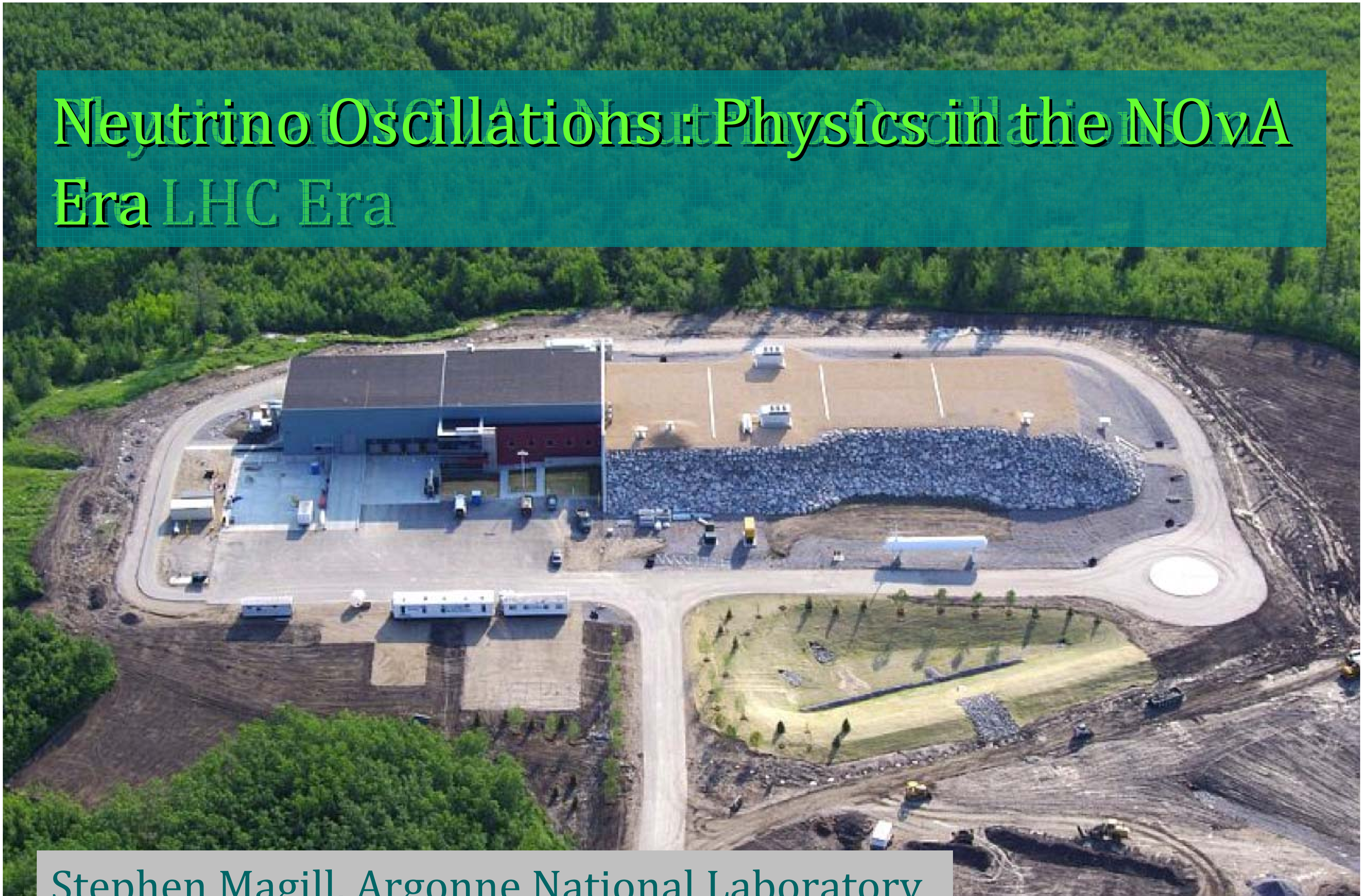
Neutrino Oscillations : Physics in the NOvA Era



Stephen Magill, Argonne National Laboratory
- for the NOvA Collaboration

Outline

- ❑ ν Mass, Mixing and Oscillations
- ❑ ν Oscillation Physics Goals of NOνA
  - ν_e Appearance Physics
  - ν_μ Measurements
- ❑ NOνA Experiment
- ❑ NDOS Operation
- ❑ Other Goals for NOνA
- ❑ Summary

NOνA Collaboration

24 Institutions
110 Physicists

Neutrino Mass → Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

Neutrinos observed as flavor states - ν_e, ν_μ, ν_τ which are unique combinations of mass states - ν_1, ν_2, ν_3

Propagate as mass components (mass states have different masses → different propagation speeds)
Upon detection, mass state combination can be different than at creation

→ neutrinos oscillate between flavor states!

Oscillation probability (P) depends on :

→ neutrino energy (E)
→ distance traveled (L)
→ difference in squared mass ($\Delta m^2_{ij} = m_i^2 - m_j^2$)
→ mixing amplitude ($U_{\alpha i}$)

Minima and maxima in $P(\nu_\alpha \rightarrow \nu_\beta)$ occur at distinct L/E for a given oscillation

→ long baseline experiments are situated at desired L for the neutrino energy E, i.e., at the first oscillation maximum

U – the PMNS Mixing Matrix

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

$\nu_\mu \rightarrow \nu_\tau$

(23) Sector: Atmospheric + Accelerator

L/E ~500 km/GeV

$|\Delta m^2_{32}|$ (Δm^2_{atm}) = 2.3 × 10^{-3} eV^2

$\sin^2(2\theta_{23})$ >0.96

$\nu_e \rightarrow \nu_\mu, \nu_\tau$

(12) Sector: Reactor + Solar

L/E ~15000 km/GeV

Δm^2_{21} (Δm^2_{sol}) = 7.5 × 10^{-5} eV^2

$\tan^2\theta_{12}$ = 0.45

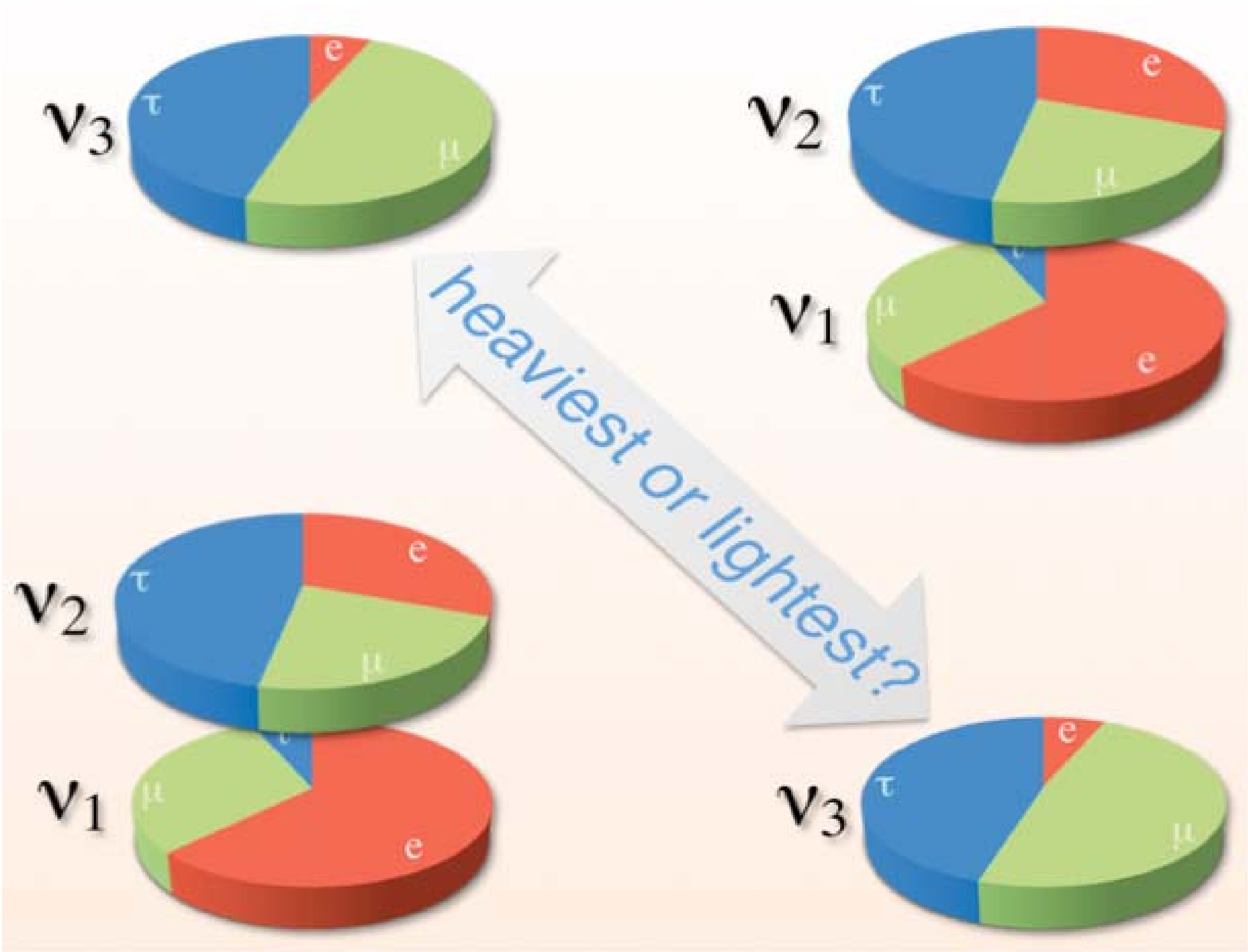
$\nu_\mu \rightarrow \nu_e$

(13) Sector: 6 events seen so far!

Analogous to CKM Quark Mixing Matrix :

- Mixing in lepton sector larger than in quark sector
- θ_{23} maximal, θ_{12} large, θ_{13} very small, zero?
- CP violation present in lepton sector? Large enough to explain observed matter-antimatter asymmetry?

The Neutrino Mass Hierarchy



Normal Hierarchy (NH) Inverted Hierarchy (IH)

$P(\nu_\mu \to \nu_e)$ in vacuum

$$P(\nu_\mu \to \nu_e) = |U^*_{\mu 3}\, \Phi_1\, U_{e3} + U^*_{\mu 2}\, \Phi_2\, U_{e2} + \cancel{U^*_{\mu 1}\, \Phi_3\, U_{e1}}|^2$$

where $\Phi_k = \exp(-im^2_k L/2E)$ k=1,2,3

$U^\dagger U = UU^\dagger = 1$ assumption

$$= |2U^*_{\mu 3}\, U_{e3} \sin\Delta_{31} \exp(-i\Delta_{32}) + 2U^*_{\mu 2}\, U_{e2} \sin\Delta_{21}|^2$$

where $\Delta_{ij} = \Delta m^2_{ij} L/4E$

$$\Delta_{32} \equiv \frac{1.27 \Delta m^2_{32} [\text{eV}^2] L\ [\text{km}]}{E\ [\text{GeV}]} = \frac{1.27 \cdot 2.32 \times 10^{-3} \cdot 810}{2.1} \simeq 1.1$$

For NOvA:
$$\Delta_{31} \equiv \frac{1.27 \Delta m^2_{31} [\text{eV}^2] L\ [\text{km}]}{E\ [\text{GeV}]} \simeq \Delta_{32}$$

$$\Delta_{21} \equiv \frac{1.27 \Delta m^2_{21} [\text{eV}^2] L\ [\text{km}]}{E\ [\text{GeV}]} = \frac{1.27 \cdot 7.58 \times 10^{-5} \cdot 810}{2.1} \simeq 0.04$$

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}} \exp(-i(\Delta_{32} + \delta)) + \sqrt{P_{sol}}|^2$$

-(+) δ for $\nu(\bar{\nu})$

$$P_{atm} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\Delta_{31}$$
$$P_{sol} = \cos^2\theta_{23} \cos^2\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21}$$
$$P(int) = 2\sqrt{P_{atm}}\sqrt{P_{sol}}(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta)$$

CP violating term
- for neutrinos
+ for anti-neutrinos

$P(\nu_\mu \rightarrow \nu_e)$ through matter

$$P(\nu_\mu \to \nu_e) \simeq |\sqrt{P_{\rm atm}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\rm sol}}|^2$$
$$= P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm} P_{\rm sol}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$\sqrt{P_{\rm atm}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}$$

$$\sqrt{P_{\rm sol}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

dependence on relative sign of $\boldsymbol{\Delta_{31}}$ and ***a***

"fake" CP violation as ***a*** changes sign for antineutrinos

$$a = G_F N_e / \sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

$aL = 0.08$ for $L = 295$ km

$aL = 0.23$ for $L = 810$ km

From M. Messier

So, oscillation probability is enhanced (reduced) for neutrinos (antineutrinos) with normal hierarchy; the opposite for inverted hierarchy

And, the effect is larger for NOνA than for, e.g., T2K

NOνA Physics Goals

- Search for appearance of ν_e and $\bar{\nu}_e$ indicating oscillations of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- ν_e, $\bar{\nu}_e$ appearance – Primary goals of NOνA :
  - Measure the *mixing angle θ_{13}*
  - Determine the *neutrino mass hierarchy* by comparing ν and $\bar{\nu}$ oscillations
  - Study the phase parameter for *CP violation (δ_{CP})*
- ν_μ measurements - Secondary goals of NOνA :
  - Precision measurement of θ_{23}
  - Precision measurement of Δm^2_{32}
- Also :
  - Search for sterile neutrinos
  - Measurement of neutrino NC cross sections at 2 GeV
  - Measurement of neutrinos from a galactic supernova

NOνA Sensitivity to θ_{13}

NOνA sensitivity to (non-zero) θ_{13}

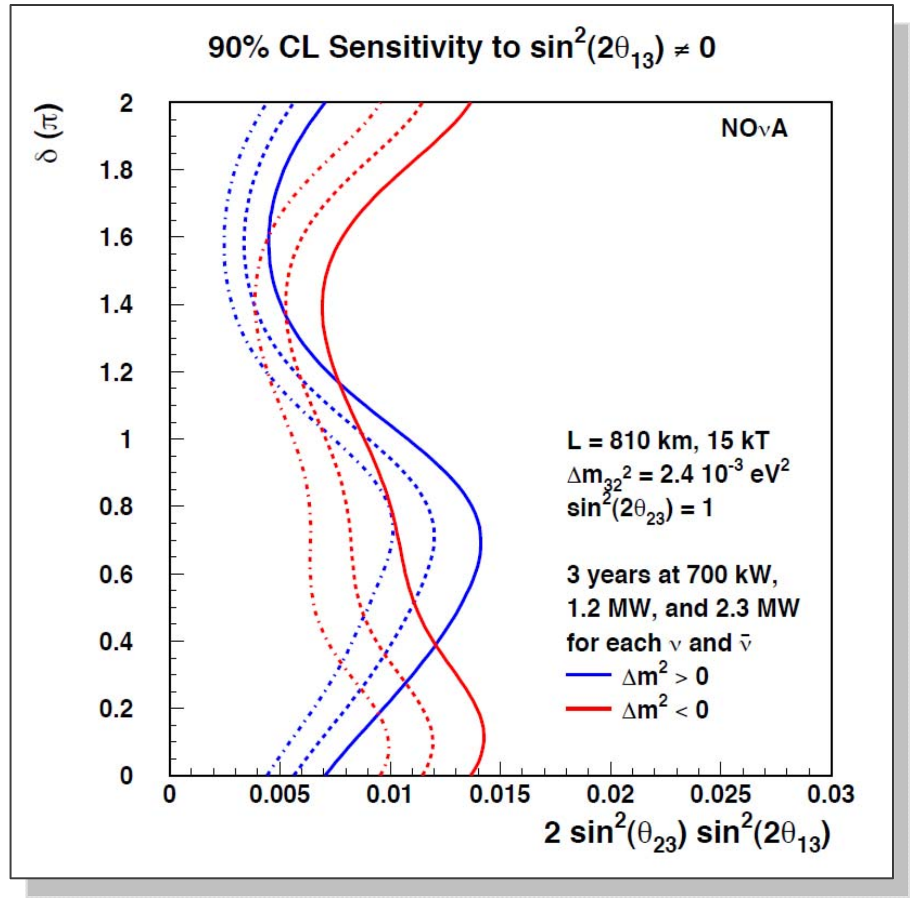
Shown for full range of CP phase (δ)

Normal mass hierarchy (blue) and inverted mass hierarchy (red)

For a 15 kT Far Detector, 10% systematics on backgrounds

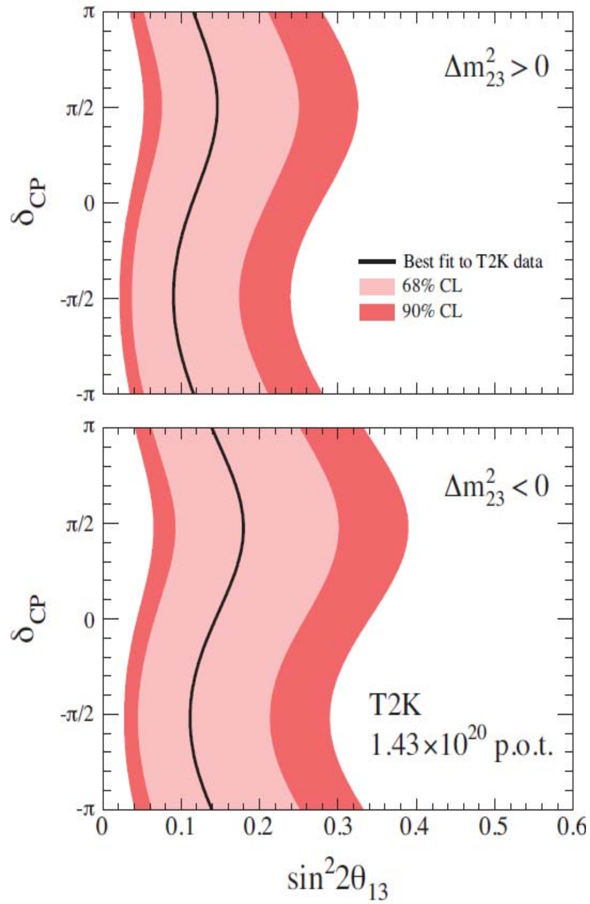
3 years running for each ν and νbar

700 kW beam (solid) and 2 possible beam upgrades (dashed)

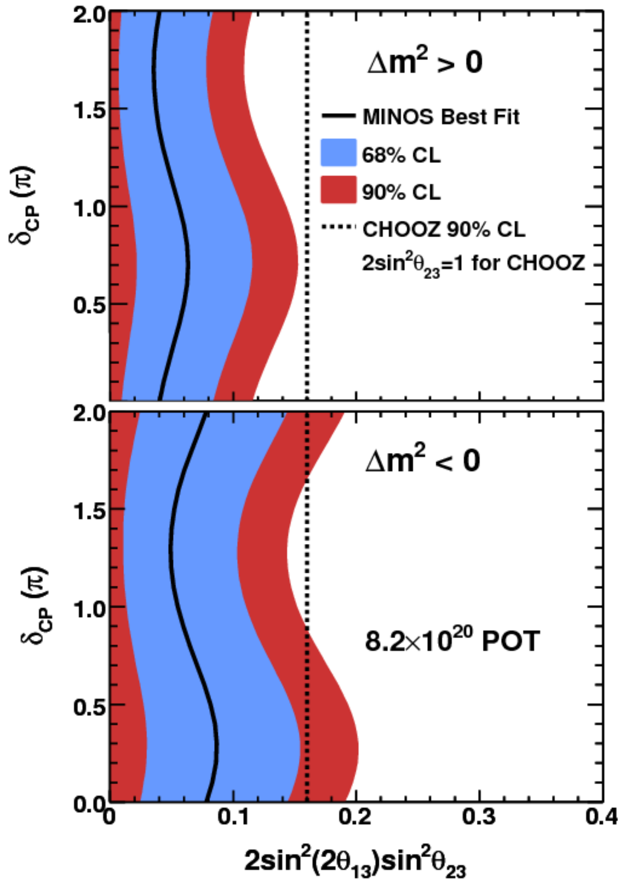


θ_{13} results from T2K, MINOS, Double Chooz

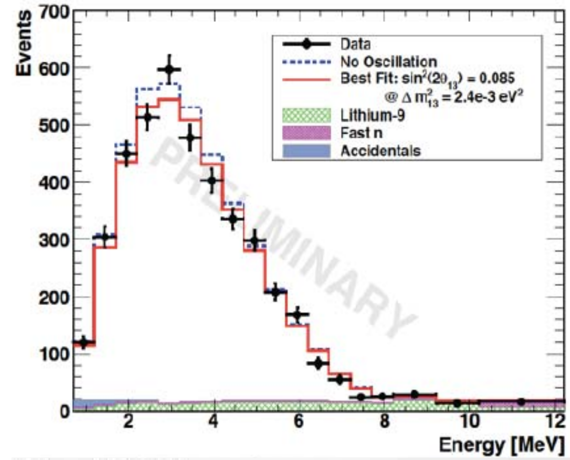
T2K

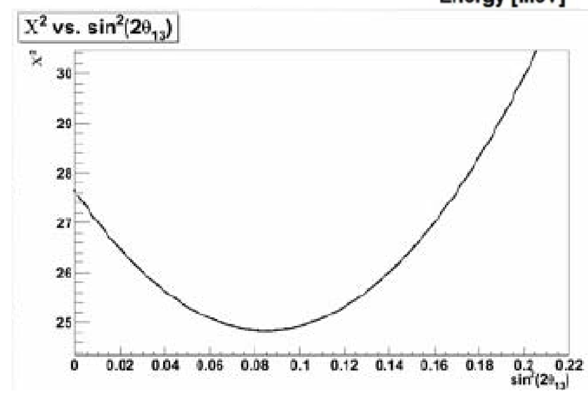


MINOS



Double Chooz





T2K Best Fit point(s)
(Δm^2_{32}=2.4x10^{-3} eV^2, $\sin^2(2\theta_{23})$=1, δ_{CP}=0)

$\sin^2(2\theta_{13})$ = 0.11 NH
$\sin^2(2\theta_{13})$ = 0.14 IH

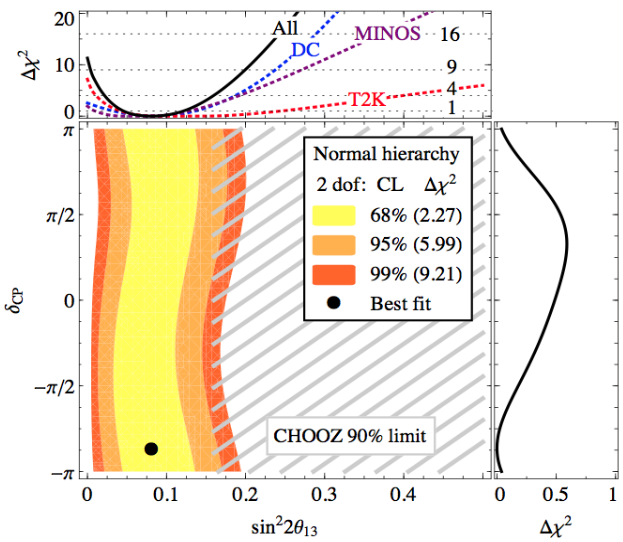
MINOS Best Fit point(s)
(Δm^2_{32}=2.3x10^{-3} eV^2, δ_{CP}=0)

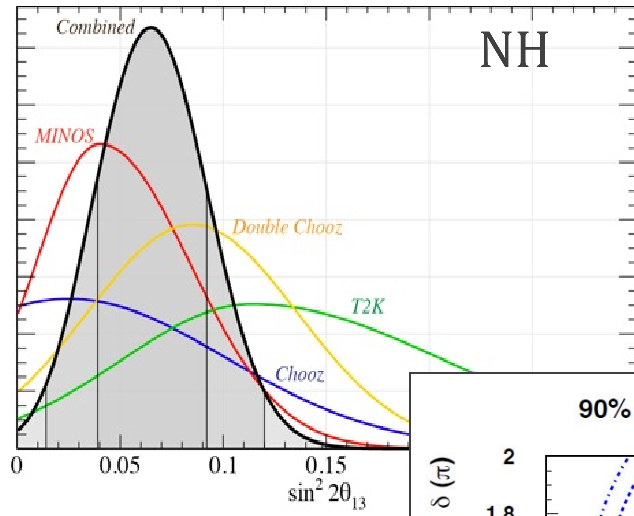
$2\sin^2\theta_{23}\sin^2(2\theta_{13})$ = 0.041 NH
$2\sin^2\theta_{23}\sin^2(2\theta_{13})$ = 0.079 IH

DC Best Fit point
(Δm^2_{31}=2.4x10^{-3} eV^2)

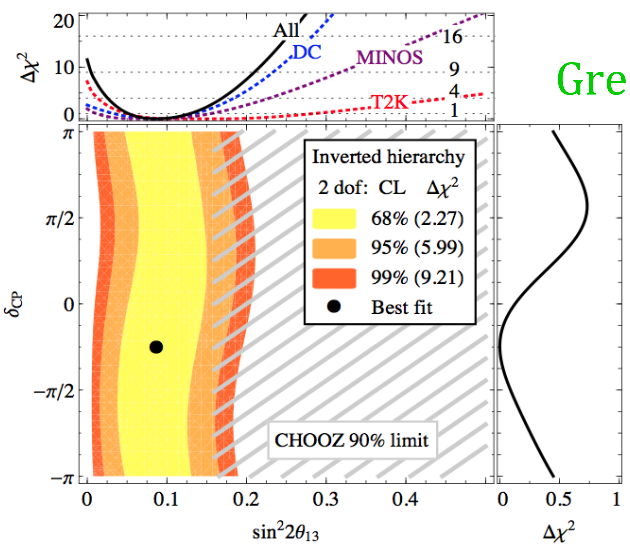
$\sin^2(2\theta_{13})$ = 0.085

Implications of Recent Results for NOνA

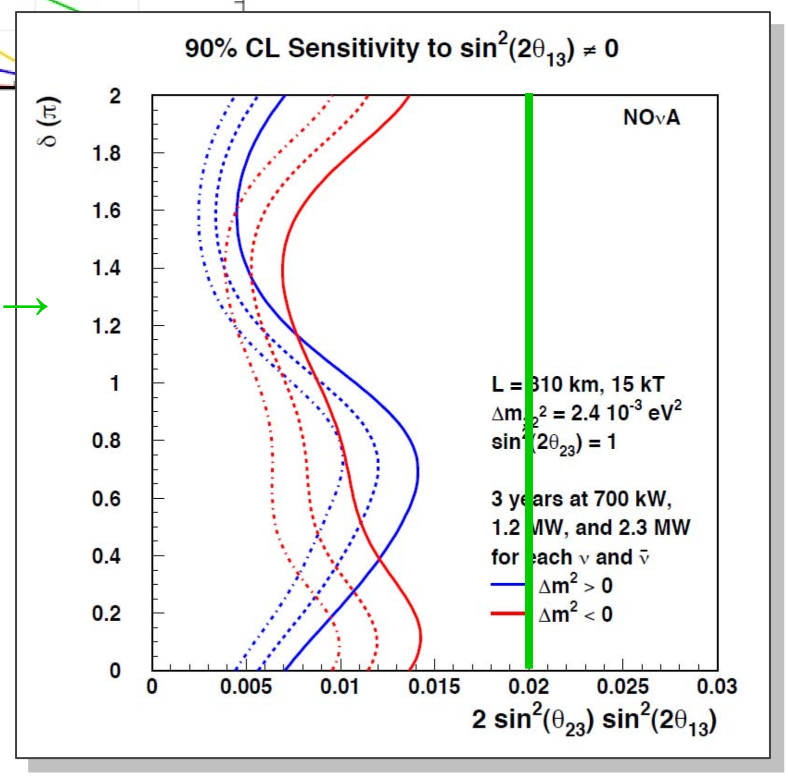




← Mean of combined fit is off this page →

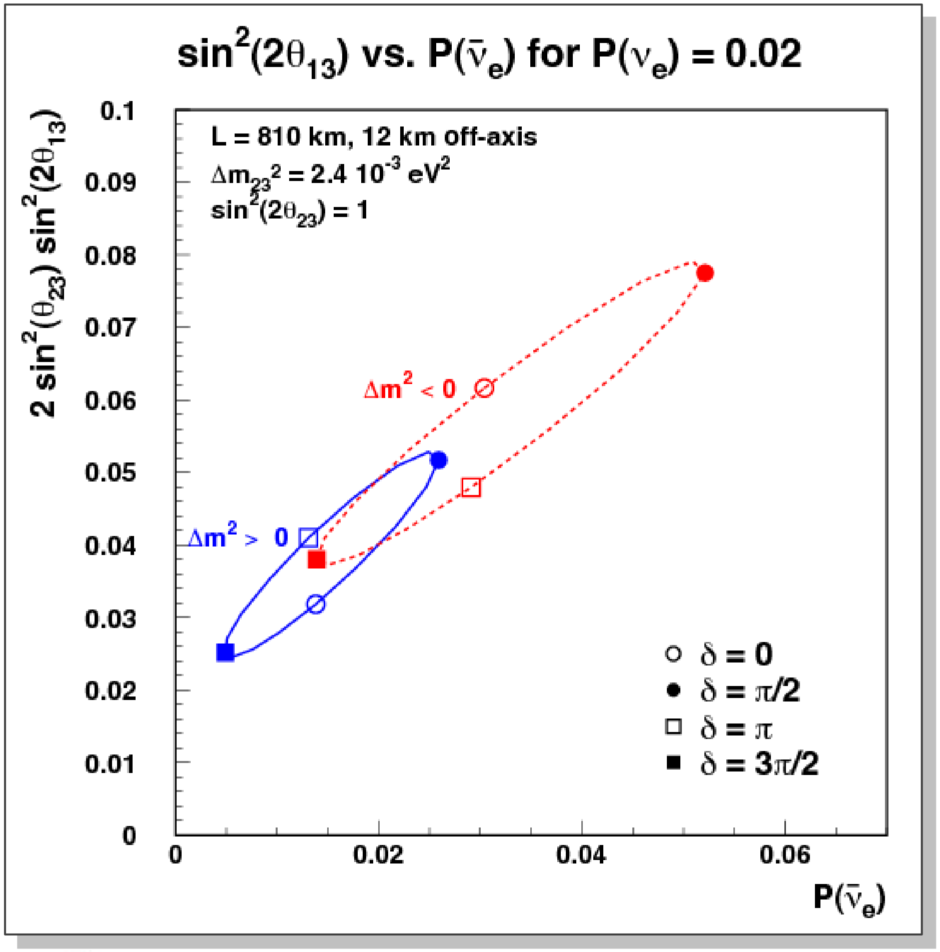


Green line is 90% CL from T2K + MINOS →
(previous slide)



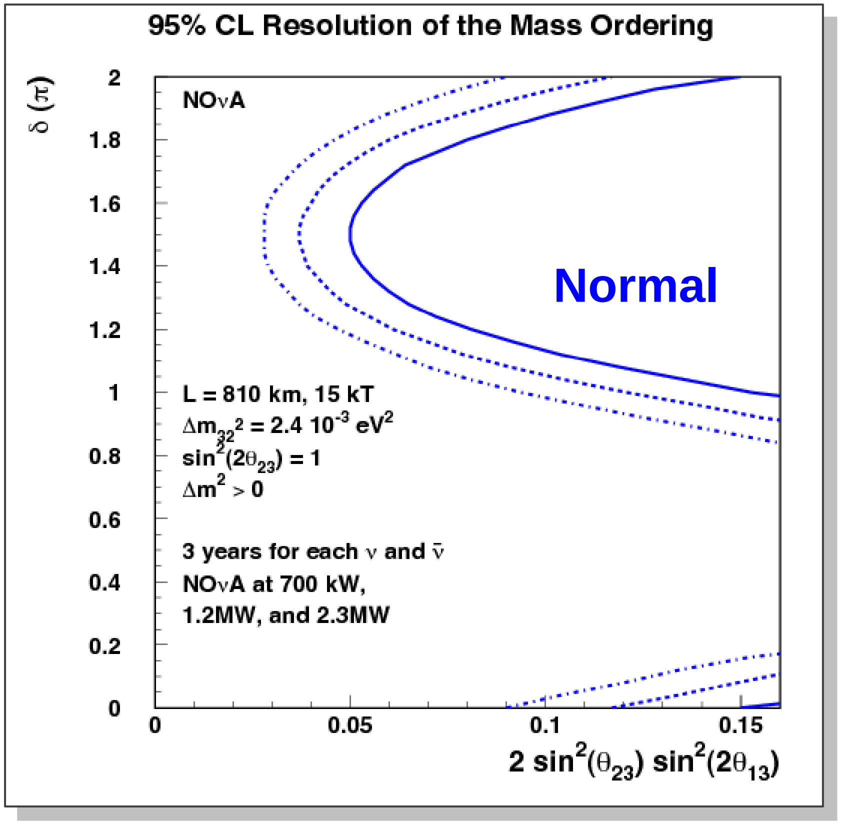
NOνA Sensitivity to Neutrino Mass Hierarchy

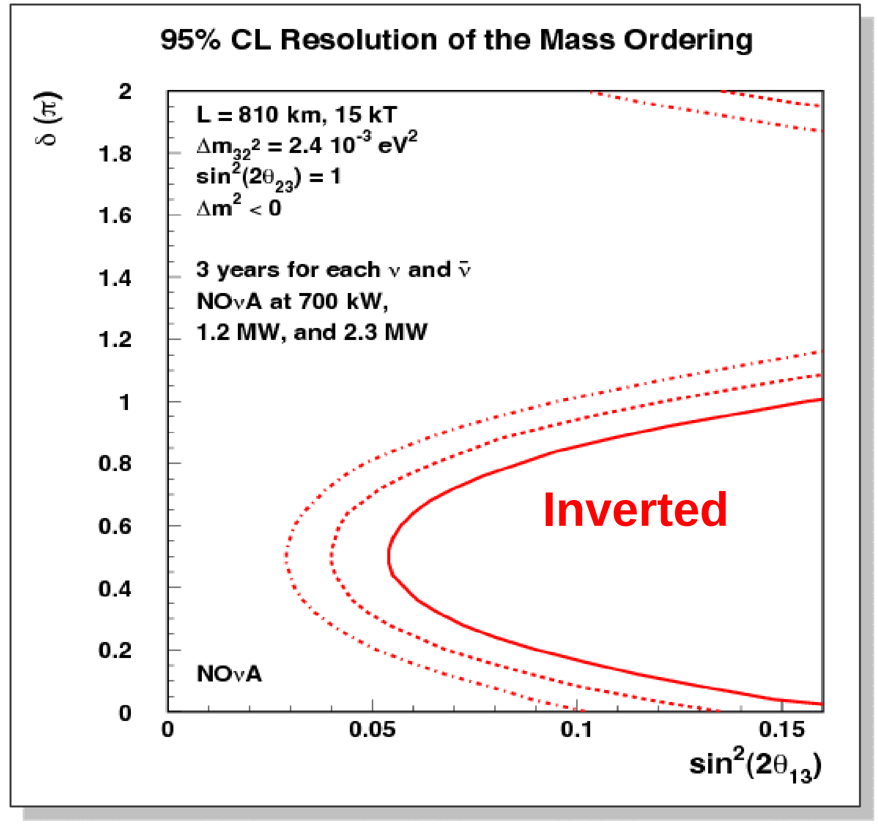
Comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$:
For a measured $P(\nu_e)$, a plot of $2\sin^2\theta_{23}\sin^2(2\theta_{13})$ vs $P(\overline{\nu}_e)$ has overlapping ellipses of normal and inverted hierarchy as the CP phase δ changes from $0 \rightarrow 2\pi$



- If matter effects and CP effect have the same signs (near $\pi/2$ for inverted hierarchy or near $3\pi/2$ for normal hierarchy), then NOνA can determine the mass ordering alone
- However, if δ is in a region where the ellipses overlap, then there is ambiguity in the NOνA-only measurement
- Resolved by:
  - Measurement at a different baseline
  - Measurement at a different oscillation maximum

Mass Hierarchy Contours for NOνA

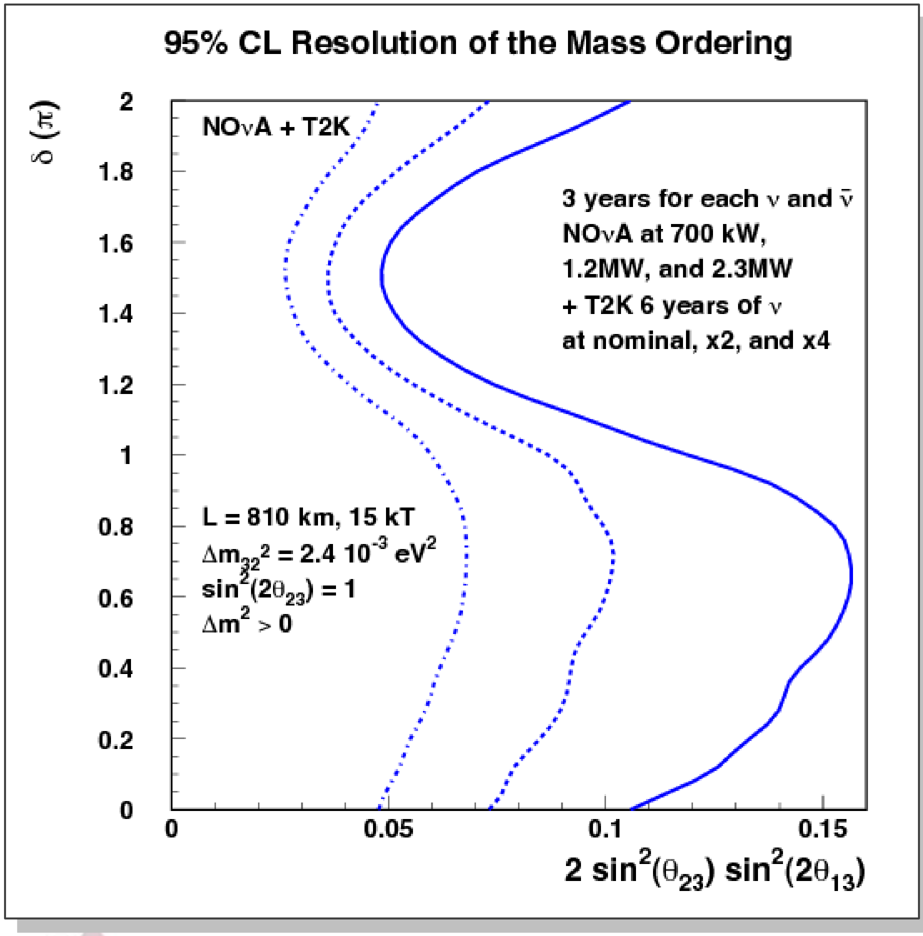


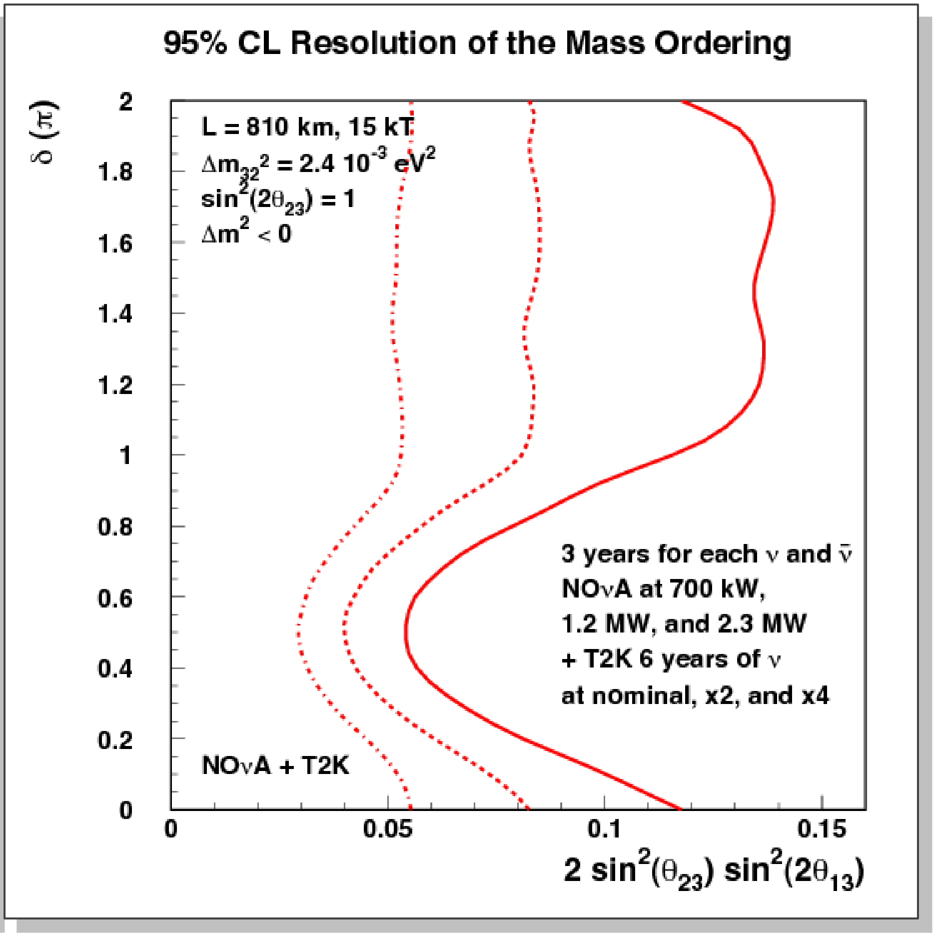


- Assumes 15 kT detector, 6 years of running (neutrino and antineutrino)
- Intensities at the baseline 700 kW (upgrades of 1.2 MW and 2.3 MW)
- NOνA may resolve the mass hierarchy if θ_{13} is large enough and if there is no ambiguity caused by matter and CP effects canceling each other, i.e., if δ_{CP} is $3\pi/2$ or $\pi/2$ with large enough θ_{13}

Mass Hierarchy Contours - NOνA + T2K

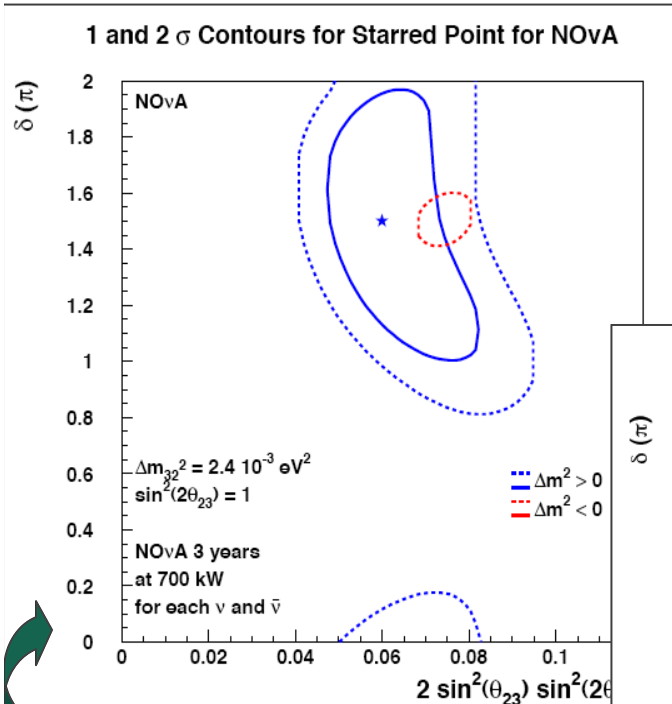
To resolve the hierarchy ambiguity from a single experiment, inclusion of oscillations at a different baseline helps





NOνA Sensitivity to CP Phase δ_{CP}

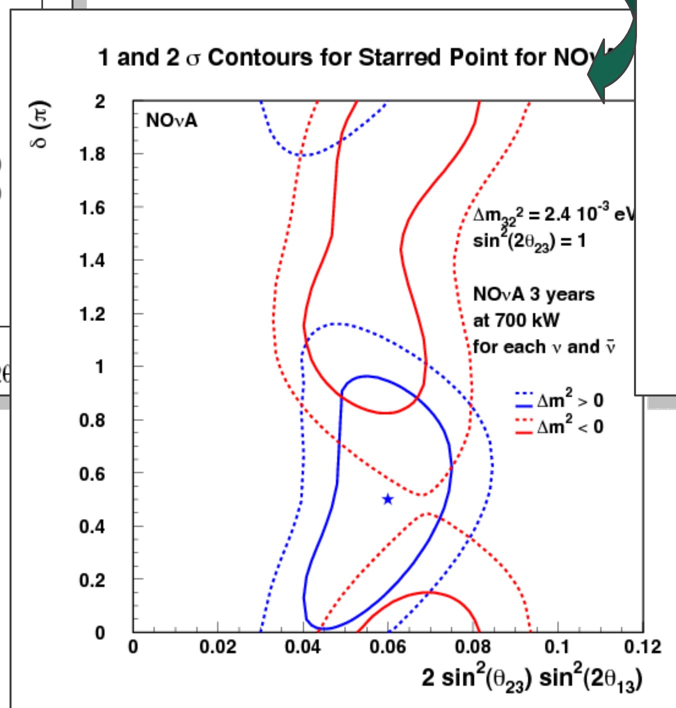
1- (solid) and 2- (dashed) σ contours in δ_{CP} - $2\sin^2(\theta_{23})\sin^2(2\theta_{13})$ space for NH (blue) and IH (red)

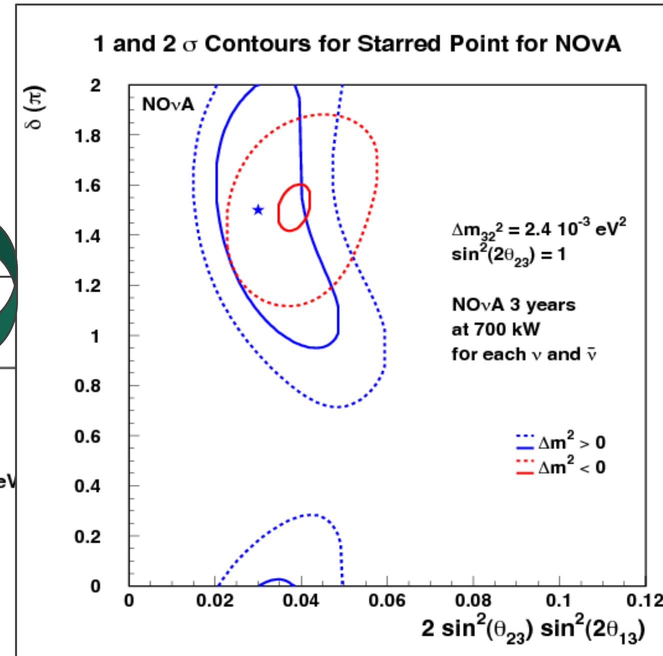


Mass hierarchy is resolved (large enough θ_{13})
δ_{CP} constrained to the range ($\pi \rightarrow 2\pi$)

θ_{13} too small to resolve hierarchy

Contours overlap at 1σ



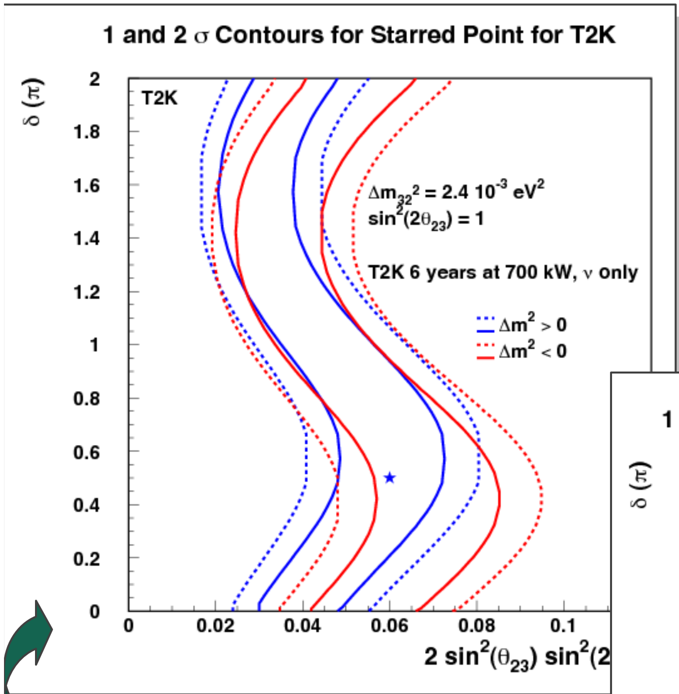


Here, θ_{13} large enough, but δ_{CP} is in the range ($0 \rightarrow \pi$)
Contours overlap at 1σ so mass hierarchy not resolved

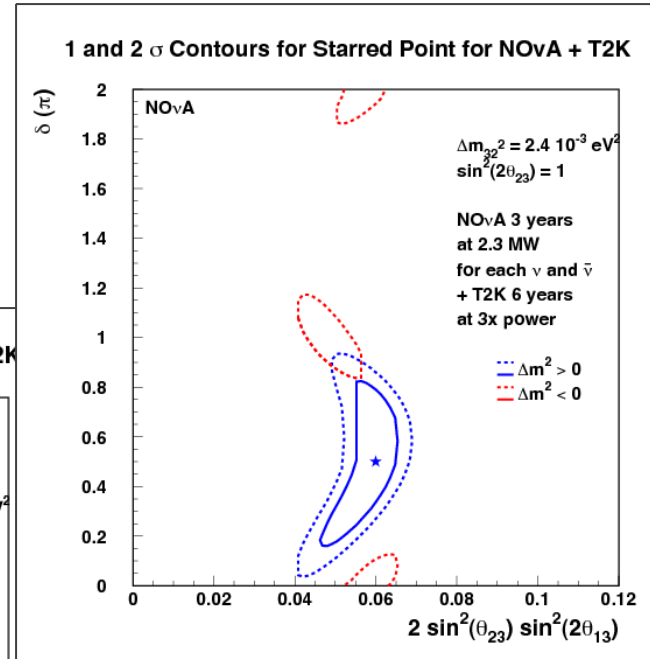
δ_{CP} unconstrained

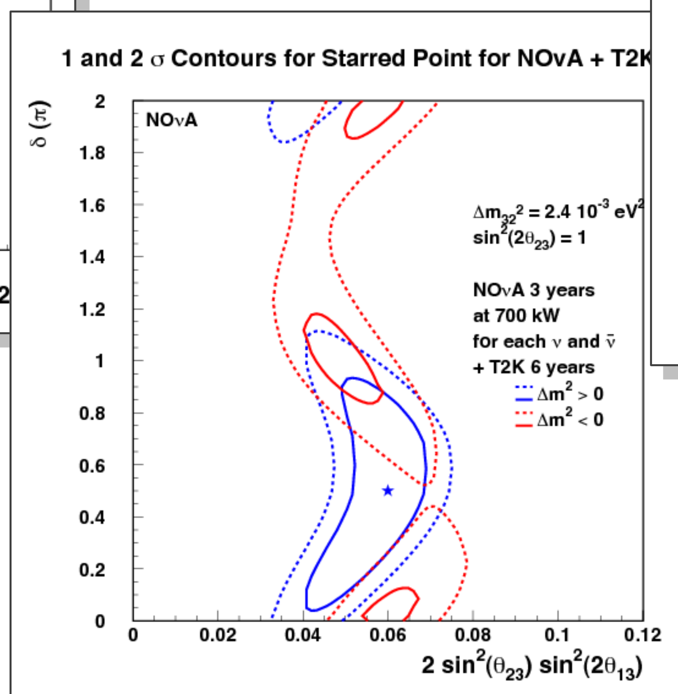
δ_{CP} Resolution - NOνA + T2K

1- (solid) and 2- (dashed) σ contours in δ_{CP} - $2\sin^2(\theta_{23})\sin^2(2\theta_{13})$ space for NH (blue) and IH (red)



Combined NOνA + T2K results in more resolution power





T2K results - ν only

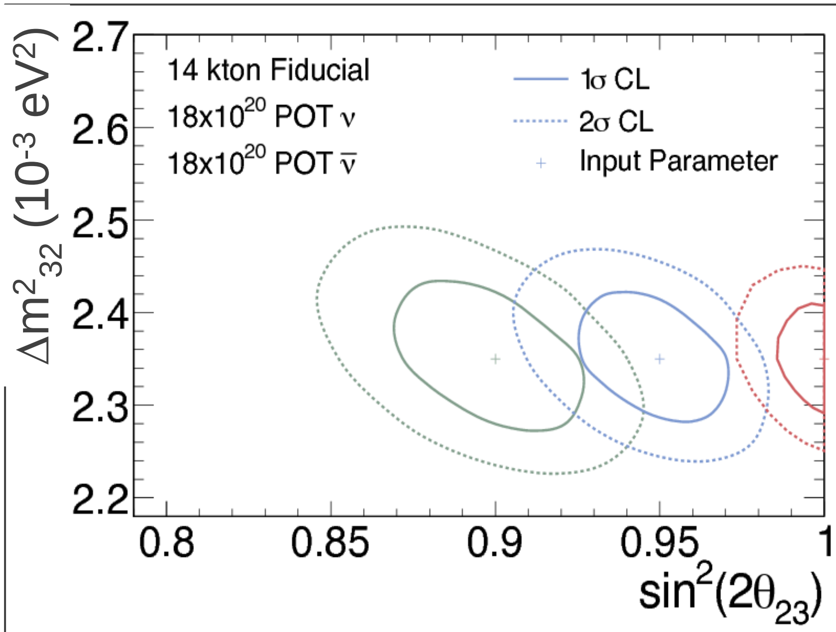
No information on δ_{CP}

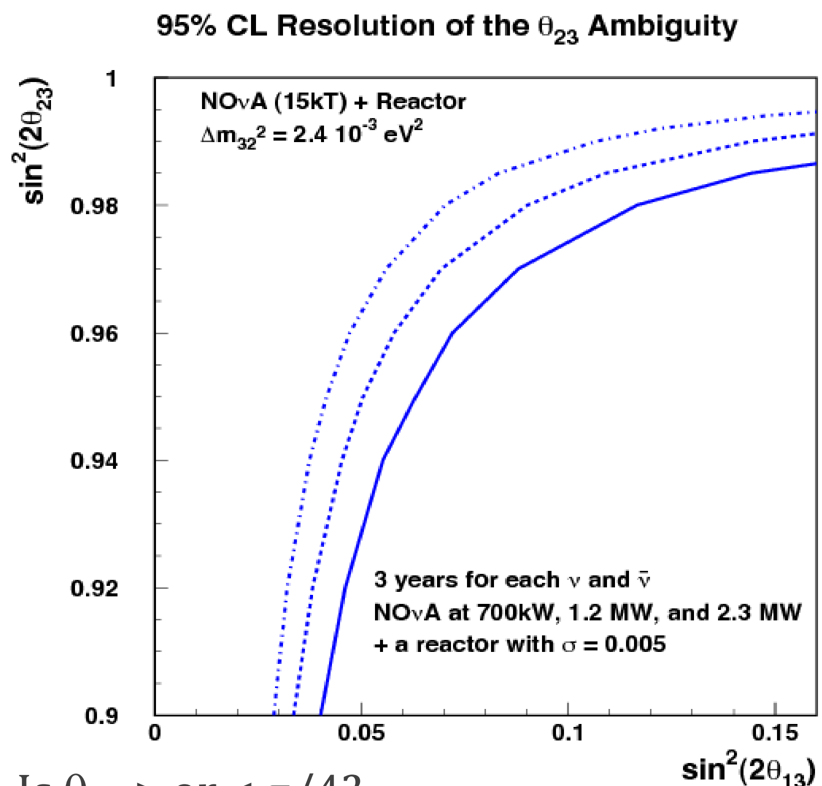
Different baseline
- overlap with NOνA only in part of δ_{CP} range

δ_{CP} constrained if both NOνA and T2K operated with higher beam intensity

Precision Measurements of θ_{23} and Δm^2_{32}

NOνA sensitivity at 3 points in allowed region of $\sin^2(2\theta_{23})$





Is θ_{23} > or < $\pi/4$?

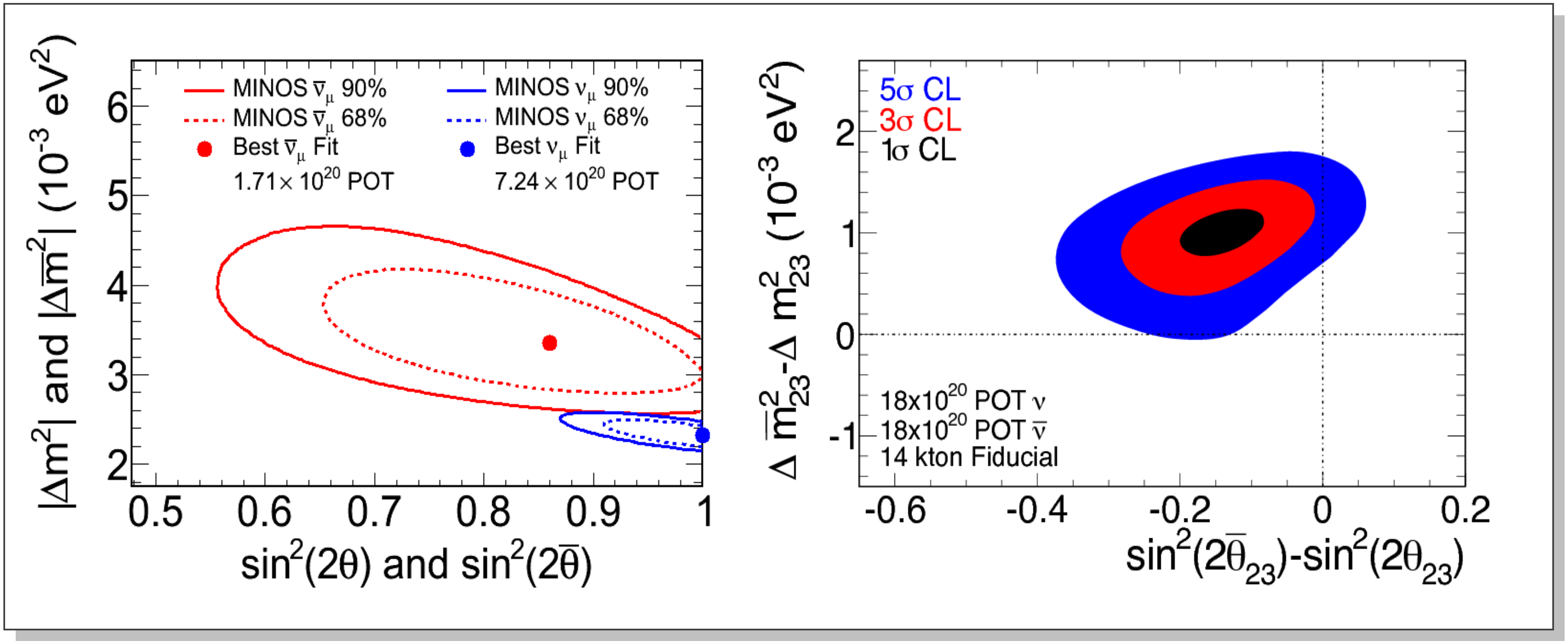
$\nu_e \rightarrow \nu_\mu$ or $\nu_e \rightarrow \nu_\tau$ more dominant?

Combine NOνA + reactor

$\rightarrow$ 1σ sensitivity of 0.005 in $\sin^2(2\theta_{13})$

$\rightarrow$ sign of $\cos(2\theta_{23})$ can be resolved to the right of curves

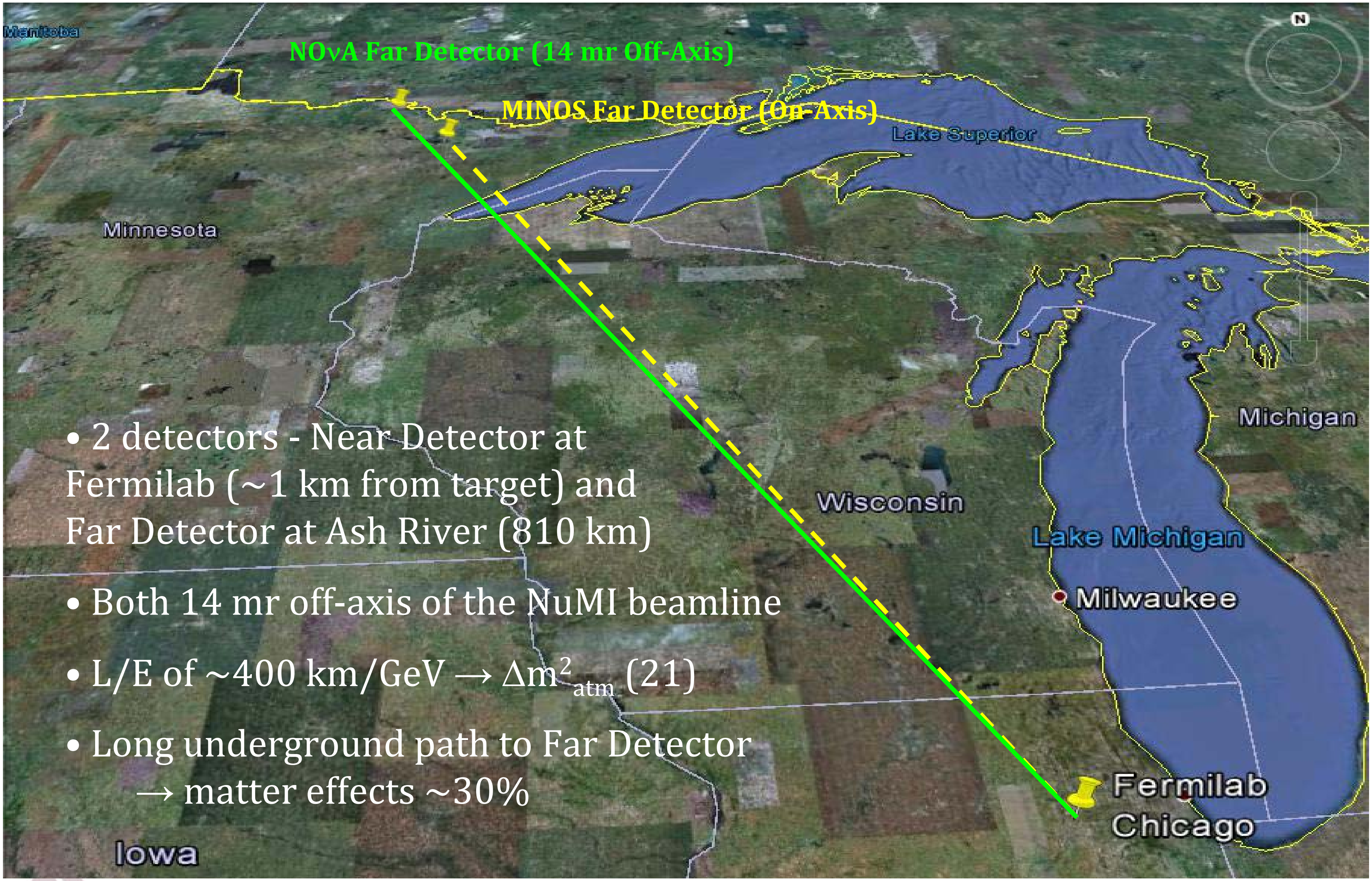
ν_μ vs $\bar{\nu}_\mu$ Disappearance Comparison



Latest MINOS results for $\bar{\nu}_\mu$ and ν_μ disappearance

NOνA 3σ contour resolves apparent difference

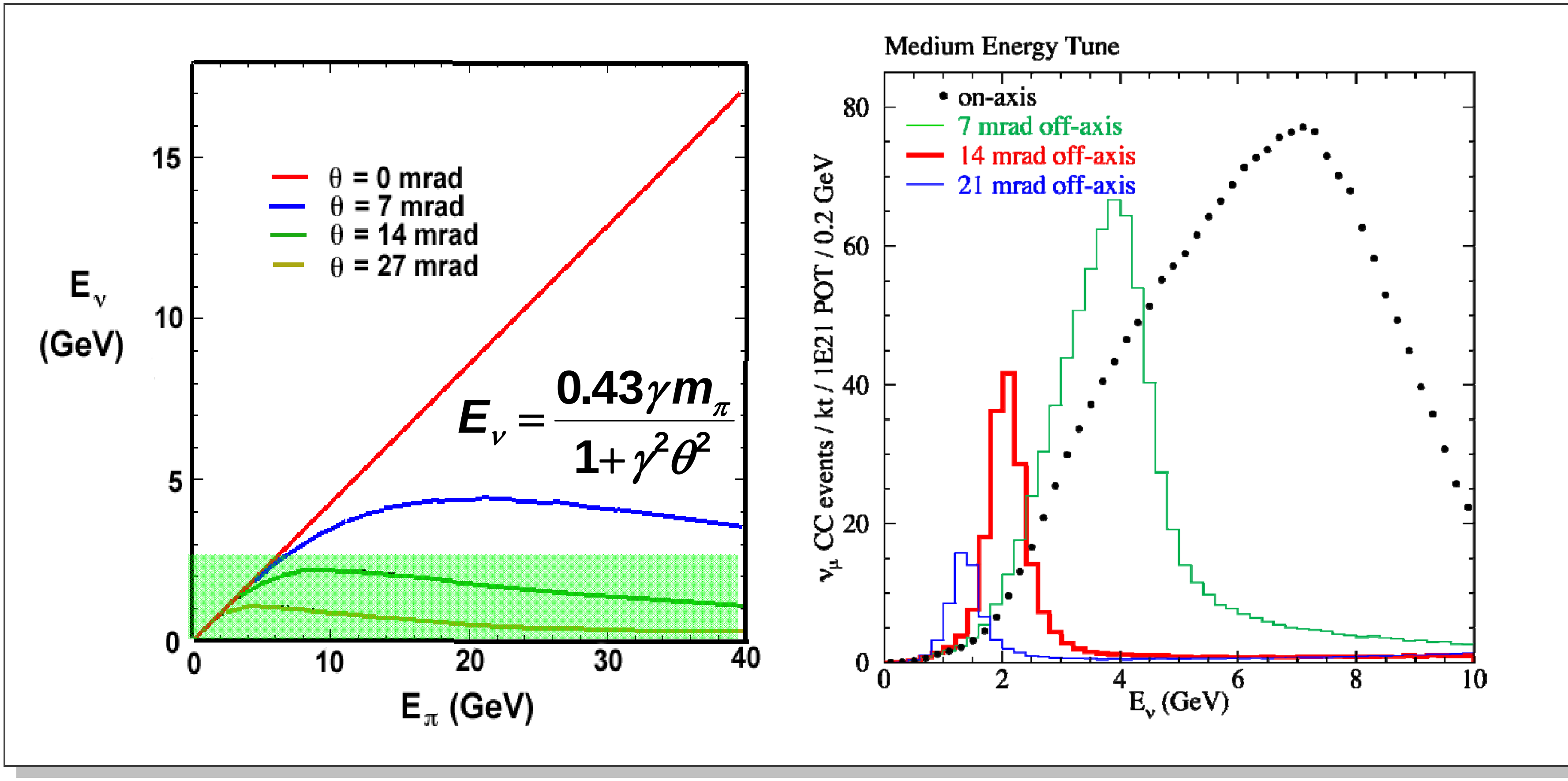
NOνA Long-Baseline Neutrino Experiment



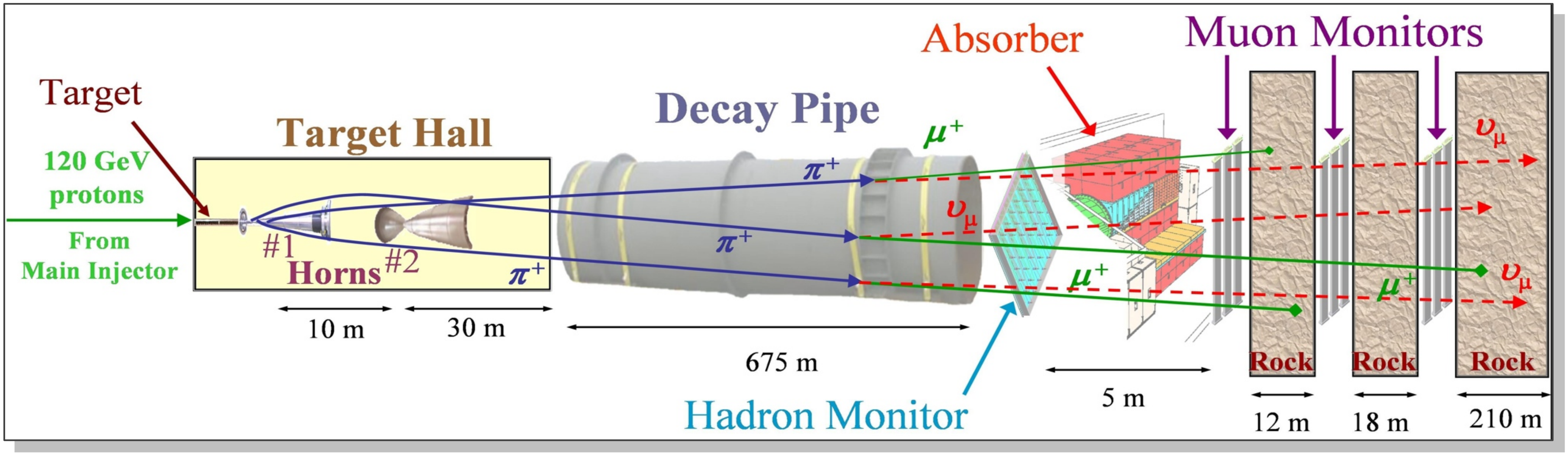
- 2 detectors - Near Detector at Fermilab (~1 km from target) and Far Detector at Ash River (810 km)
- Both 14 mr off-axis of the NuMI beamline
- L/E of ~400 km/GeV → Δm^2_{atm} (21)
- Long underground path to Far Detector
  → matter effects ~30%

Why Detectors are Off-axis

- Neutrino beam E distribution is narrower
- Less overall flux, but even less background off-axis
  - → ν_e from K decay and higher energy NC events



NuMI (Neutrinos at the Main Injector) at FNAL



- Pions and kaons produced in the target are focused by the magnetic horns into the decay pipe where they decay into muons and neutrinos

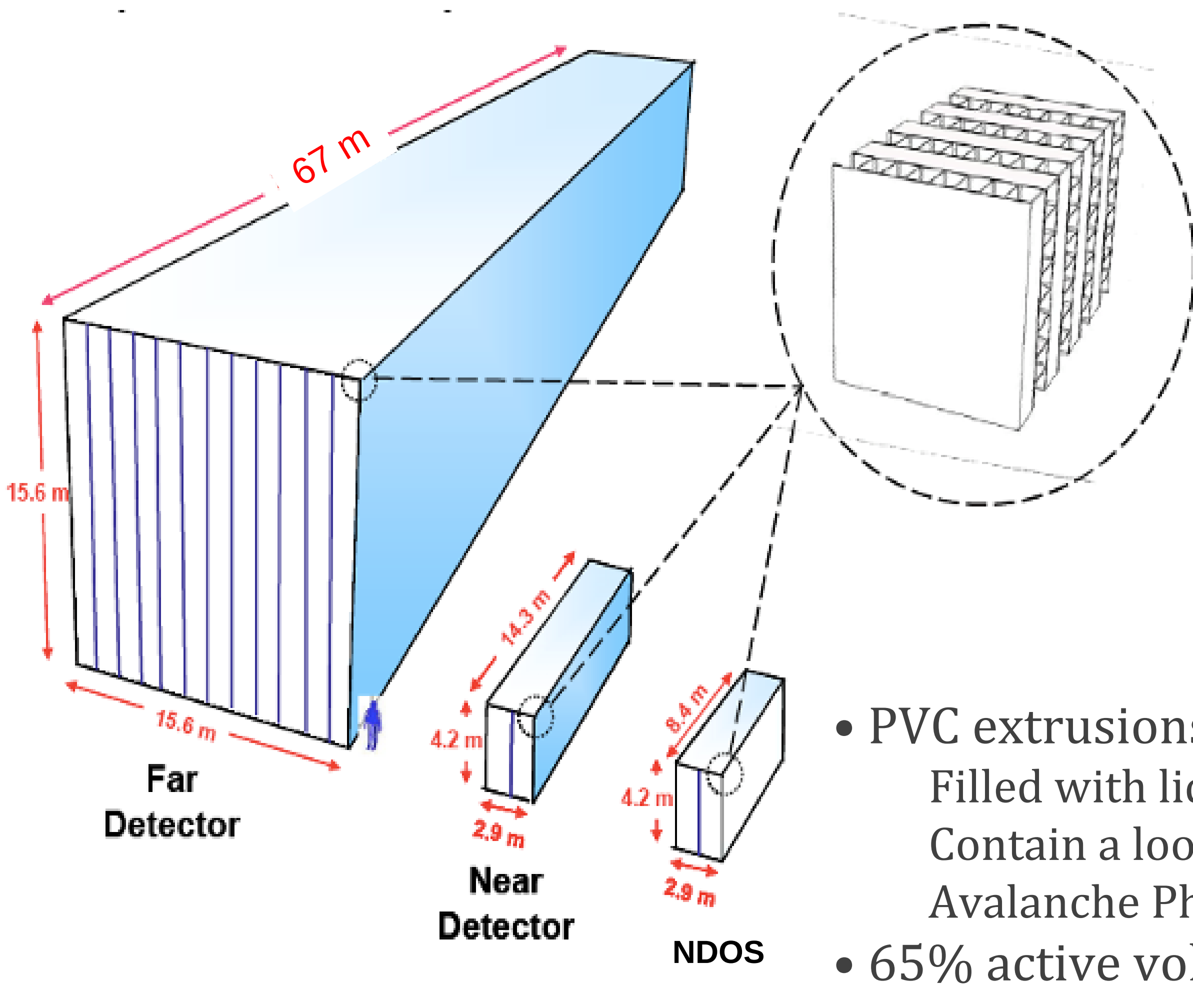
  → neutrinos and anti-neutrinos can be selected by horn current
- Operates with a 10 us beam spill every 2.2 sec
- Beam power of ~300 kW
- Beam since 2005 supplied to MINOS, MINERνA, ArgoNeuT
- NOνA Upgrades :

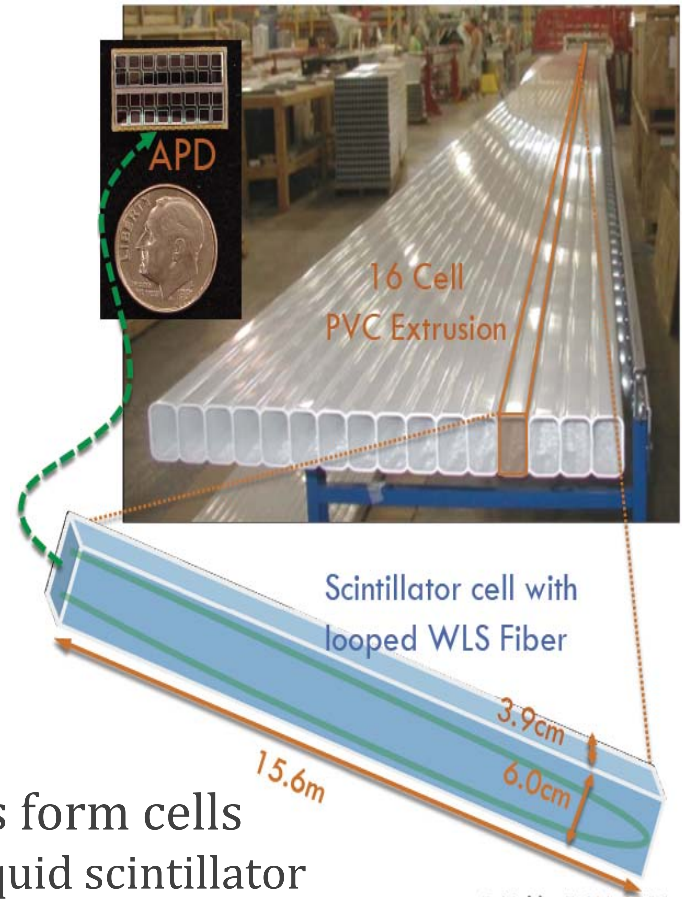
  -> Increase beam power to 700 kW

  -> Reduce cycle time to 1.33 sec

  -> Upgrades to target, horns

NOνA Detectors

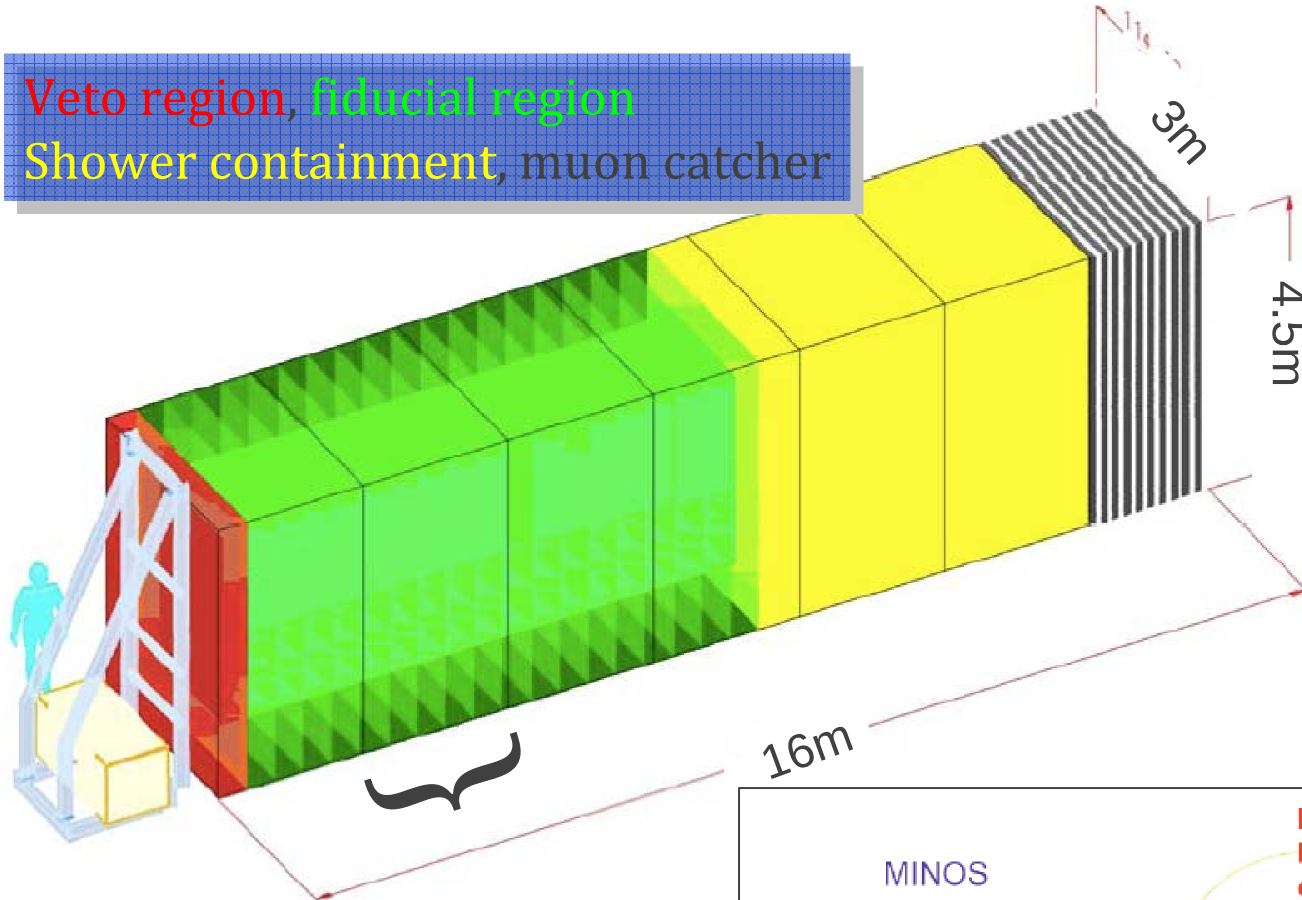




- PVC extrusions form cells
  - Filled with liquid scintillator
  - Contain a looped wavelength shifting fiber
  - Avalanche Photodiode (APD) readout
- 65% active volume
- ~40 cm X_0, 11 cm R_M, ~85 cm λ_I
- >370000 cells, >10k 32-pixel APDs

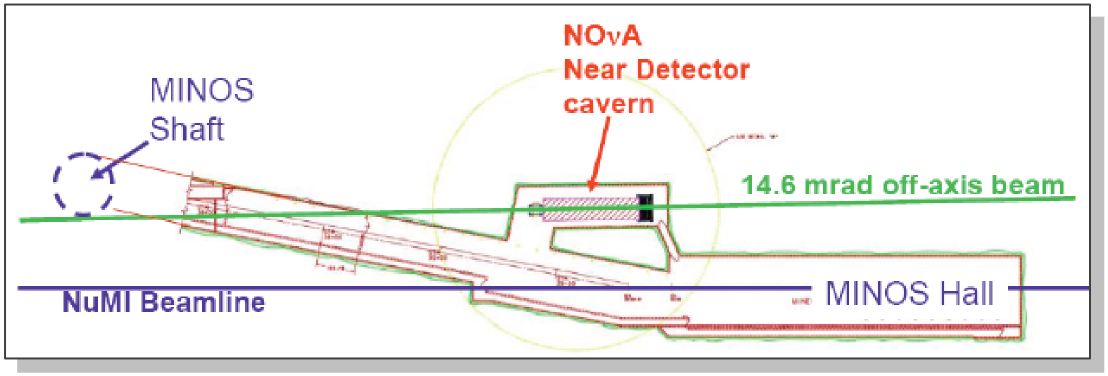
NOνA Near Detector

Veto region, fiducial region
Shower containment, muon catcher

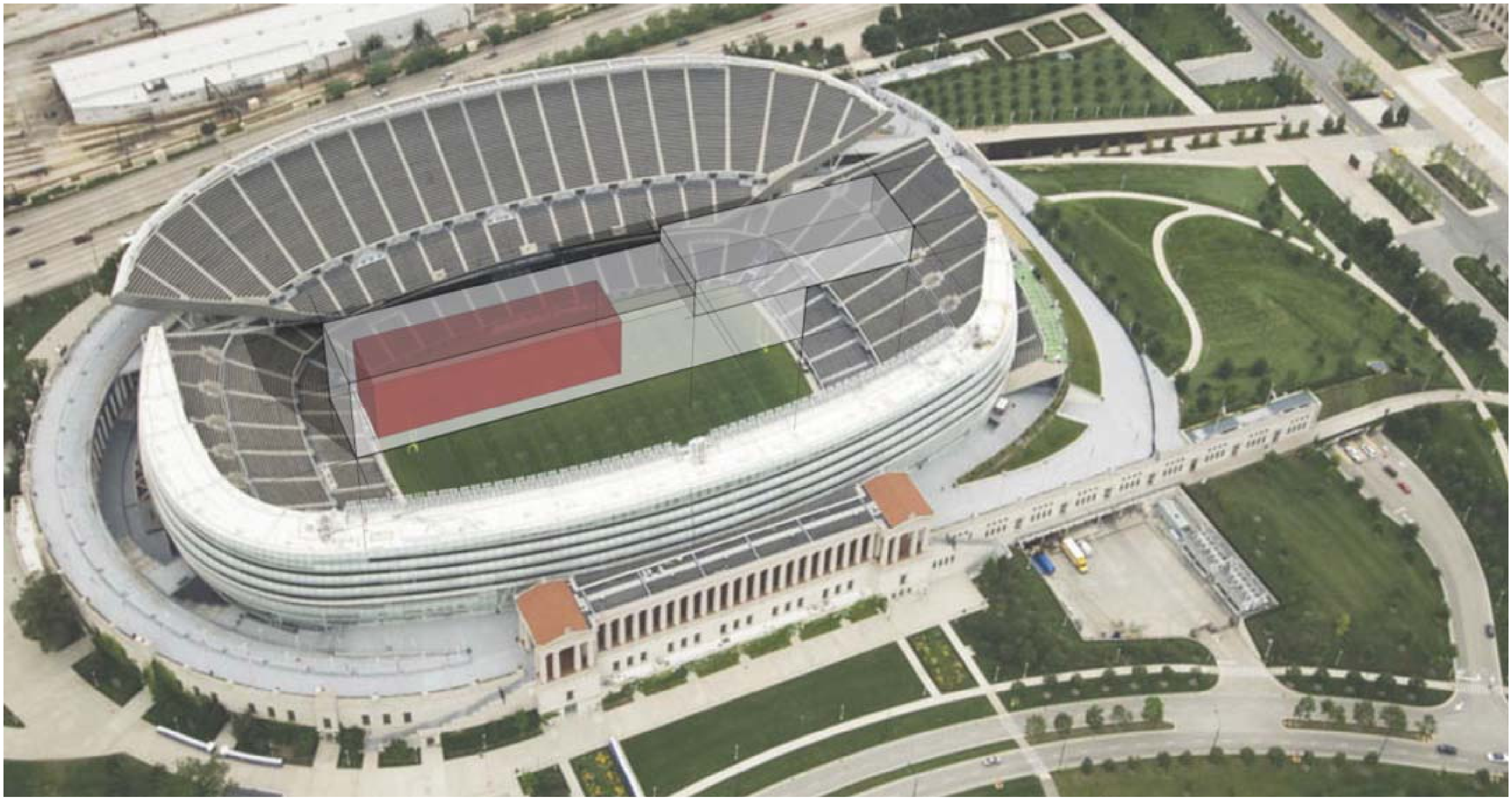


- 220 ton detector mass
- 6 blocks (PVC planes) + muon catcher (PVC + steel absorbers)
- Resides in off-axis underground cavern

Basic detector unit is a block
$\rightarrow$ 32 planes of alternating views horizontal and vertical

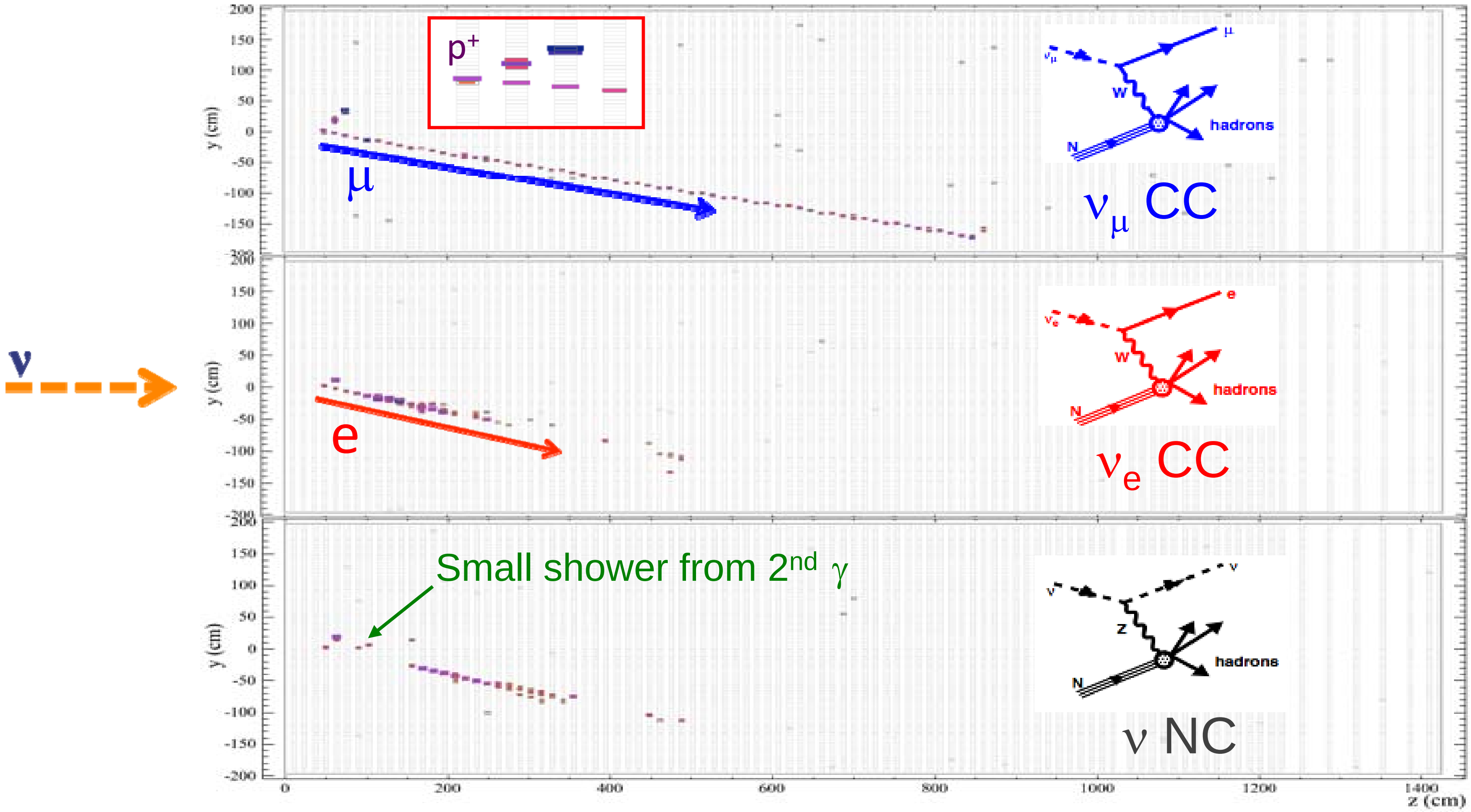


NOνA Far Detector



- 15 kiloton detector mass
- 29 blocks → >900 PVC planes
- Comparison to Soldier Field in Chicago - NOνA detector + Service Building

Neutrino Event Signatures in NOνA



Simulated neutrino events

NOvA Project Timeline

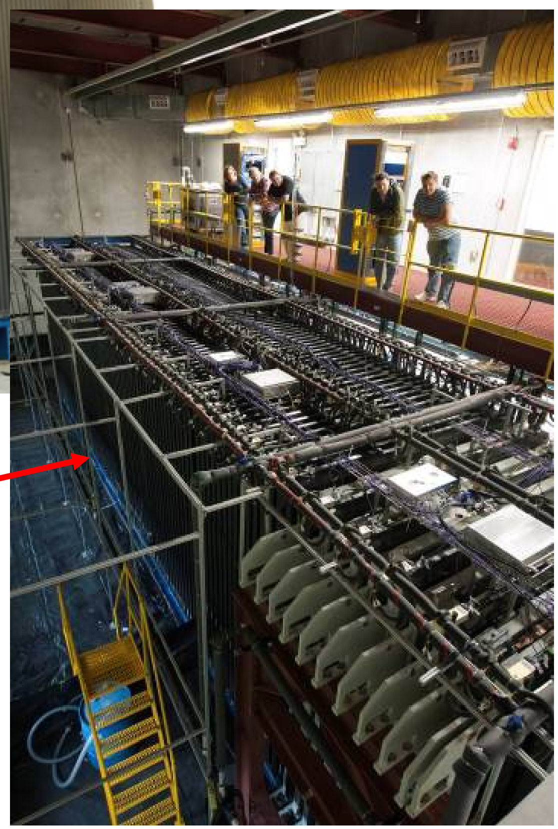
Beam Upgrade :
-> Spring 2012: accelerator shutdown - NuMI beam power from 300 kW to 700 kW

Far Detector Construction :
-> Start January 2012
-> 1 block installed, filled and instrumented by start of accelerator shutdown
-> 50% complete by end of accelerator shutdown – data-taking starts
-> 2014: 15kT complete

Near Detector Construction :
-> Current: NDOS (Near Detector On the Surface) prototype in operation at Fermilab
-> Spring 2012 – 2013: underground cavern excavation
-> New ND installed by Spring 2013

NOνA Near Detector On the Surface (NDOS)

- 210 ton prototype detector at ground surface
- ~15000 cells, full instrumentation by Feb 2012
- Data-taking started Oct 2010 – will continue until Spring 2012 FNAL accelerator shutdown



Pre- and Post-instrumentation

Includes muon-catcher w/steel absorber

Operational Goals

-> Full test of assembly and integration of all detector components
-> Signal studies – light yield, APD performance, fiber attenuation
-> Test ground for DAQ and DCS functionality and stability

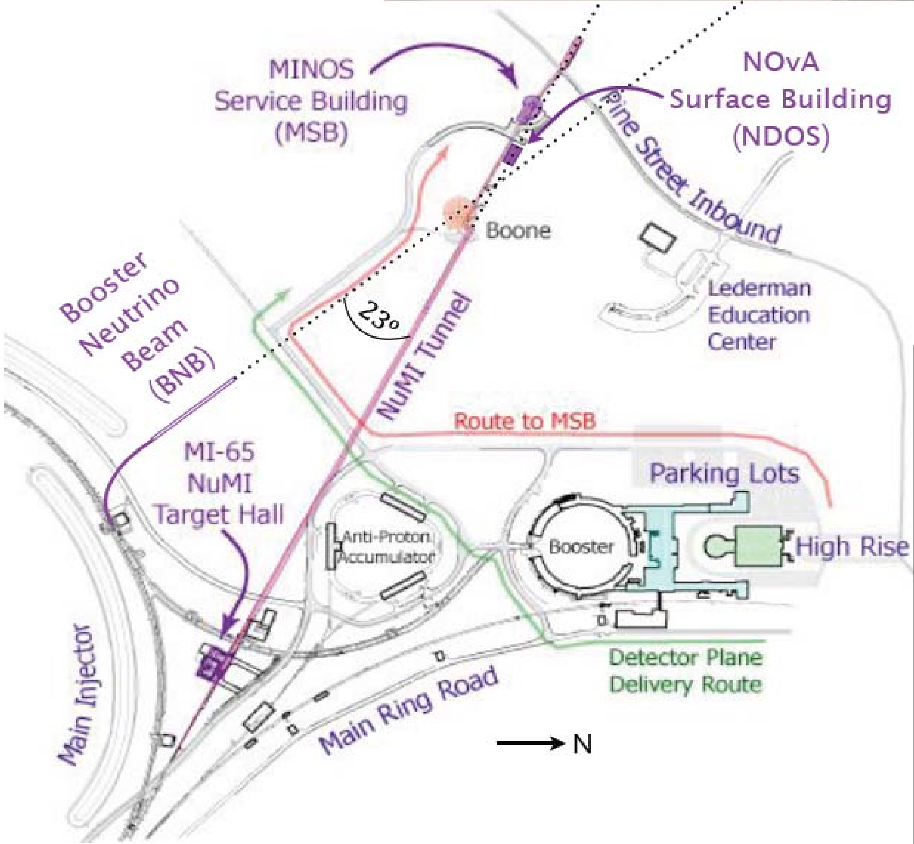
Physics Studies

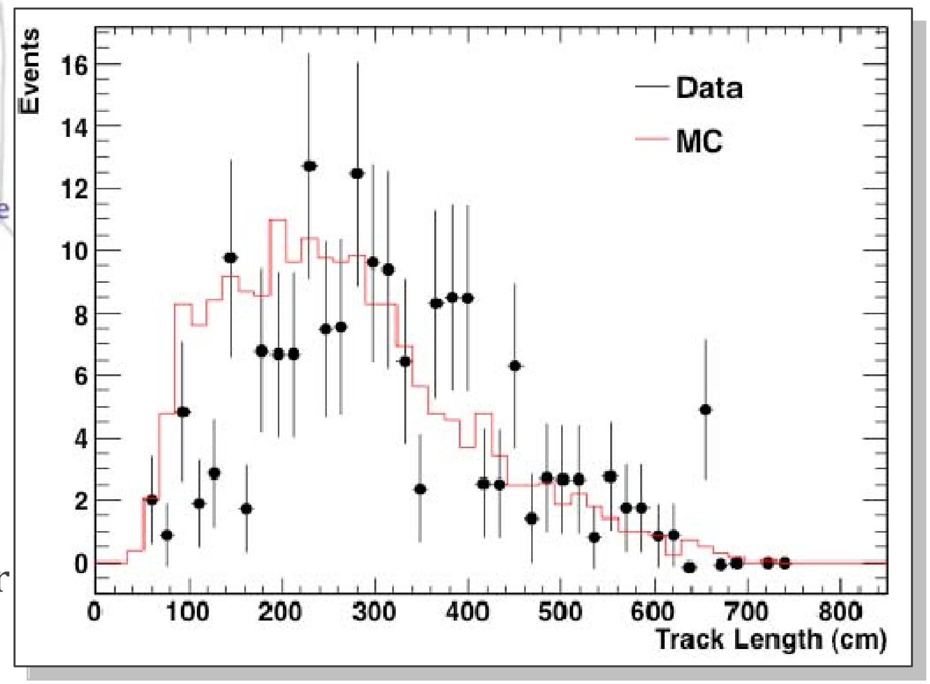
-> Development of calibration techniques
-> Improvements in MC detector response simulation
-> CR background measurements
-> Neutrino CC and NC event rates
-> Off-axis beam composition

NDOS Location!

NDOS is exposed to neutrinos from both NuMI and Booster beamlines

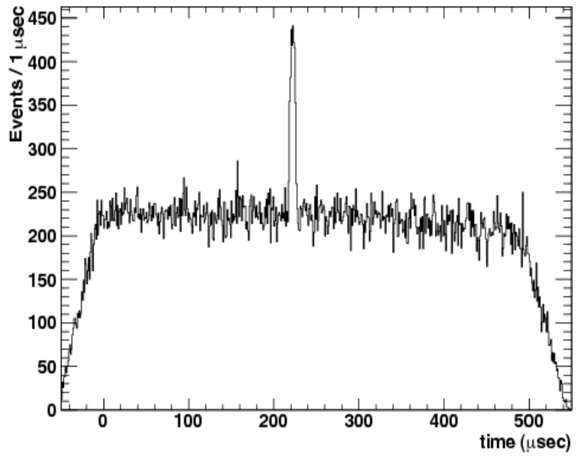
- -> ~6^{o} off-axis above NuMI and longitudinally aligned along beamline
- -> sits ~in the Booster beam, but rotated ~23^{o} wrt the beamline



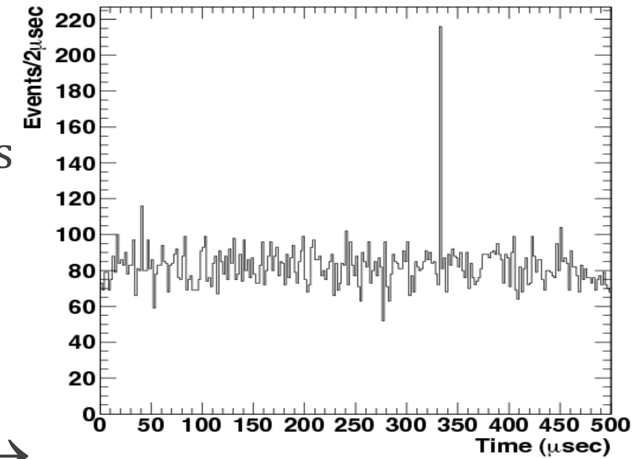


MC-Data comparison of reconstructed leading track length for NuMI events after timing cut and requiring $\cos\theta_{NUMI}$>0.7

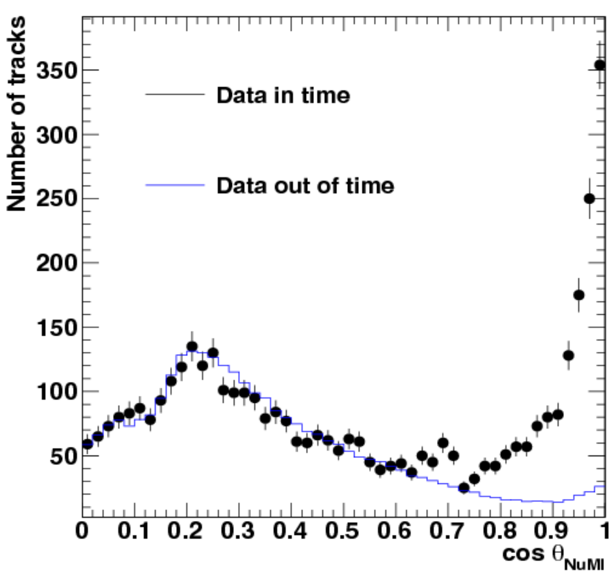
Events from Neutrino Beams at NDOS



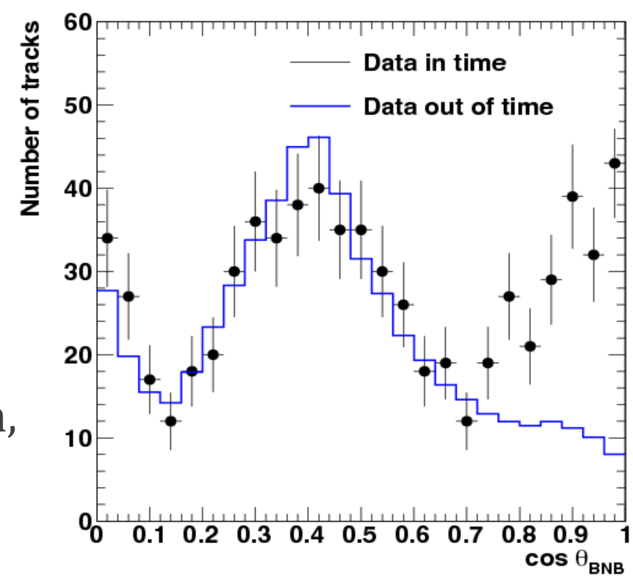
500 μsec trigger windows around expected beam times



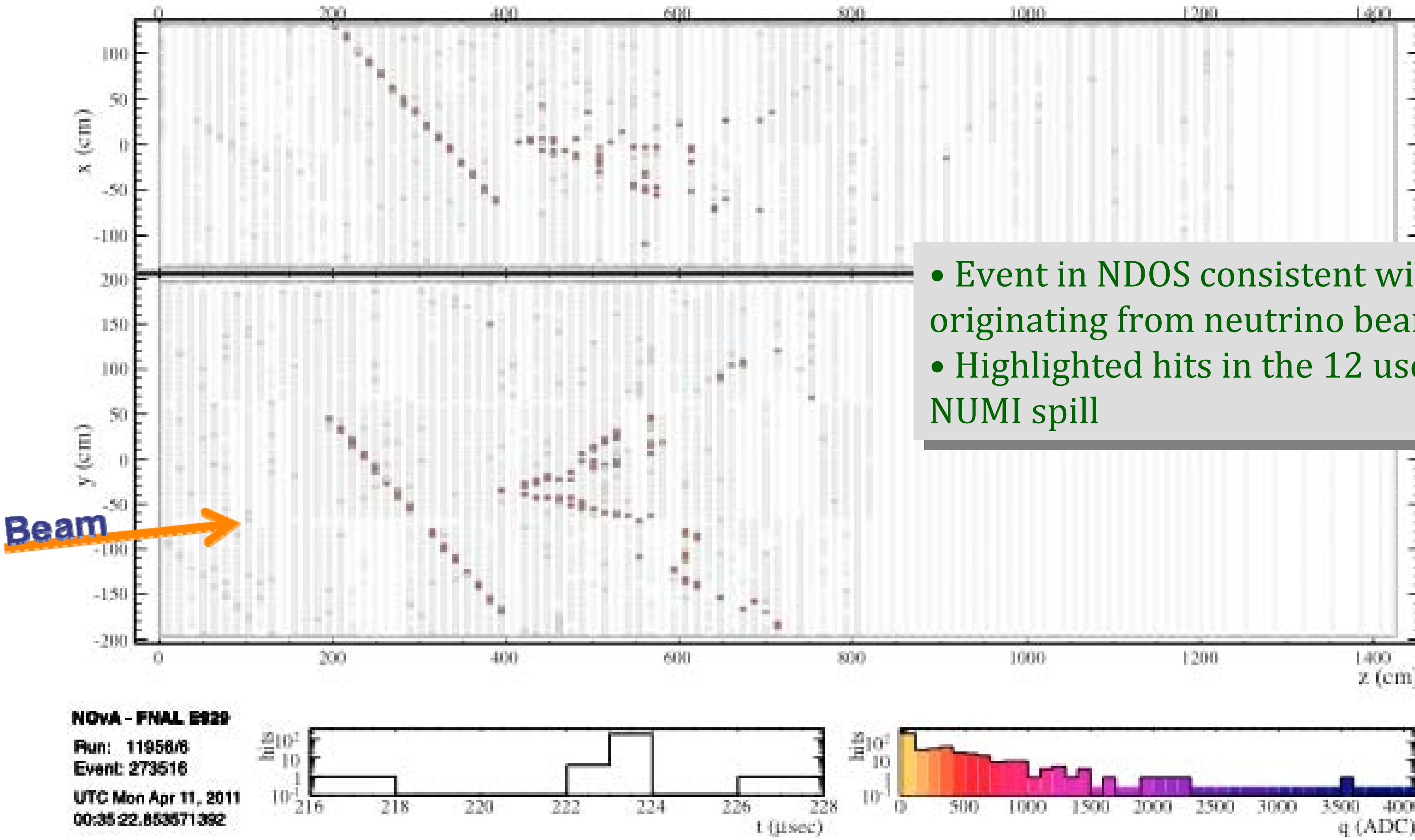
← NuMI Booster →



tracks in-time (close to beam direction) and out-of-time (cosmic direction, detector orientation)

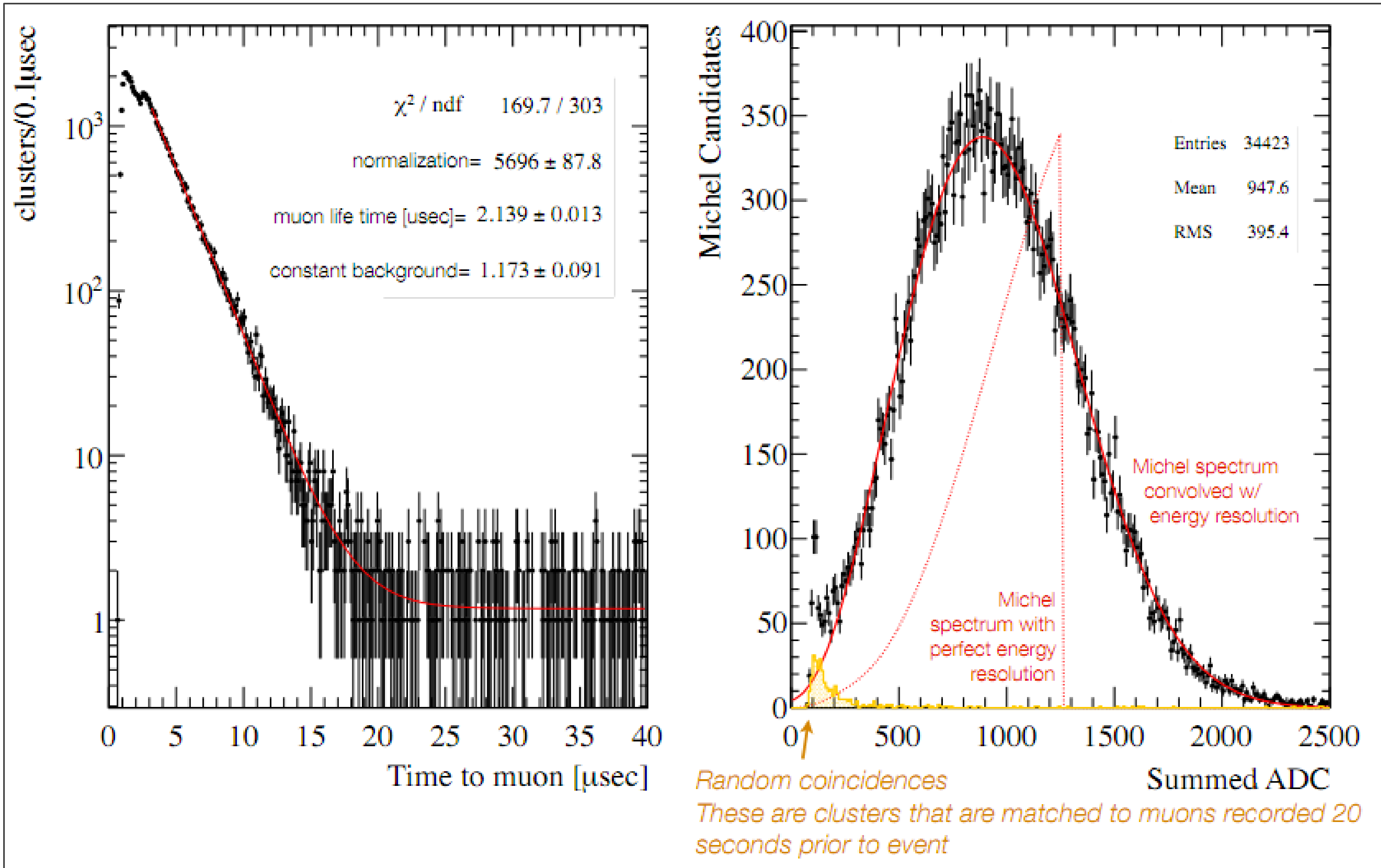


Neutrinos at NDOS



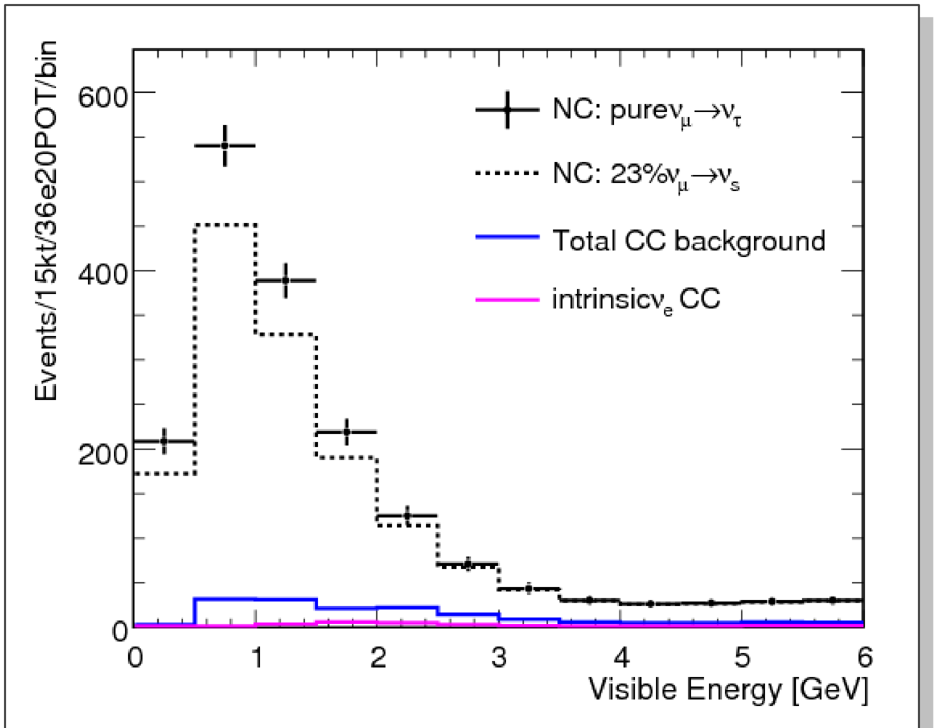
- Event in NDOS consistent with originating from neutrino beam
- Highlighted hits in the 12 usec NUMI spill

Neutrino Physics at NDOS – Michel Electrons



More NOνA Physics – Sterile Neutrinos?

- Possibility remains that oscillations at the atmospheric scale could involve a 4th neutrino flavor
- To agree with LEP measurements that are consistent with 3 interacting neutrinos, a 4th neutrino would have to be sterile – no coupling to Z or W bosons
- Current limit on the amount of sterile neutrino content from $\nu_\mu \rightarrow \nu_\tau$ or ν_s is below 23% at the 90% confidence level

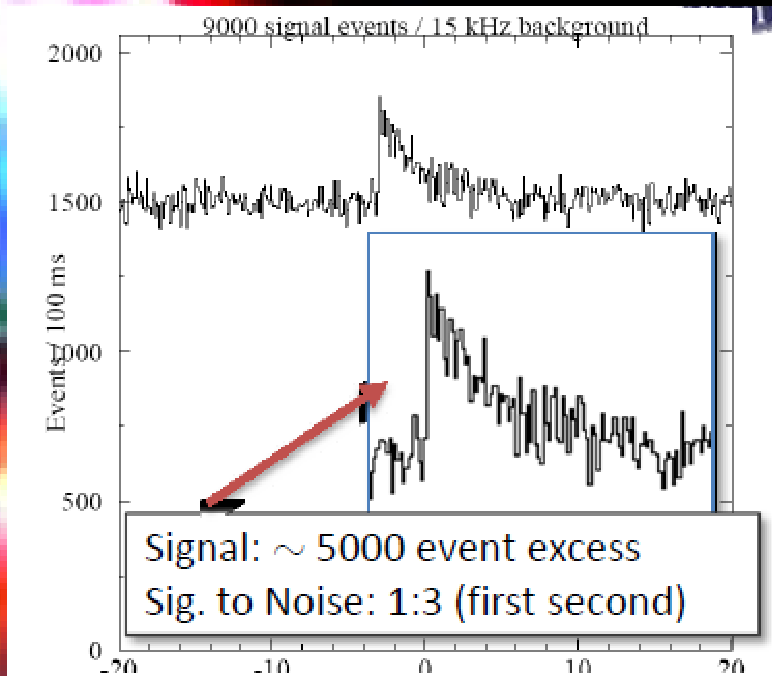


- From a selected NC event sample, NOνA can reconstruct the visible energy spectrum $(\nu + \overline{\nu})$
- Increasing the admixture of $\nu_\mu \rightarrow \nu_s$ affects the spectrum below ~2 GeV
- Ratio of number of events below 2 GeV to the number above measures the sterile neutrino content
- Expect to limit the admixture of ν_s to below 11% at the 90% confidence level

Supernova Neutrinos in NOvA

- Neutrinos produced by:

  $NN \rightarrow NN\nu\bar{\nu}$, $e^+e^- \rightarrow \nu\bar{\nu}$, . . .
- Trapped in core collapse, reach thermal equilibrium, then escape in burst
- Duration of neutrino burst: 1-10 sec
- Neutrino luminosity is upwards of 100 times greater than optical luminosity
- Neutrino flash preceeds primary photons by 5-24 hours

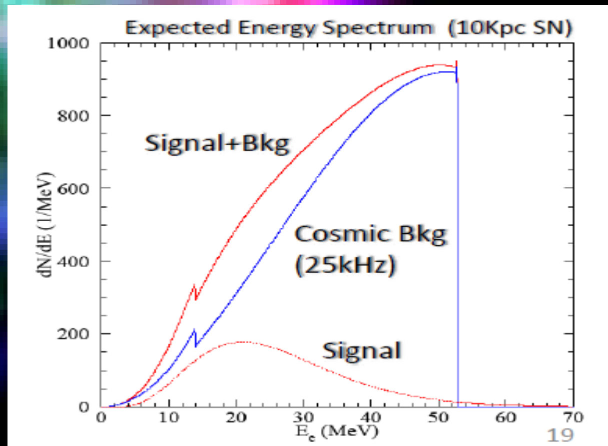


Primary detection signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

For a supernova located 10 kpc distant, total signal is expected to contain:

- 5000 total interactions over a time span of ~10 sec
- Half of the interactions occur in the first second
- Energy peaks at 20 MeV and falls off to ~60 MeV



Summary

The NOνA experimental program addresses 7 of the 8 questions posed by the P5 strategic plan (May 2008) for neutrino physics :

- What is the value of θ_{13}?
- Is θ_{23} maximal?
- Do neutrinos violate CP?
- What is the mass hierarchy of the known neutrinos?
- Are neutrinos their own anti-particles (Majorana or Dirac)? ☹
- What can neutrinos tell us about physics beyond the standard model? Existence of sterile neutrinos?
- What can we learn from the neutrino burst of a near galactic Supernova?

NOνA will make major contributions in this decade towards a full understanding of mixing in the lepton sector