The NOvA Experiment

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On behalf of the NOvA collaboration
College of William and Mary
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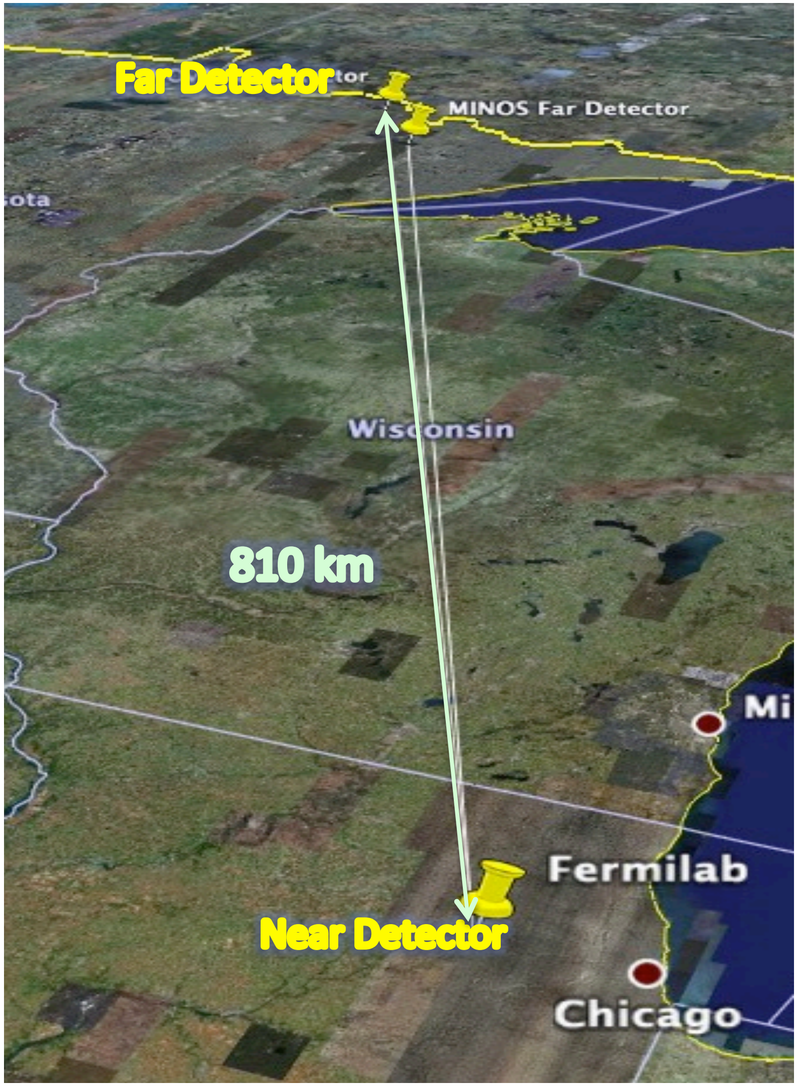
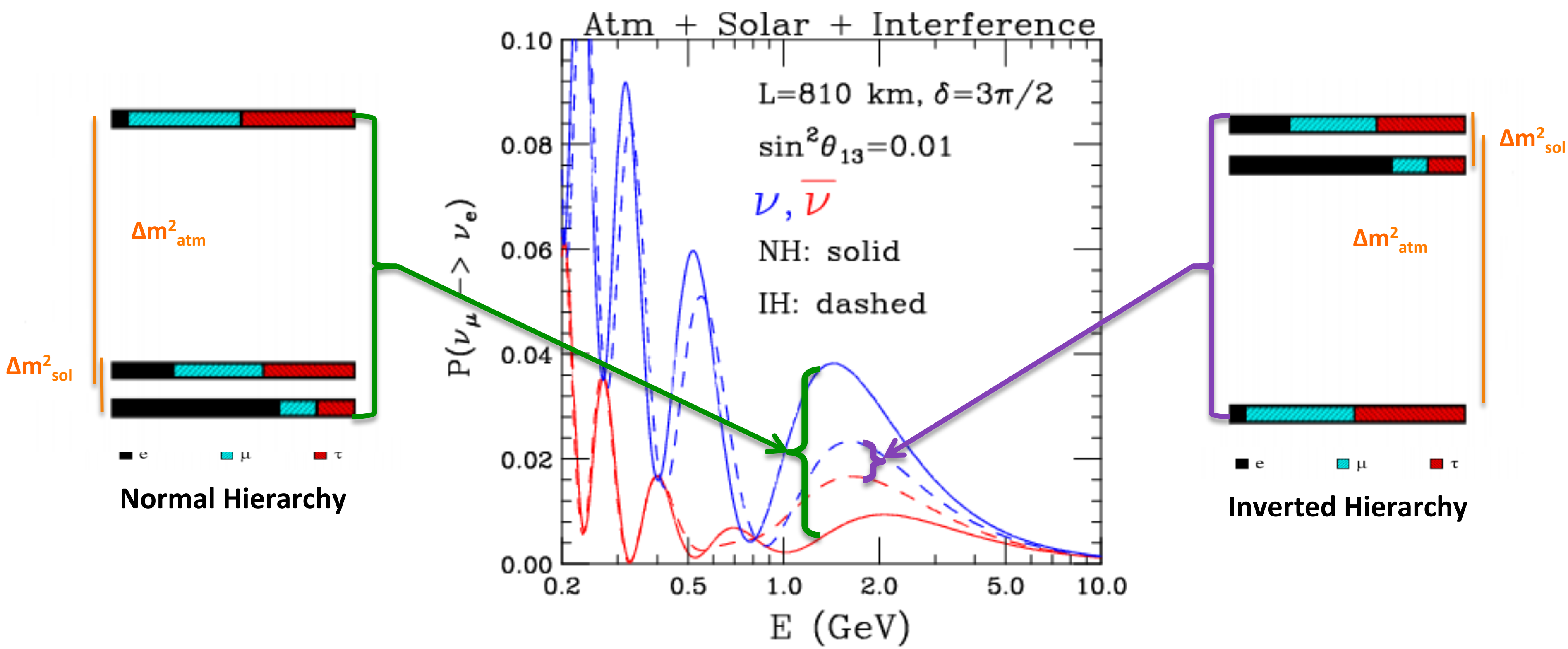
NOvA

- Long-baseline neutrino oscillation experiment currently under construction
- Off-axis neutrinos from NuMI beam
- Two identical mostly active liquid scintillator detectors
  - Near Detector: serves as a non-oscillation reference
  - Far Detector: measure oscillations
- Primary goal: observe and study $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ oscillations at the atmospheric oscillation length/energy.
  - Gives NOvA sensitivity to θ_{13} , mass hierarchy, δ_{cp}
  - Secondary goal: measure $\sin^2\theta_{23}$ and Δm^2_{32} to better precision

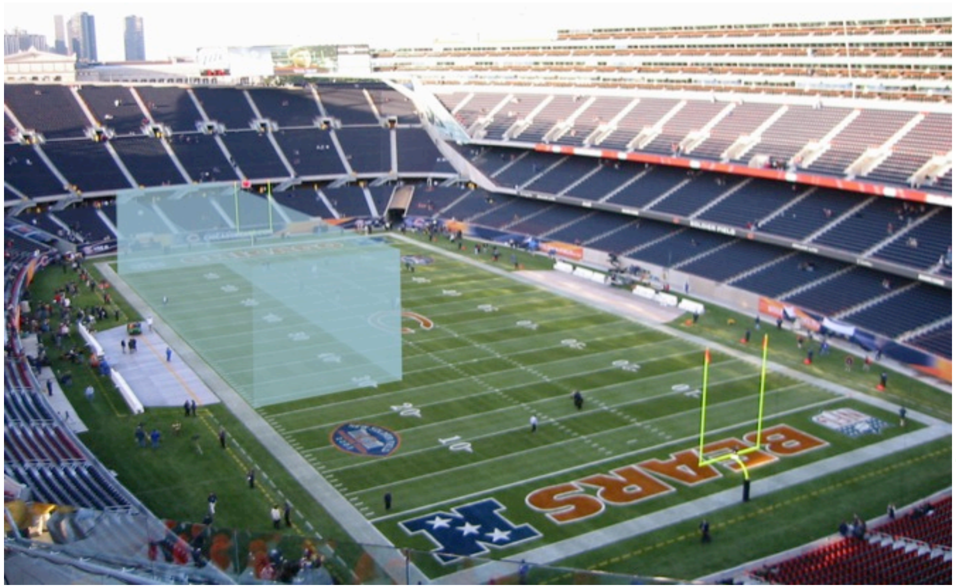


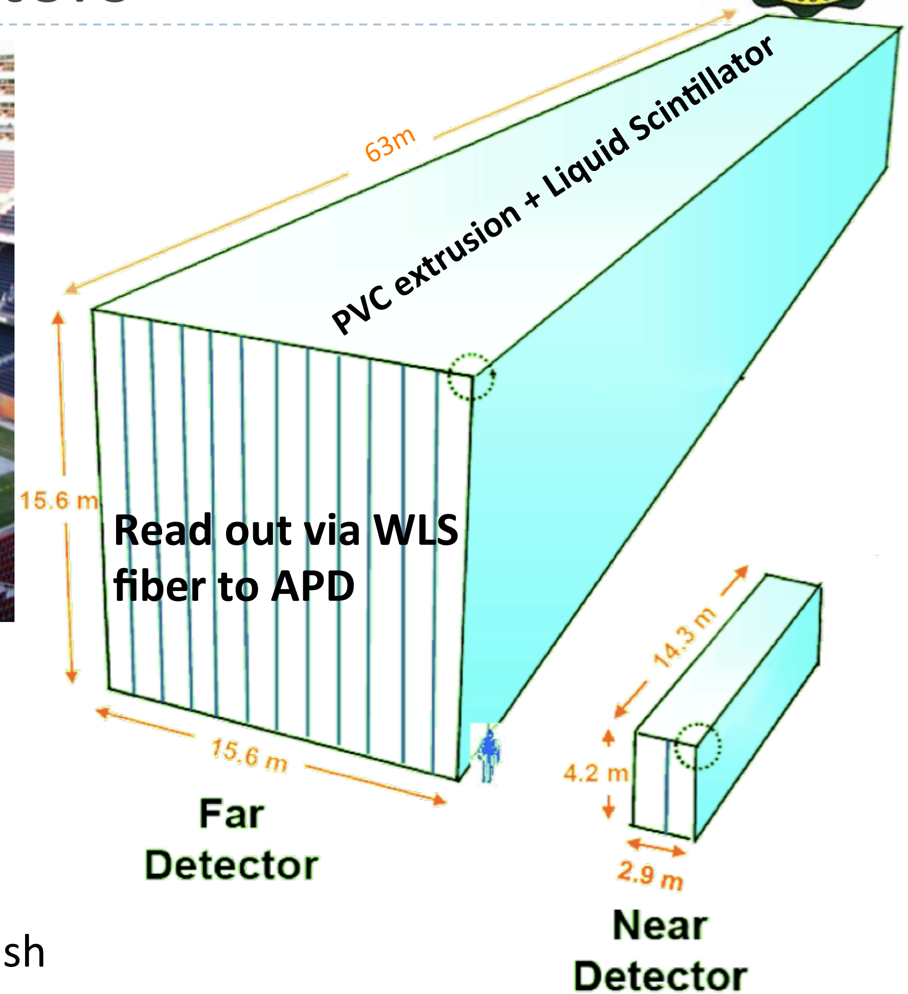
Neutrino Oscillation Channels

- Accelerator experiments looks for ν_e appearance
  - Oscillation probability depends on $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$, δ_{cp} and mass hierarchy
  - Probability can differ between ν and $\bar{\nu}$



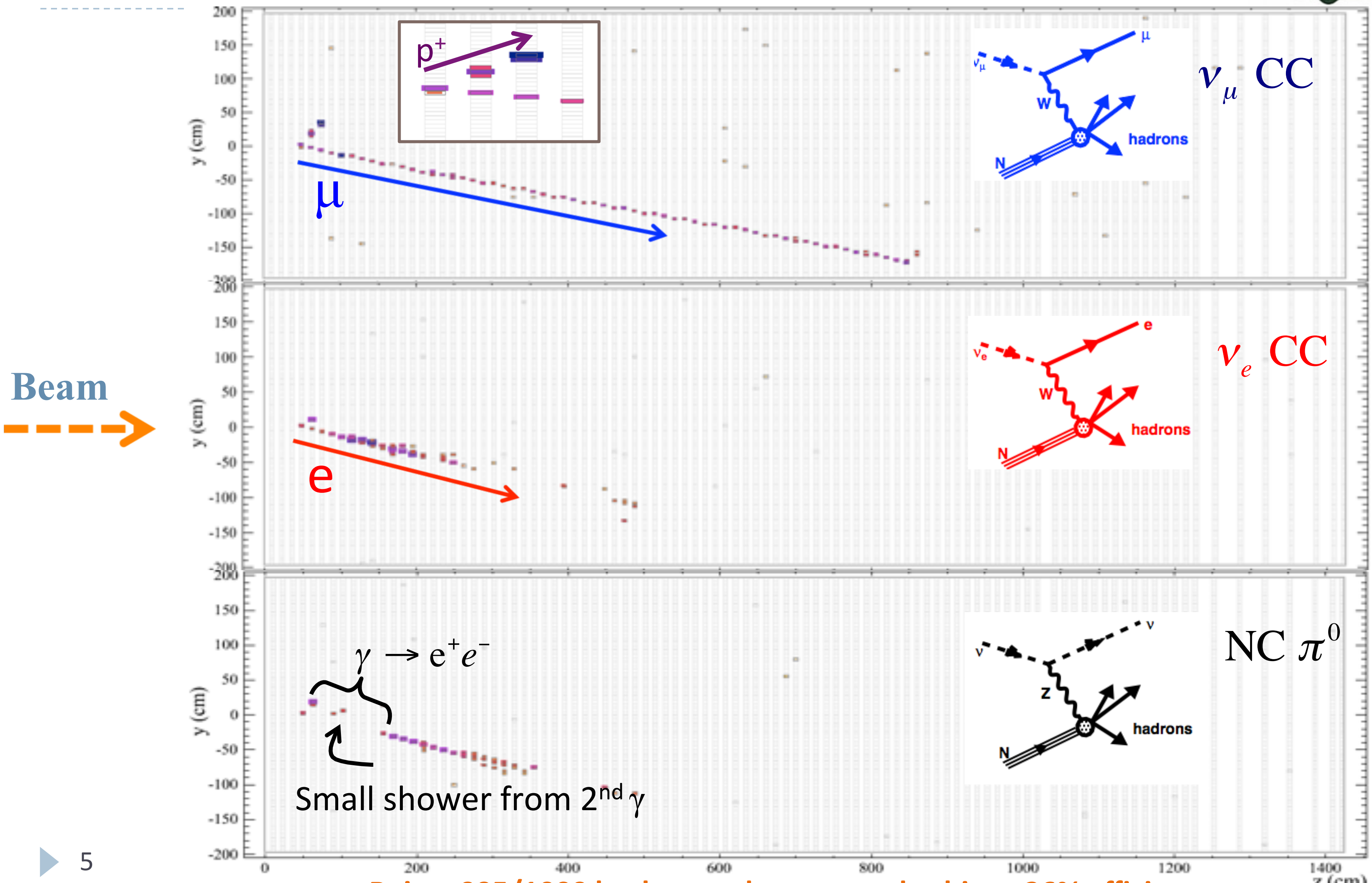
Detectors





- Massive, 65% active Far Detector
  - 15 kton, 810 km from source
- Functionally equivalent Near Detector
  - 220 ton, 1 km from source
- Both have fine spatial resolution to distinguish ν_e and NC events
  - 0.15 X_0 per layer

MC Events in NOvA

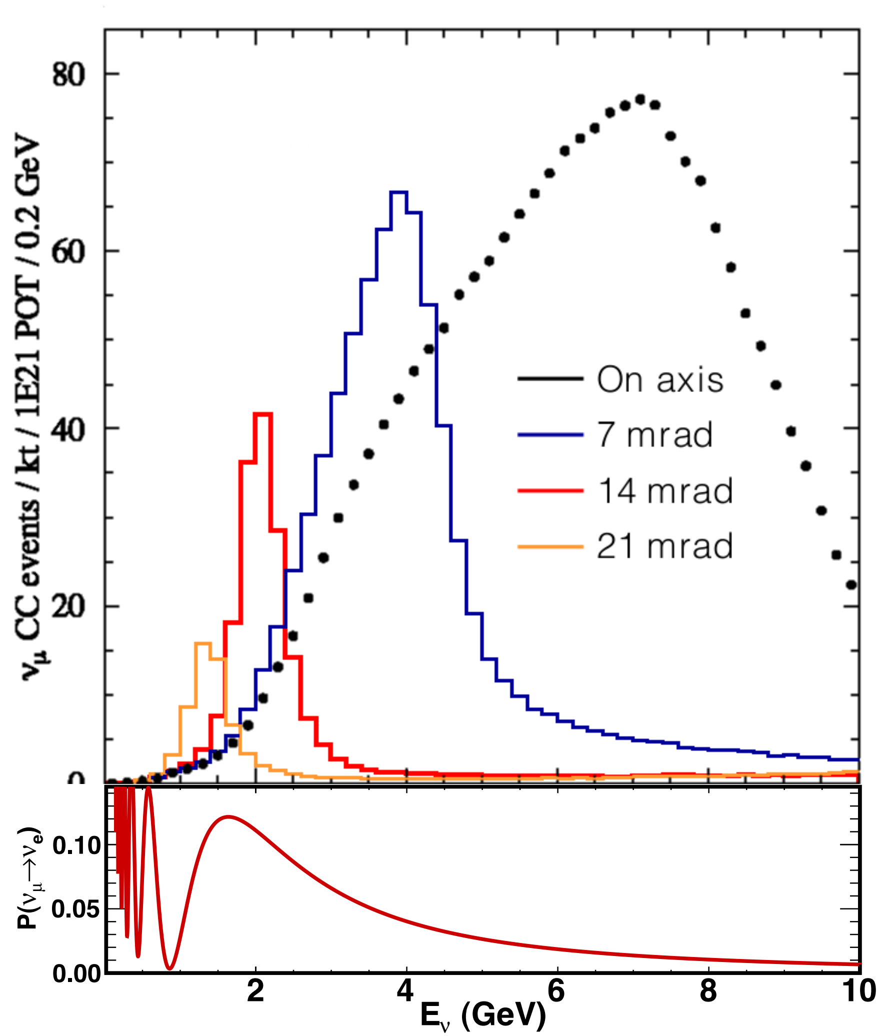


Reject 995/1000 background events and achieve 26% efficiency

Off-Axis Feature

Both detectors will be sited 14 mrad off the NuMI beam axis.

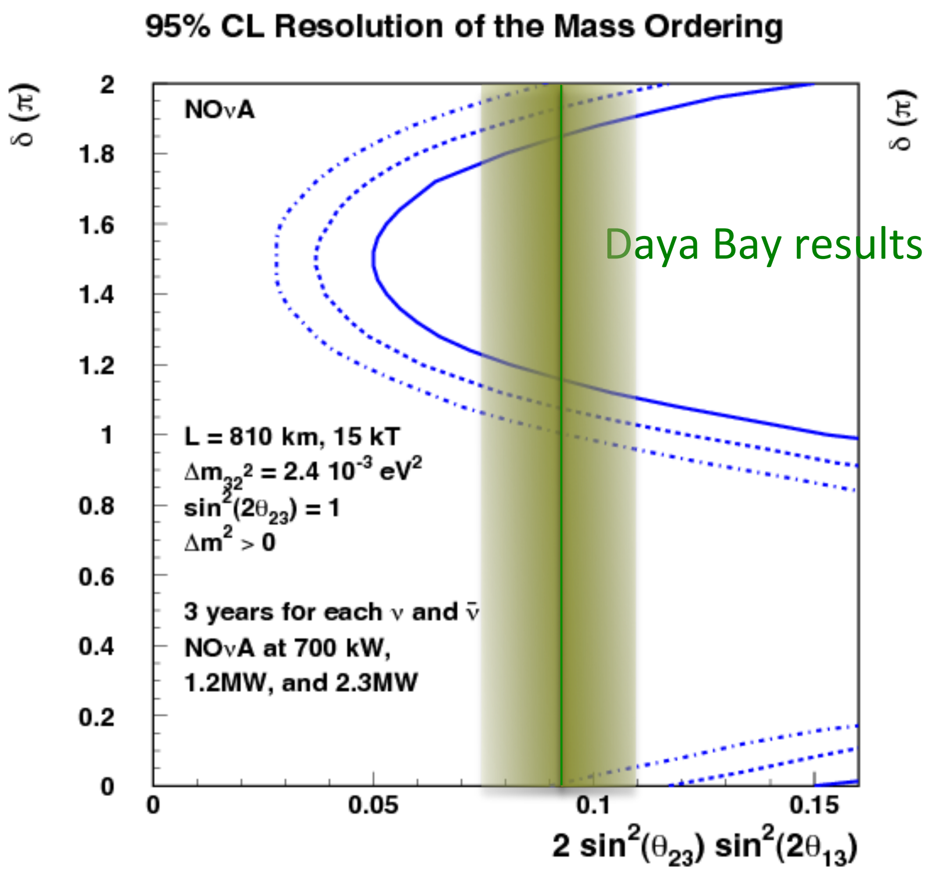
- Increase low-energy neutrino flux
- Narrow energy spectra enhances background rejection
- narrow band beam peaked at 2 GeV, well matched to peak oscillation probability

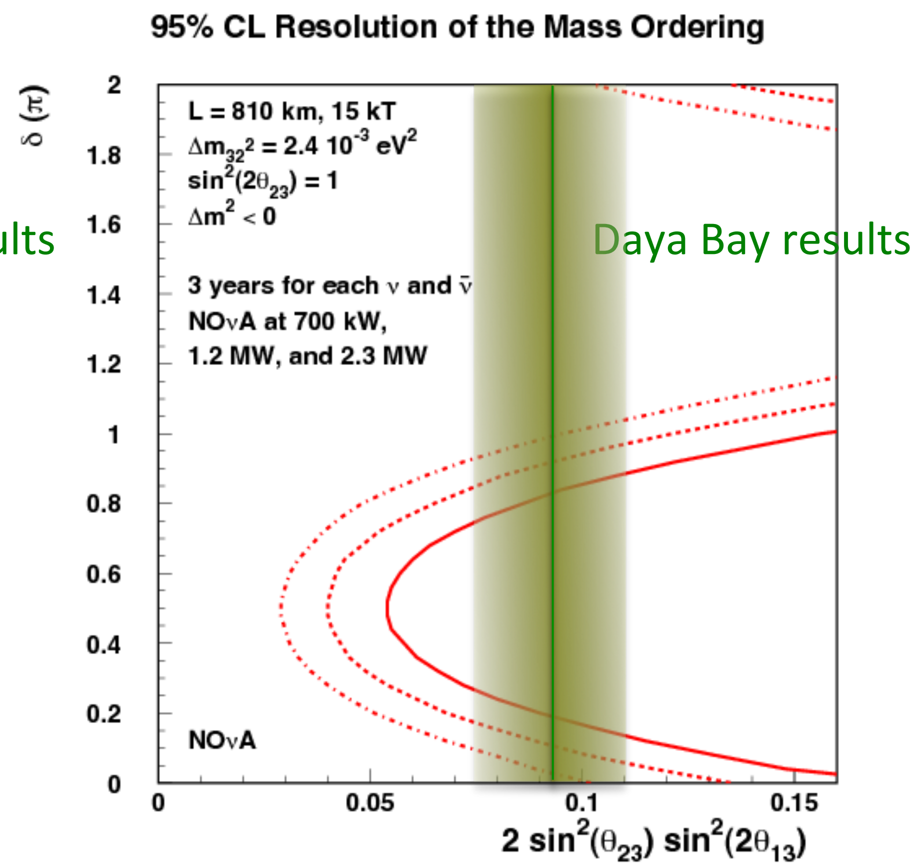


Sensitivity to Mass Hierarchy

Normal Hierarchy

Inverted Hierarchy

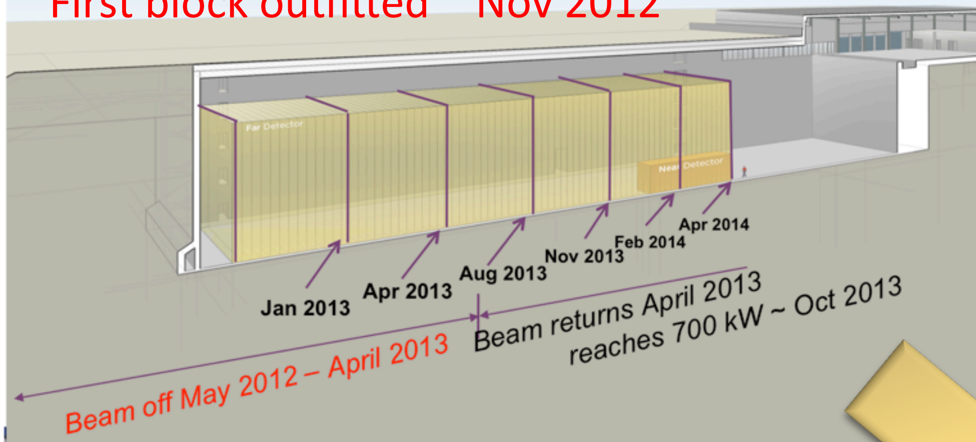




Daya Bay results is assuming $2\sin^2(\theta_{23}) = 1$

Far Detector Construction

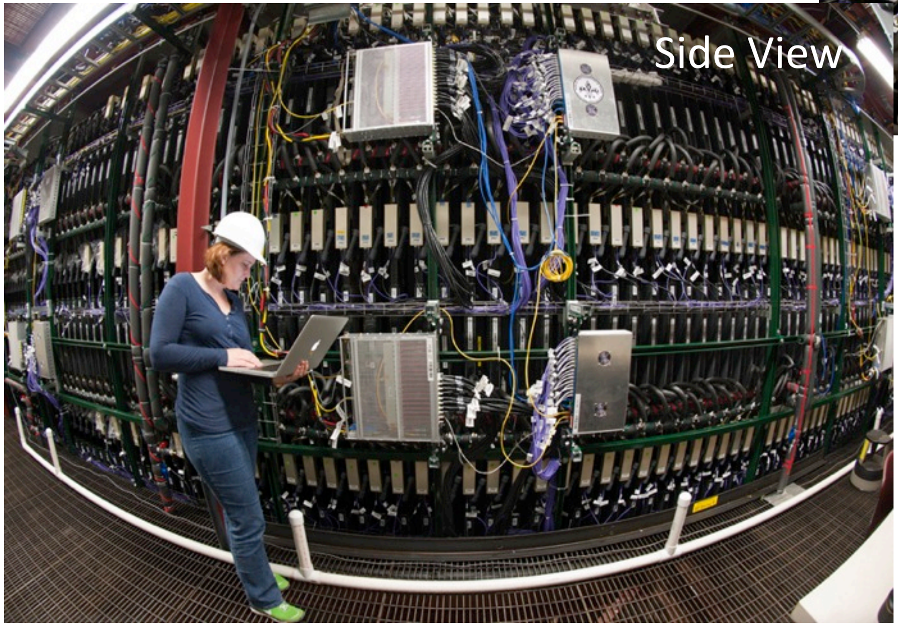
First block in place ~ early June 2012
First block filled ~ Aug 2012
First block outfitted ~ Nov 2012



FIRST DATA
~ 1 YR. FROM NOW

Near Detector On the Surface (NDOS)

- Near detector prototype constructed on the surface in Fall 2010
- Currently taking data from the NuMI & Booster neutrino beams

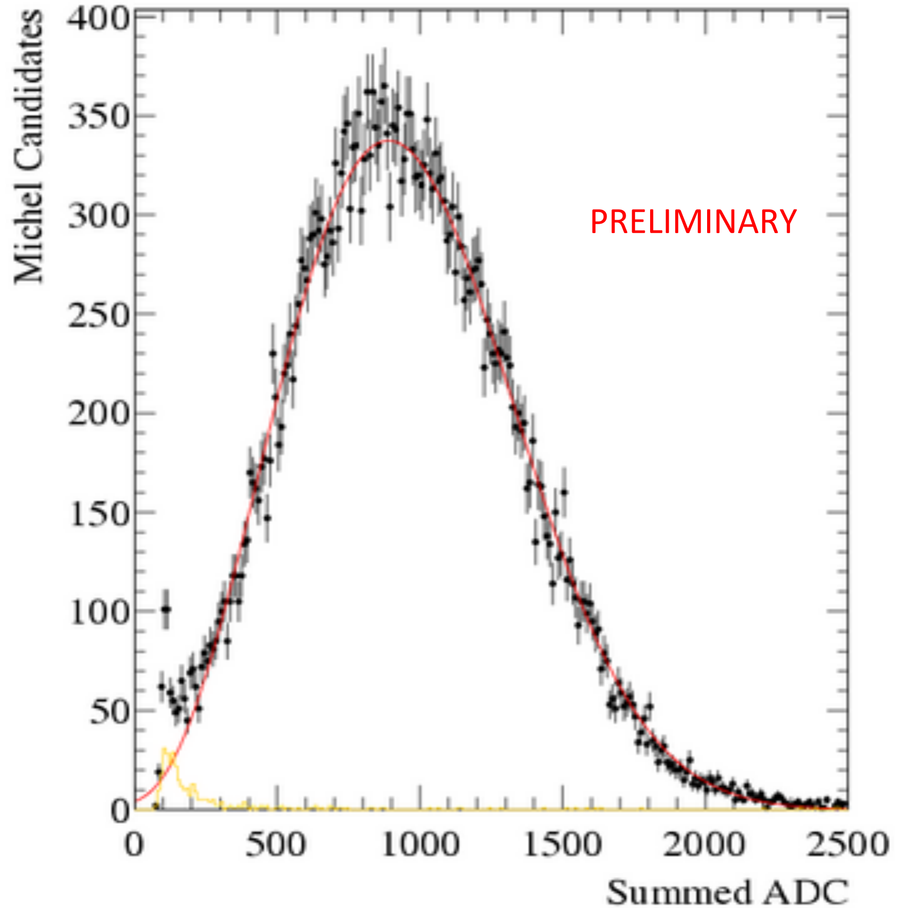


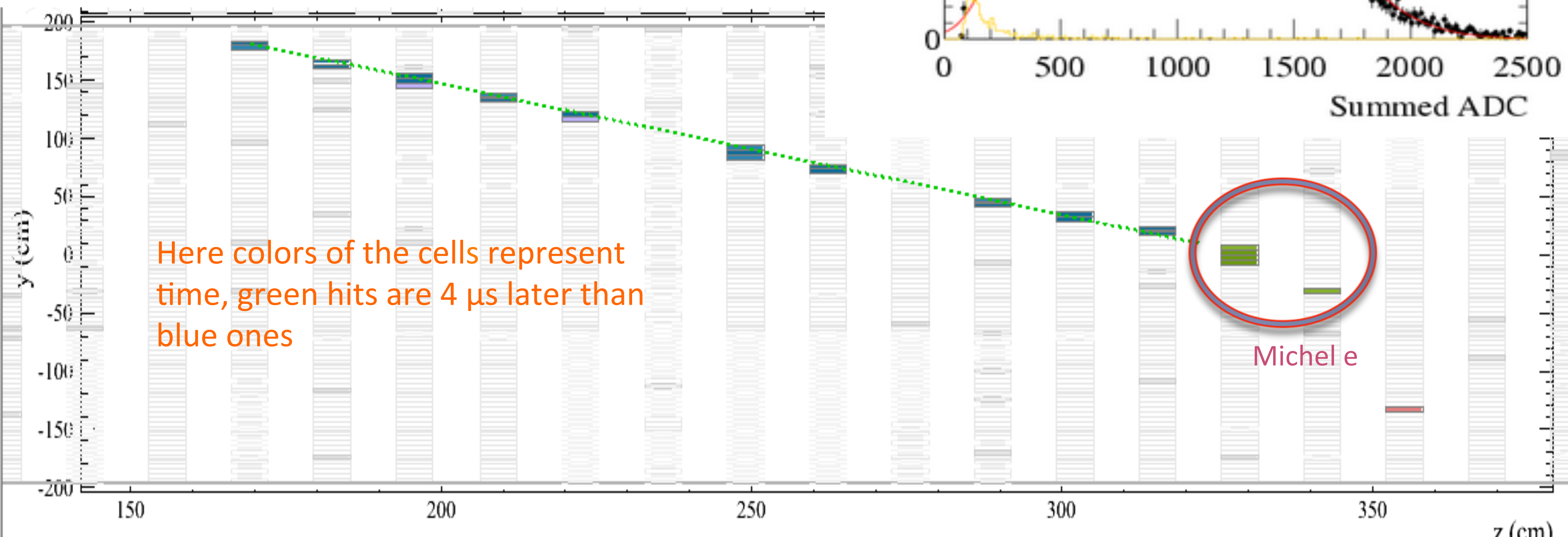
- Physics goal of NDOS:
  - Study response of the detector to neutrinos
  - Investigate the cosmic ray background
  - Calibrate the detectors

(Seen T. Kutnink's talk for more details)

Michel Electrons

- Use for electro-magnetic energy calibration
- Easy to identify by looking at the end of the muon tracks for late hits
- Have average ~ 4 hits per event





Conclusion

- NOvA is on track to make many important contributions to neutrino physics
  - Measurement of θ_{13}
  - Determination of mass hierarchy
  - More precise measurements of Δm^2, $\sin^2(2\theta_{23})$
- Far detector construction is starting and will take its first data in ~ 1 year
- Prototype detector has been running for one year
  - Studying calibration
  - Initial studies of neutrino interactions

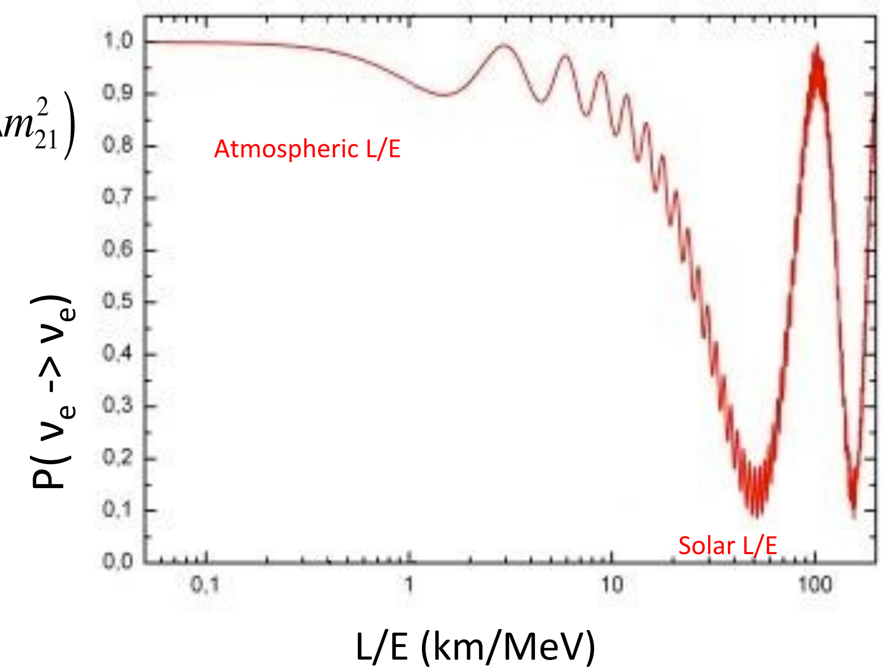
Back-up Slides

Neutrinos Oscillation Channels

- ν_e disappearance reactor experiments
  - Looking for ν_e disappearance
  - Probability depends on $\sin^2 2\theta_{13}$ and Δm^2
  - CHOOZ, Double-Chooz and Daya Bay

$$P(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) + o\left(\Delta m^2_{21}\right)$$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\left|m^2_{31}\right| + \sin^2\theta_{12}\left|m^2_{32}\right|$$



Neutrinos

- Neutrinos have two sets of eigenstates
  - Weak eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$
  - Mass eigenstates (ν_1, ν_2, ν_3)
- Neutrinos oscillations come about because the weak eigenstates are rotated from the mass eigenstates.

weak eigenstates → $|\nu_\alpha\rangle = U^*_{\alpha j}|\nu_j\rangle$ ← mass eigenstates

↑ unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{cp}} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta_{cp}} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta_{cp}} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta_{cp}} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta_{cp}} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{jk} \equiv \cos\theta_{jk}$$
$$s_{jk} \equiv \sin\theta_{jk}$$

Neutrinos: What we know

- Mixing angle:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta_{cp}}\\0&1&0\\-\sin\theta_{13}e^{i\delta_{cp}}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mu-> tao | Mu -> e | E -> mu, tao

atmospheric and accelerator, L/E~0.5 km/MeV

Reactor + Solar, L/E~15 km/MeV

$^{*}\sin^2(2\theta_{23}) > 0.96 (90\% \text{ C.L.})$

$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$

Sin2(2θ13) = 0.092 ± 0.016(stat) ± 0.005(syst)

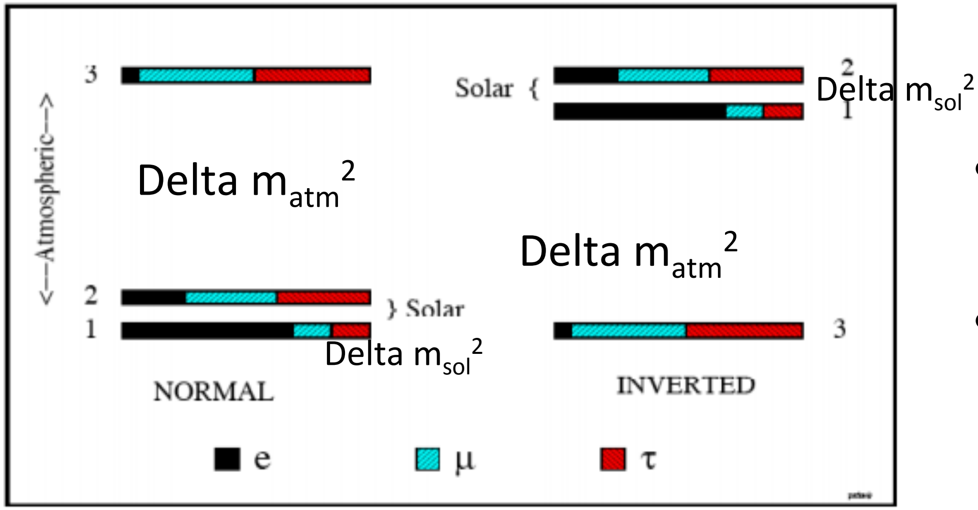
- Mass Hierarchy

Solar neutrinos: $^{\dagger}\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \text{eV}^2$

Atmospheric neutrinos: $^{\dagger\dagger}|\Delta m^2_{32}| = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$

Neutrinos: What we don’t know

- Mass Hierarchy



- Neutrino mass hierarchy
- Individual mass of neutrino

- CP violation phase is unconstrained

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta_{cp}}\\0&1&0\\-\sin\theta_{13}e^{i\delta_{cp}}&0&\cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

NOvA Features

- ## Long baseline & Matter effects

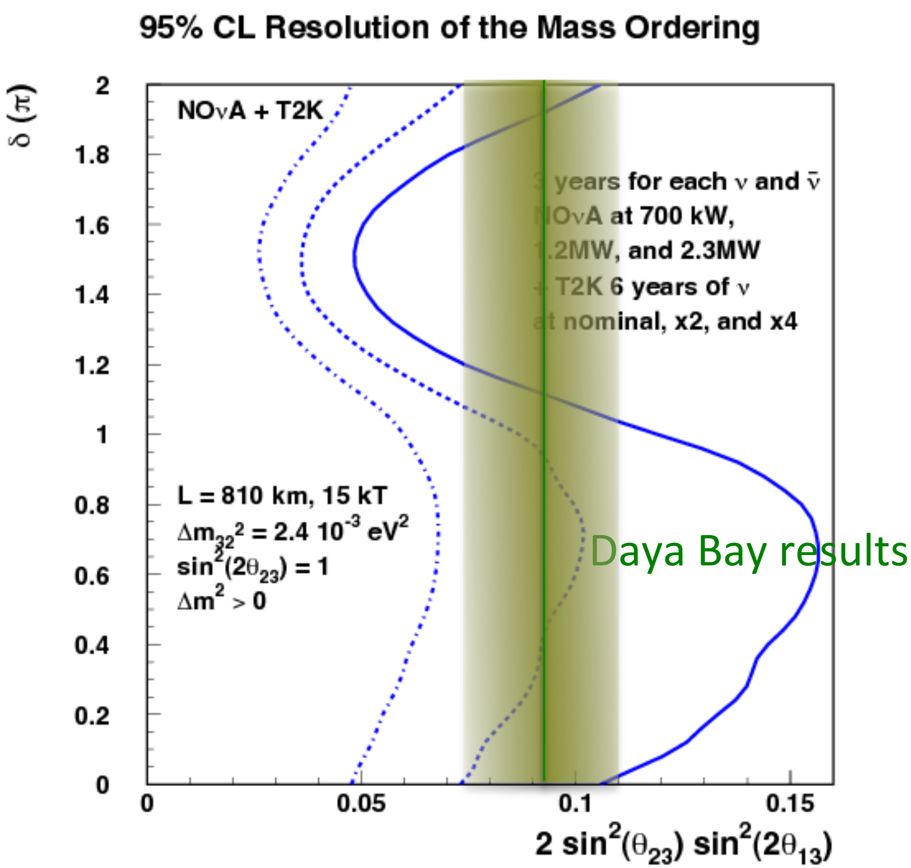
The neutrinos in the NuMI beam propagate through the earth and a coherent charged-current forward scattering of mu-e with electrons in the earth induces a significant change in the oscillation probabilities. These matter effects have opposite sign for neutrino and anti-neutrino and for the normal versus inverted neutrino mass ordering.

- ## Optimized for the detection of both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations

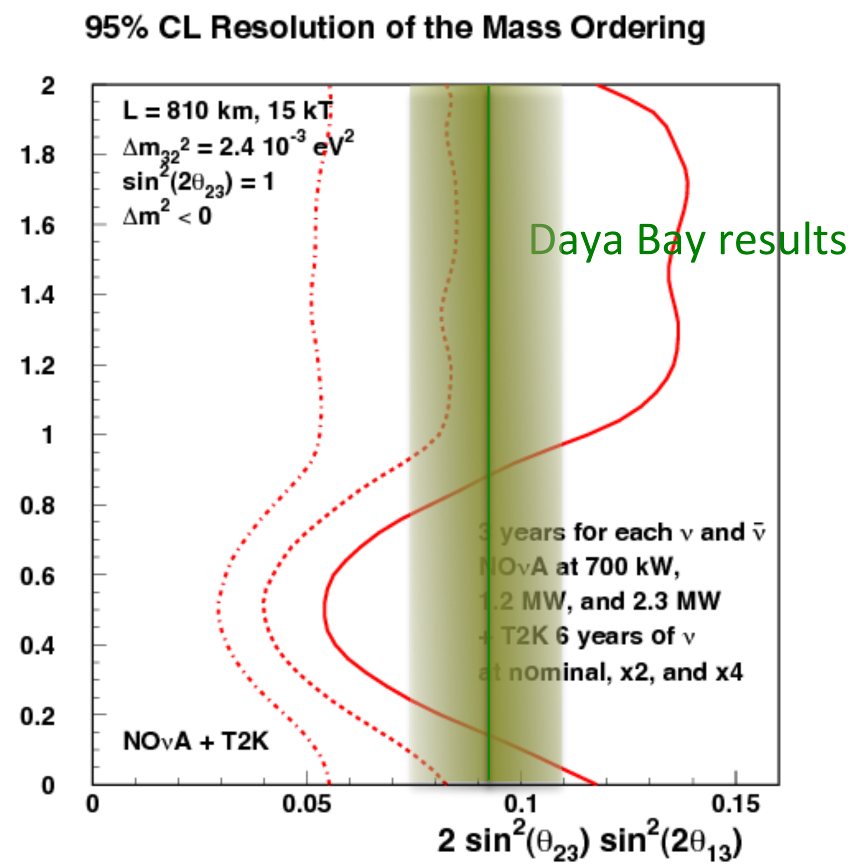
NOvA will split its running time equally between neutrino running and antineutrino running. It will make the sensitivity to seeing a signal less dependent on the value of δ_{cp} and the sign of Δm^2 and give NOvA the capability of measuring them.

Sensitivity to Mass Hierarchy Combing T2K Results

Normal Hierarchy



Inverted Hierarchy



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