Physics Goals and Sensitivity of NOvA

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I. What we want to know

Does the ν_3 mass state have a ν_e component?
Is $\theta_{13} \neq 0$?

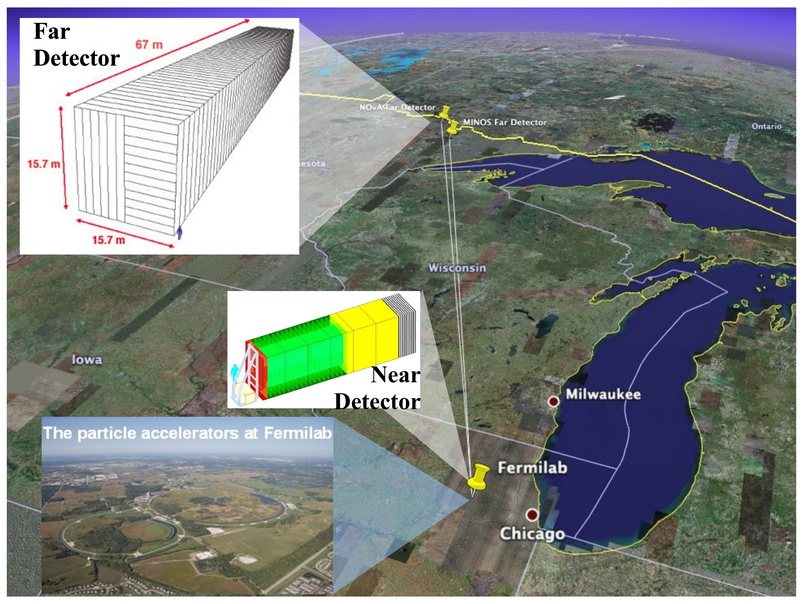
Is there CP violation in the lepton sector?
Is $\delta_{CP} \neq 0$ and $\theta_{13} \neq 0$?

Is the ν_3 mass state more massive than the ν_1 and ν_2?
Normal Hierarchy ($\Delta m^2_{31} > 0$)
or
Inverted Hierarchy($\Delta m^2_{31} < 0$)

Does the ν_3 mass state have a larger ν_μ or ν_τ component?
Is $\theta_{23} \neq \pi/4$?

II. How we might learn the answers

NuMI Off-axis ν_e Appearance Experiment



NOvA in a Nutshell

Long-baseline ν oscillation experiment

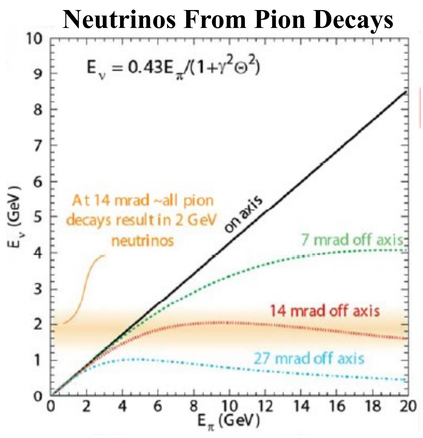
ν_μ beam produced with accelerators
- NuMI facility at Fermilab, Illinois
- 810 km beam line
- 14 mrad off-axis
- E_ν ~2 GeV

2 detectors
- Near Detector at Fermilab, Illinois
  - Measure beam before oscillations
- Far Detector at Ash River, Minnesota
  - Search for evidence of oscillations

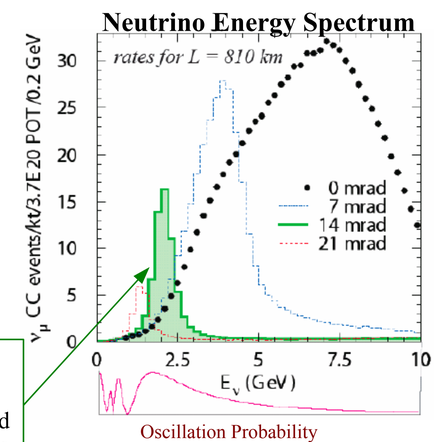
See Alec Habig's poster for more information on the detectors

The goal of NOvA is to answer the big questions in Box I

Why go off-axis?



Narrow Energy Band
- Peak near oscillation max
- Reduction in NC background from higher energy neutrinos



III. Why NOvA can do this

ν_μ Disappearance: $\nu_\mu \rightarrow \nu_\tau$ oscillations

Oscillation Probability

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23}\sin^2(1.27\,\Delta m^2_{32}\,L/E)$$

By measuring the surviving ν_μ energy spectrum NOvA can make precision measurements of $\sin^2 2\theta_{23}$ and the magnitude of $|\Delta m^2_{32}|$

Note even if the disappearance analysis determines $\theta_{23} \neq \pi/4$, this analysis alone cannot determine if $\theta_{23} > \pi/4$ or if $\theta_{23} < \pi/4$

ν_e Appearance: $\nu_\mu \rightarrow \nu_e$ oscillations

Oscillation Probability

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

The NOvA $\nu_\mu \rightarrow \nu_e$ oscillation probability depends on many parameters including:

θ_{13}, δ_{CP}, The Mass Hierarchy (the sign of Δm^2_{31})

NOvA's long-baseline means there are a lot of electrons with which a ν_e can interact

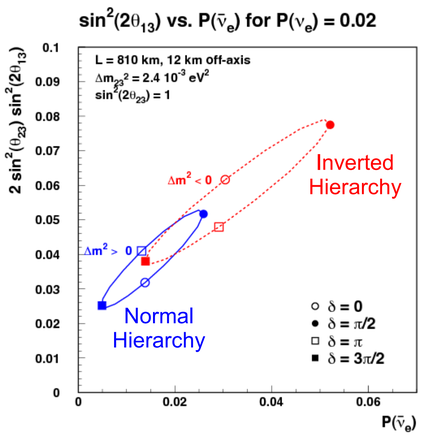
These "Matter Effects" alter the oscillation probability (ie the 'A' terms in the equation)
For NOvA this is a 30% effect

The sign of the Matter Effects depends on the Mass Hierarchy

The ν and $\overline{\nu}$ oscillation probability will differ because of CP violation and Matter Effects

NOvA will run 3 years with a ν beam and 3 years with a $\overline{\nu}$ beam

If θ_{13} is large enough, then NOvA can use the two appearance probabilities to constrain the values of θ_{13} and δ_{CP} and might even resolve the Mass Hierarchy



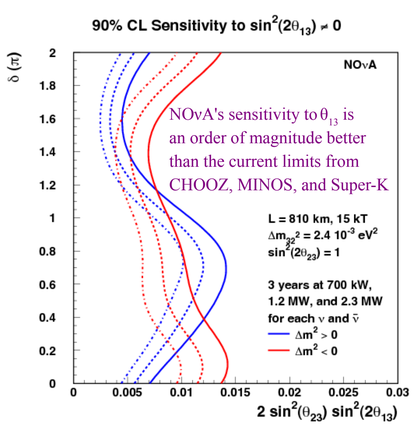
The plot to the left demonstrates the relationship between the appearance probabilities for $\nu_\mu \rightarrow \nu_e$ oscillations and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations for different values of the oscillation parameters.

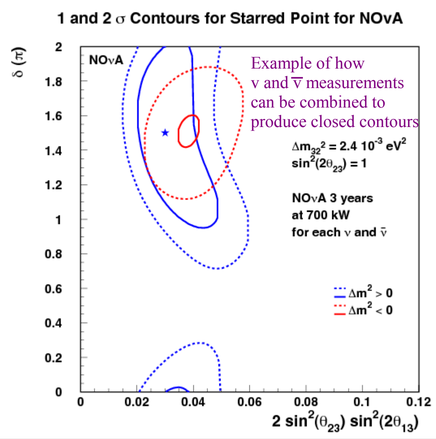
Resolve the degeneracy in the value of θ_{23}

The $\nu_\mu \rightarrow \nu_e$ oscillation probability depends on $\sin^2\theta_{23}$, hence it is sensitive to whether $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$. By also using the measurement of the $\overline{\nu}_e \rightarrow \overline{\nu}_e$ survival probability from a reactor experiment, it might be possible to determine whether θ_{23} is less than or greater than $\pi/4$

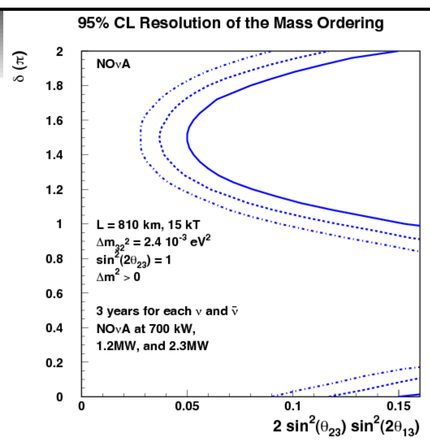
IV. NOvA's Sensitivity

Measuring θ_{13} and δ_{CP}





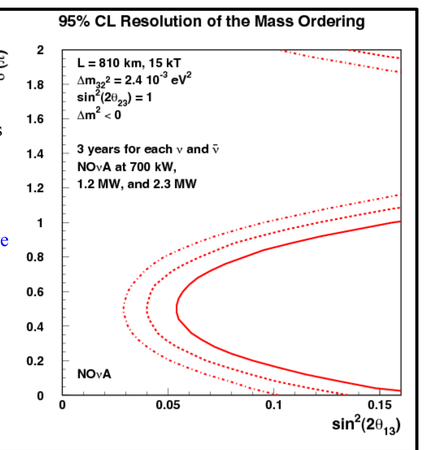
Resolving the Mass Hierarchy



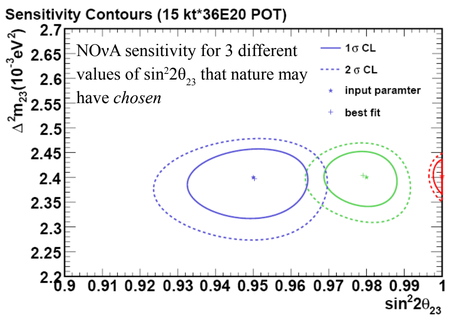
NOvA can resolve the Mass Hierarchy if nature has any of the values to the right of the plotted curves

The blue curves are if nature has a Normal Hierarchy

The red curves are if nature has an Inverted Hierarchy



Precision Measurement θ_{23} and $|\Delta m^2_{23}|$



If θ_{13} is large enough and $\sin^2 2\theta_{23}$ is small enough, then the combined measurements from NOvA and a reactor experiment can determine if $\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$

Exactly how much is large enough and how much is small enough is shown in the plot to the right