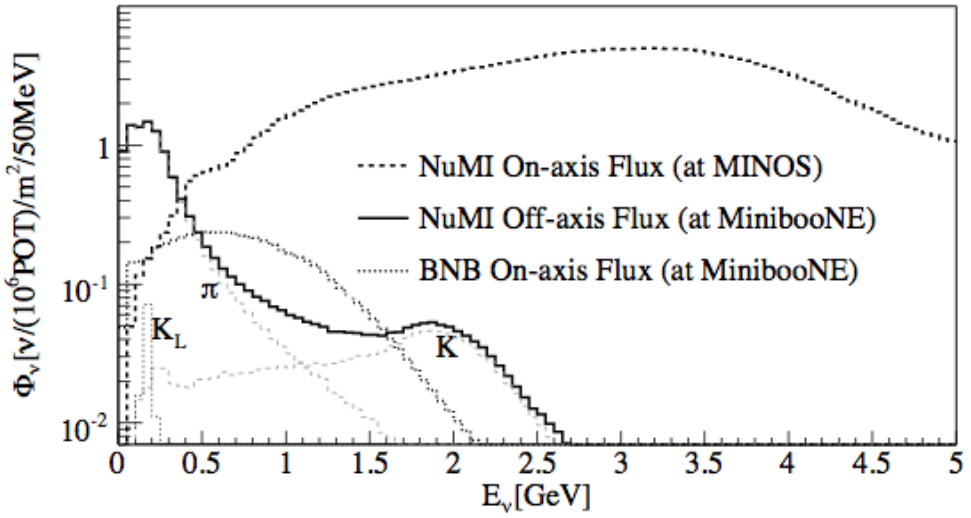
Events from NuMI detected at MiniBooNE





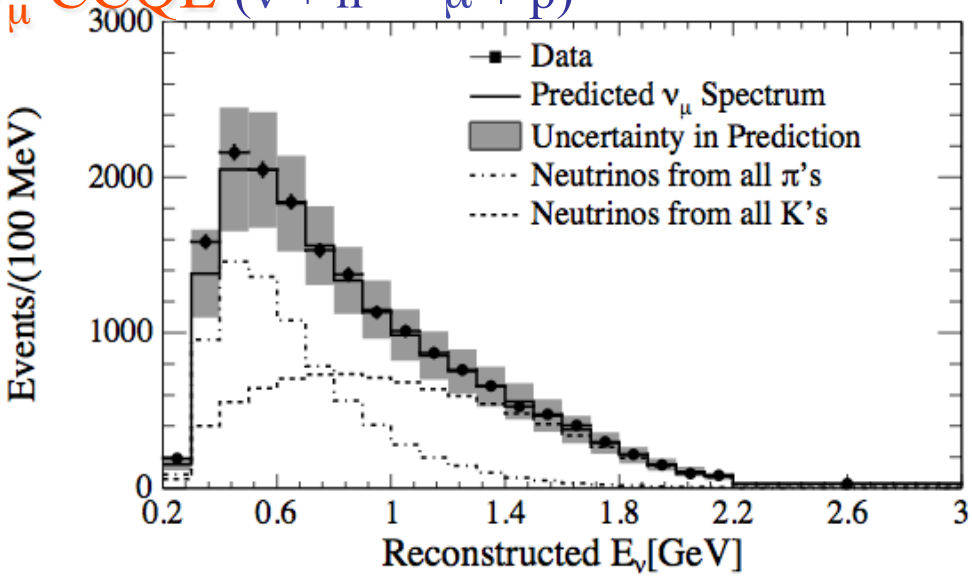
MiniBooNE detector is 745 m downstream of NuMI target.
MiniBooNE detector is 110 mrad off-axis wrt NuMI decay pipe.

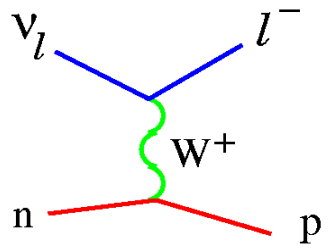
$$E_\nu \approx \frac{(1-\frac{m_\mu^2}{m_{\pi,K}^2})E_{\pi,K}}{1+\gamma^2\theta^2}$$



ν_μ CCQE and ν_e CCQE samples from NuMI at MiniBOONE

ν_μ CCQE ($\nu + n \rightarrow \mu + p$)



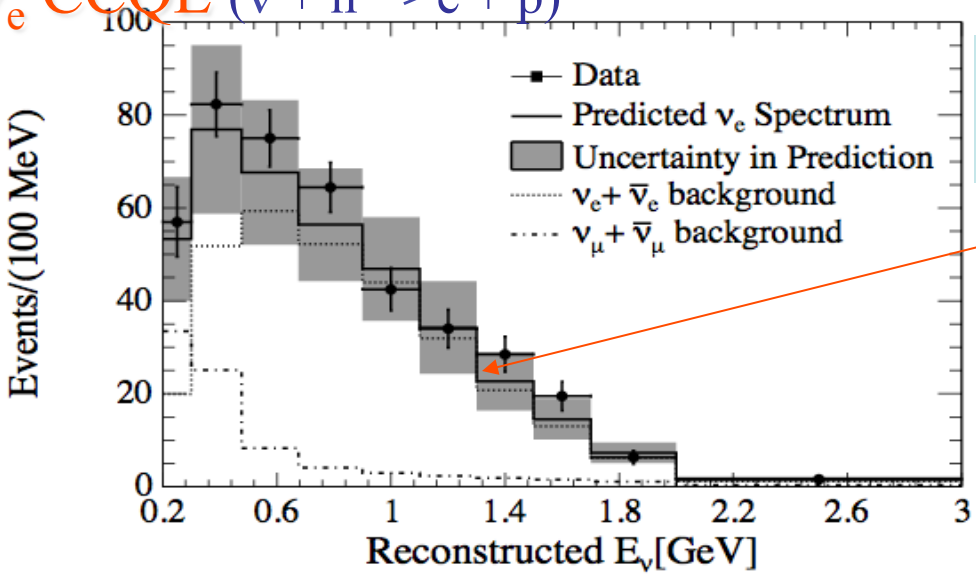


These results show that reliable predictions for an off-axis beam can be made.

Details

P.Adamson et al, PRL 102, 211801 (2009)
arXiv:0809.2447 [hep-ex].

ν_e CCQE ($\nu + n \rightarrow e + p$)



Very different backgrounds compared to BNB (Kaons vs Pions)!

Systematics not yet constrained!

We collected more data from NuMI at MiniBooNE.