The NOvA Experiment

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Overview

- The name

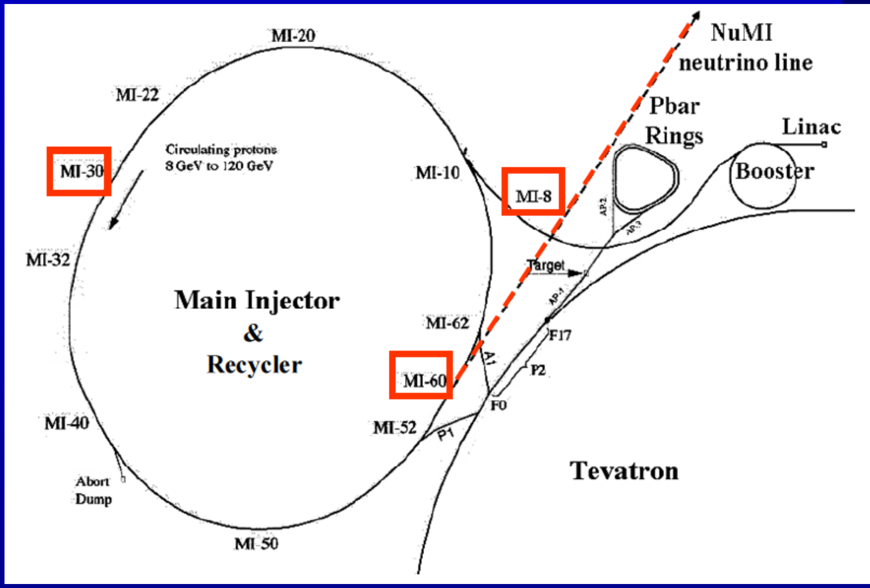
N **N**uMI = Neutrinos at the Main Injector
O **O**ff axis
v ν_e
A **A**ppearance

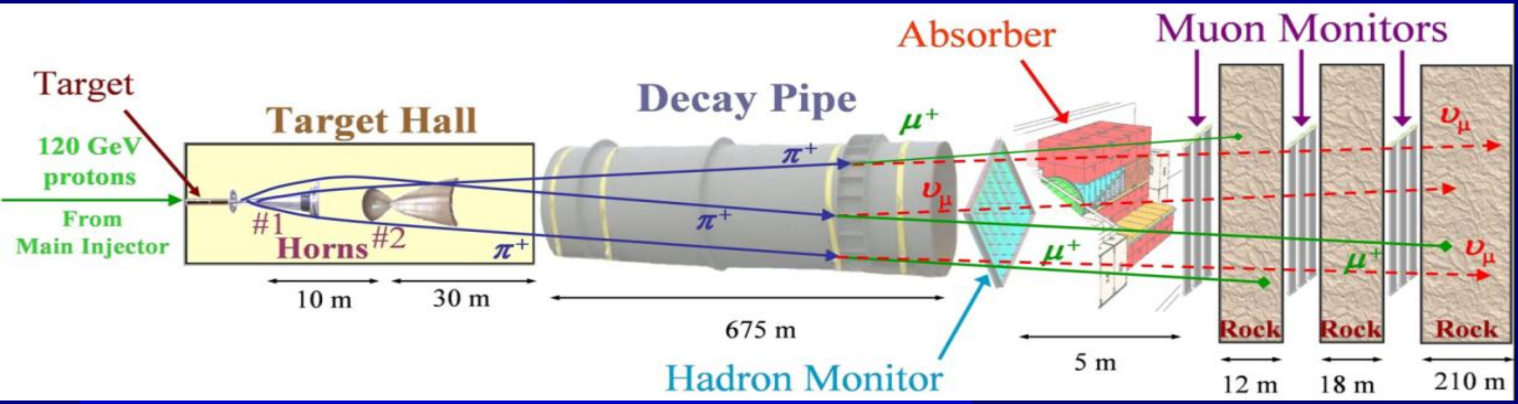
- 150+ Collaborators in
25 Institutions from 5 Countries

- The NOvA experiment
  - long baseline neutrino experiment
    - Designed to look for $\nu_\mu \rightarrow \nu_e$ oscillations
  - consists of two detectors
    - The Near Detector located at Fermilab
    - The Far Detector located in Northern Minnesota
    - 810 km away from each other

The Neutrino Source

- 120 GeV protons are extracted from Fermilab's Main Injector and get fired onto a graphite target
- Results in the creation of charged particles – in particular pions
- A magnetic horn focuses the charged pions towards the Soudan Mine (MINOS Far Detector)
- The pions decay into (anti-) muons and (anti-) muon-neutrinos traveling in approximately the same direction
- Reversal of the horn current is used to switch between neutrino and anti-neutrino mode

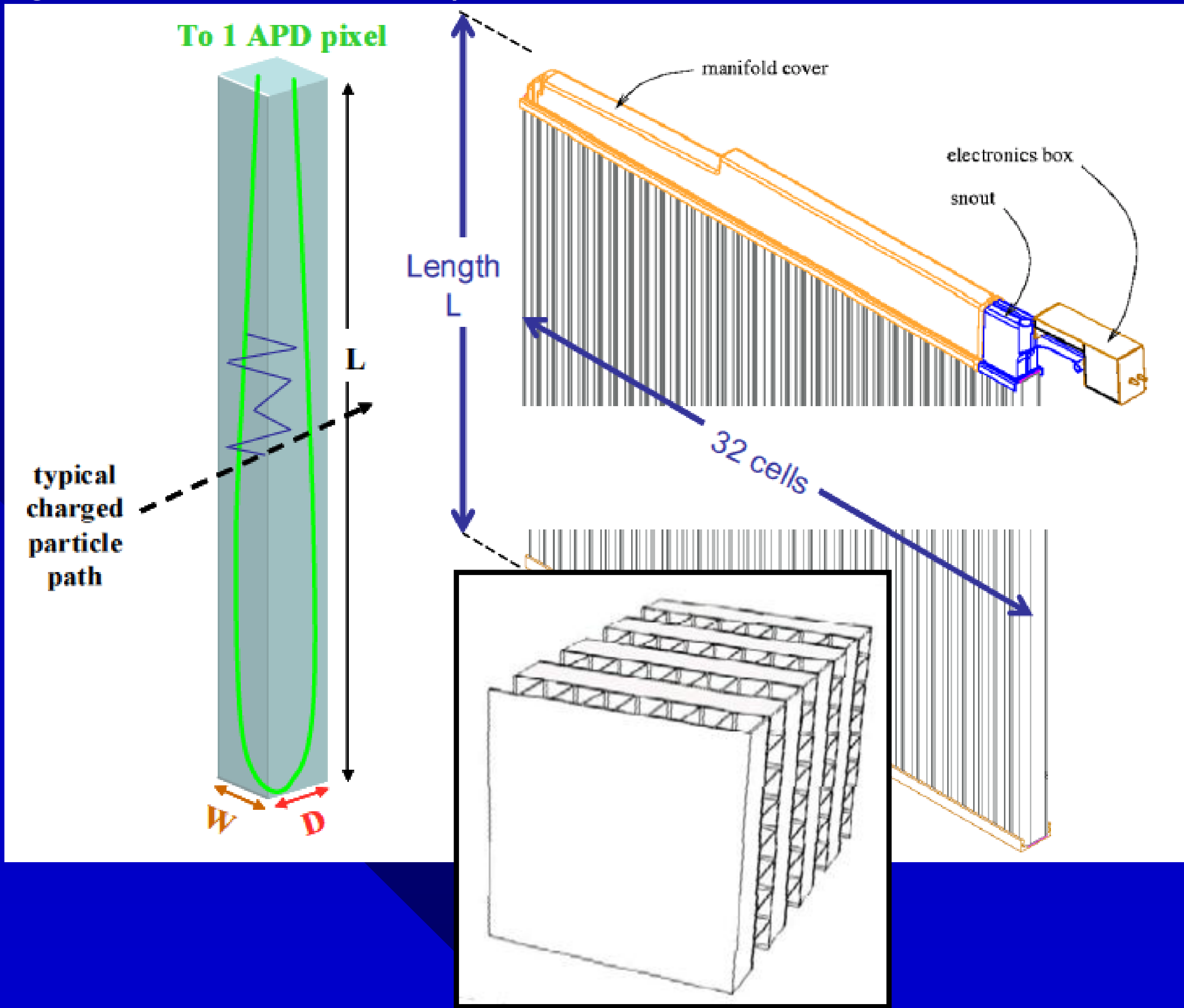




- Currently shut down for an upgrade until April 2013
  - will deliver $4.9 \cdot 10^{13}$ protons every 1.3 s for 10 μs
  - will have a beam power of 700 kW (was 380 kW before shot down)

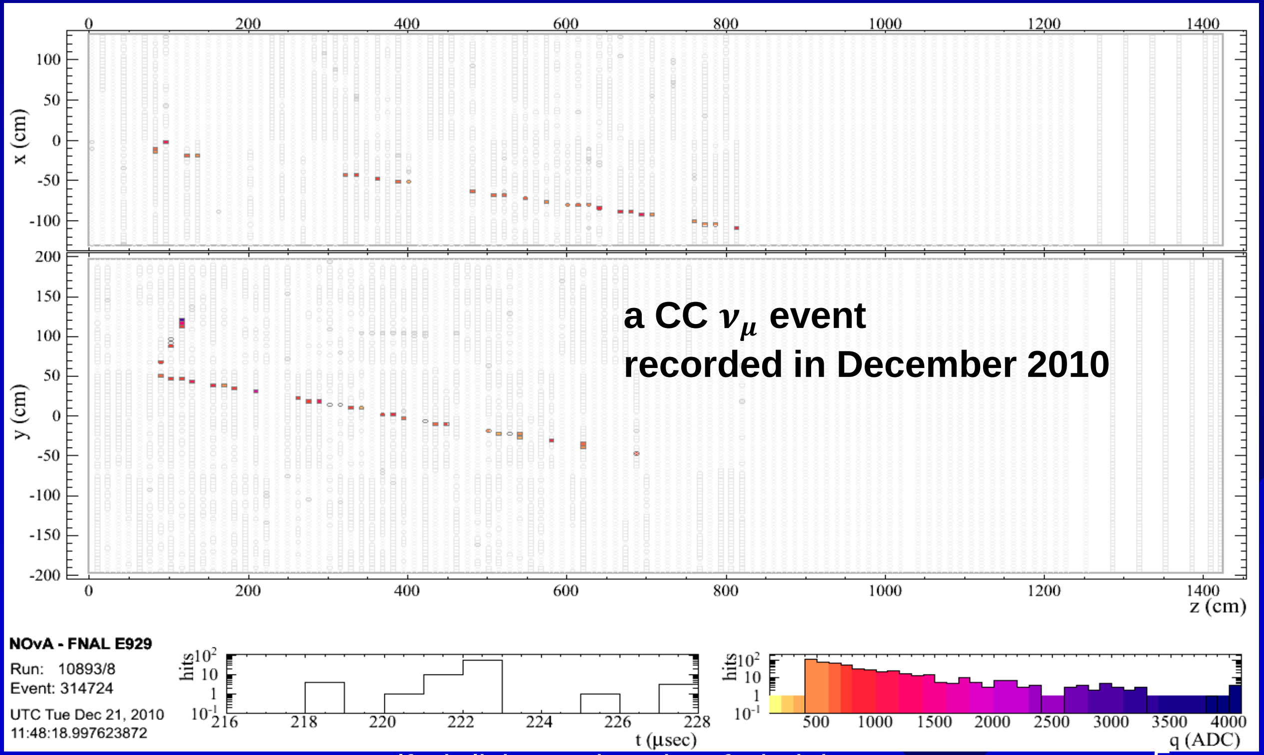
Detector Design

- The detectors are built of plastic cells
  - 4.0 cm x 6.7 cm x 15 m (Near Detector cells are shorter)
  - 32 cells form one module
  - modules arranged in alternating horizontal and vertical planes to enable a 3D reconstruction
- Cells are filled with liquid scintillator
- Charged particles due to neutrino interactions causes the scintillator to emit light
- This light gets captured by optical fibers
- Optical fibers transmit the light to Avalanche Photo Diodes (APD)
  - 85% quantum efficiency
  - Operated at 425 V
  - Cooled to -15 ºC by thermoelectric coolers
- The APD output is digitized at the Front End Boards in the electronics box at the end of manifold covers.

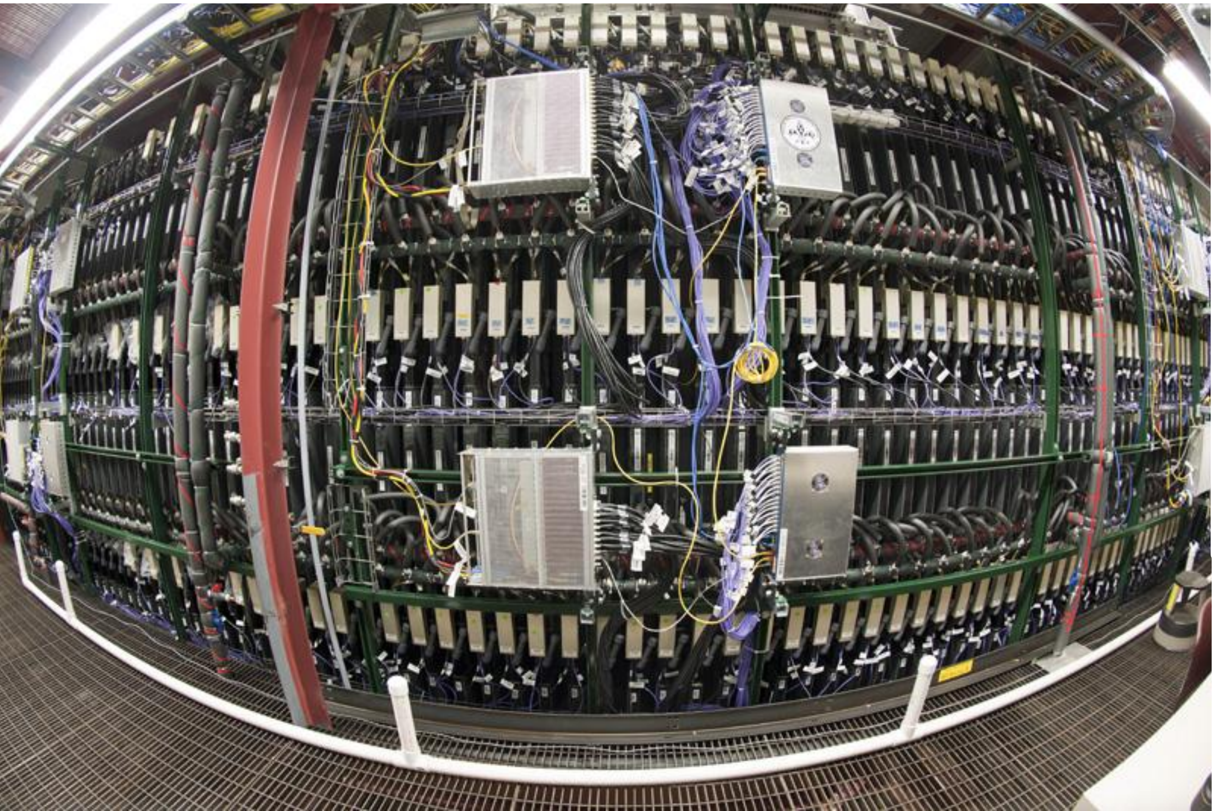


The Prototype Near Detector

- Prototype detector
  - Built to get some experience before building the “real” Near Detector and Far Detector
  - Has been invaluable for developing of reconstruction algorithms and prototyping the equipment
- Located on the surface at Fermilab 1km away from the target
- Has a “Muon Catcher” made of steel to contain muons from CC interactions
- 16,000 cells, 222 tons
- Status
  - Finished in spring 2011
  - First events recorded in fall 2010

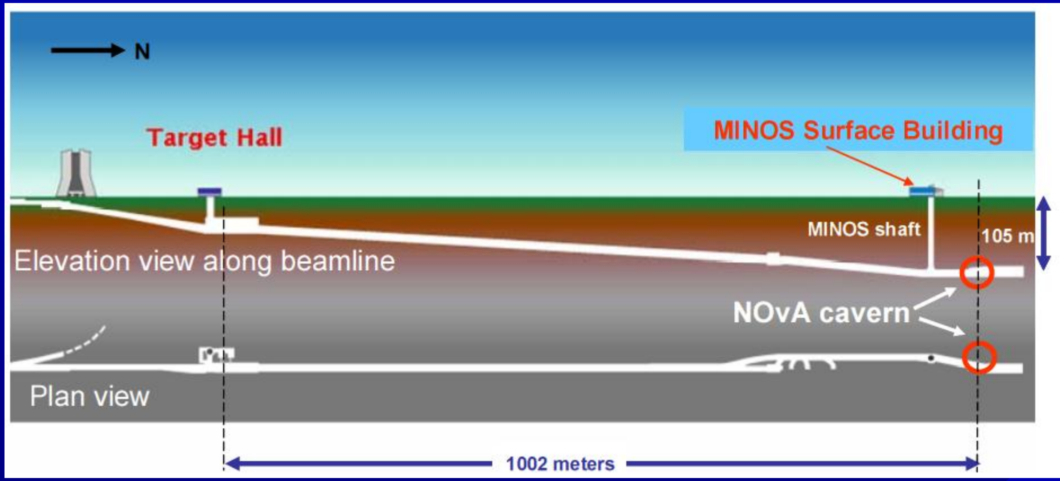


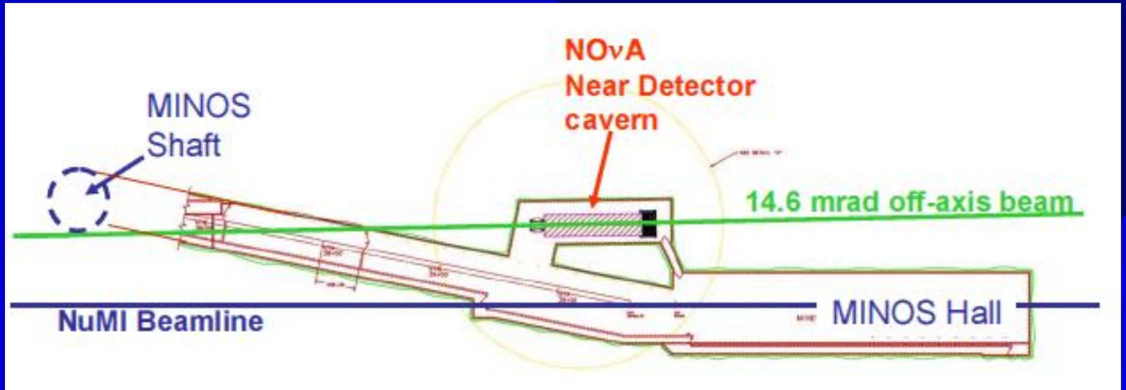
The Prototype Near Detector



The Near Detector

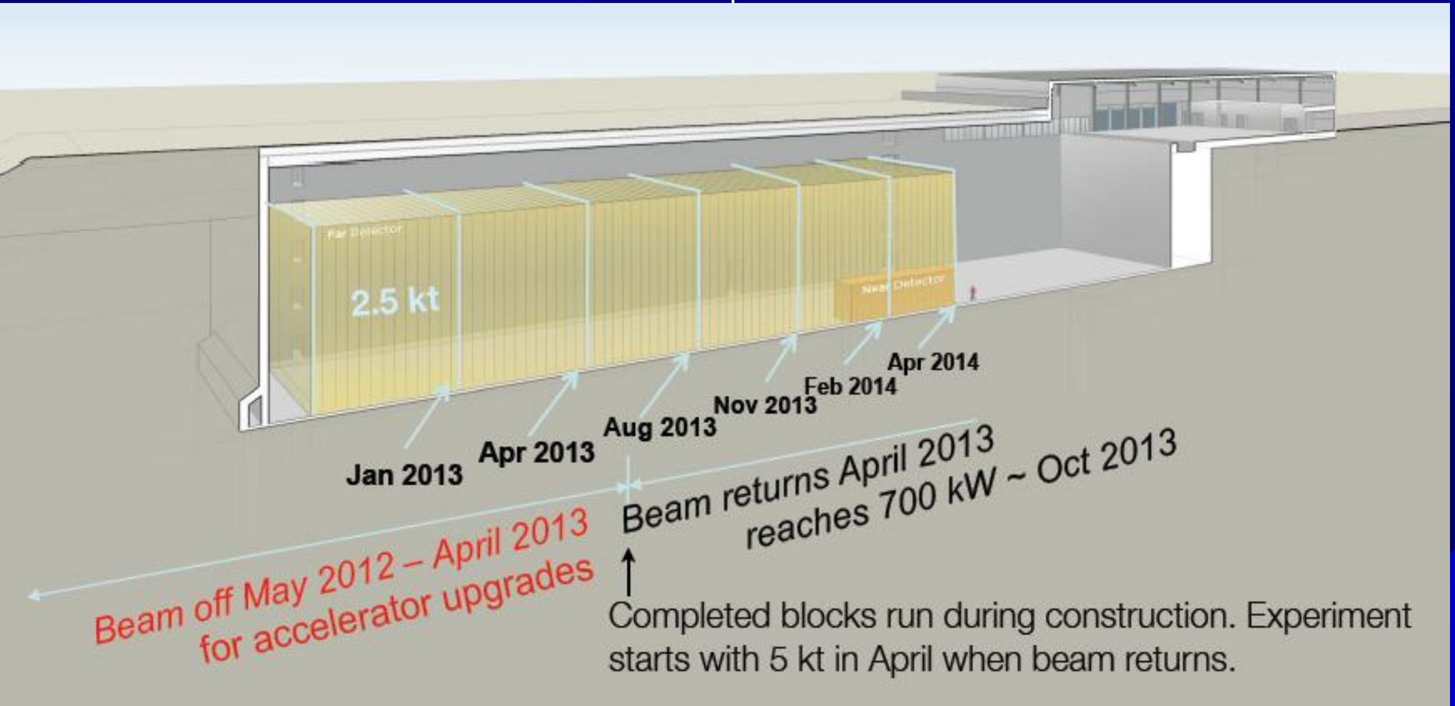
- The "real" Near Detector
- Located underground at Fermilab 1 km away from the target
- Identical design as the Far Detector – except that it is smaller
- Has a "Muon Catcher" made of steel to contain muon tracks from CC interactions
- 20,000 cells, 266 tons
- Status:
  - Construction starts in 2013
  - Construction finished in 2014
- Will be used to measure the ν_μ flux emitted at the source of the neutrino beam
- Will be used to study background events:
  - ν_e contaminations of the neutrino beam
  - neutral current ν_μ interactions



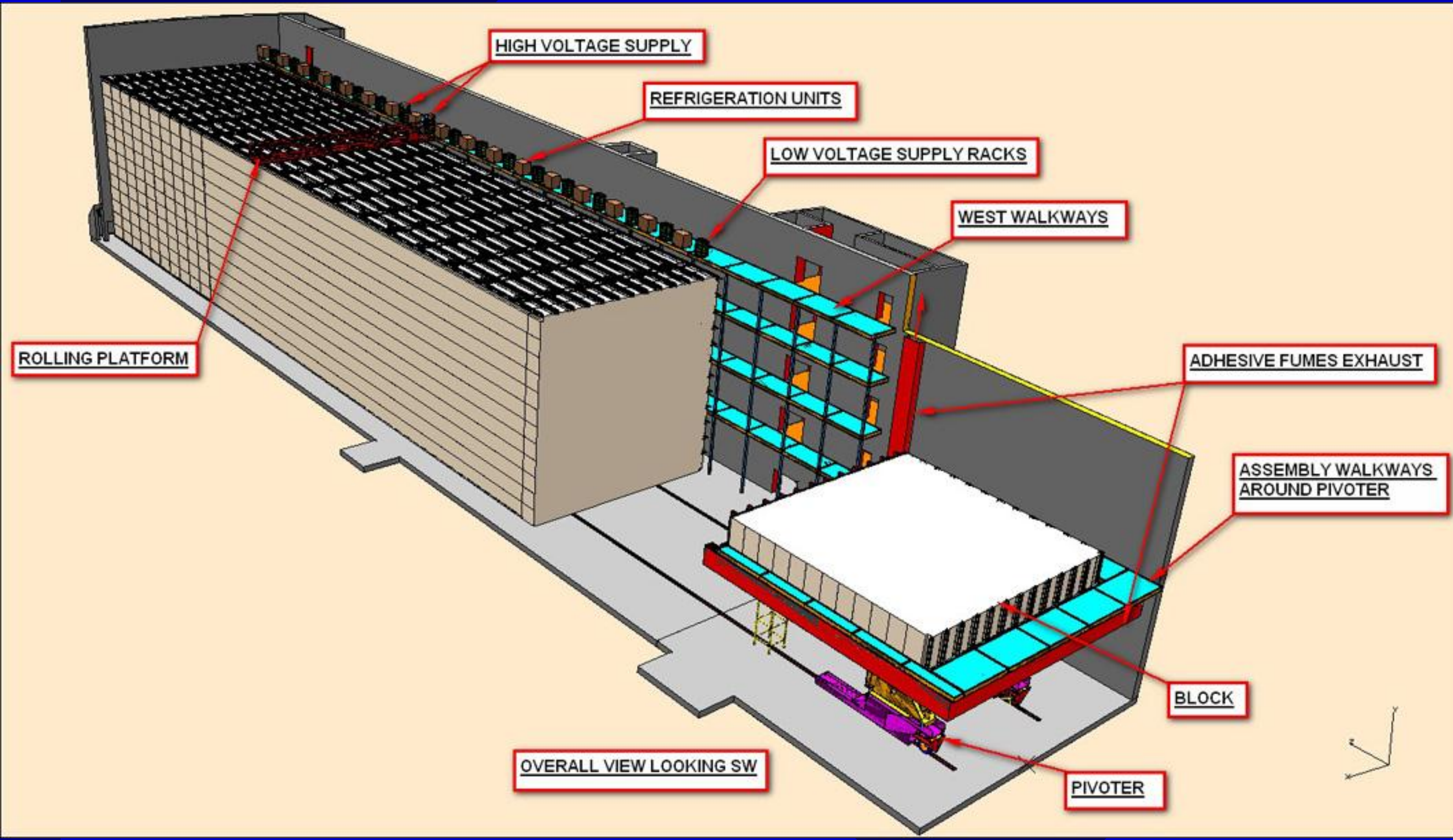


The Far Detector

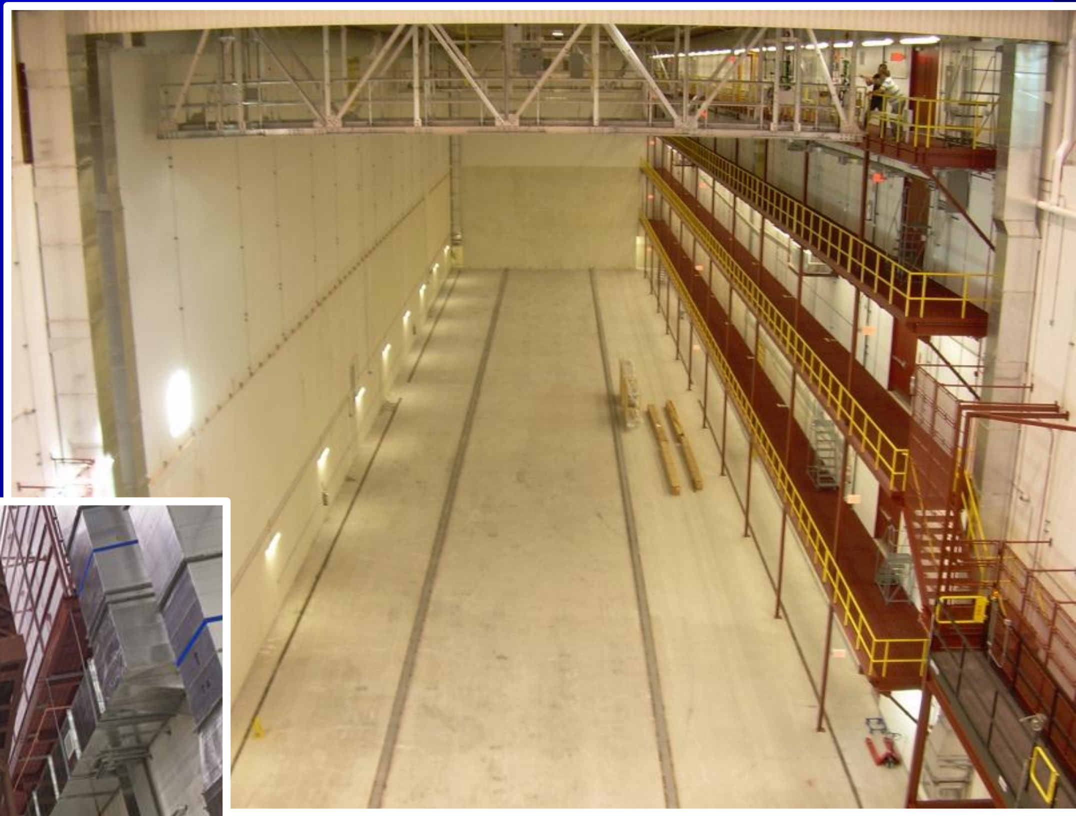
- Located in Northern Minnesota 810 km away from the neutrino source
- 356,000 cells, 14,000 tons, 15x15x63 m^3
- Status:
  - Building dedication in April 2012
  - Block installation will start in summer 2012
  - Construction will be finished in 2014
- Designed to detect the ν_e after they oscillated from ν_μ
- Sits near the first expected $\nu_\mu \rightarrow \nu_e$ oscillation peak



The Far Detector

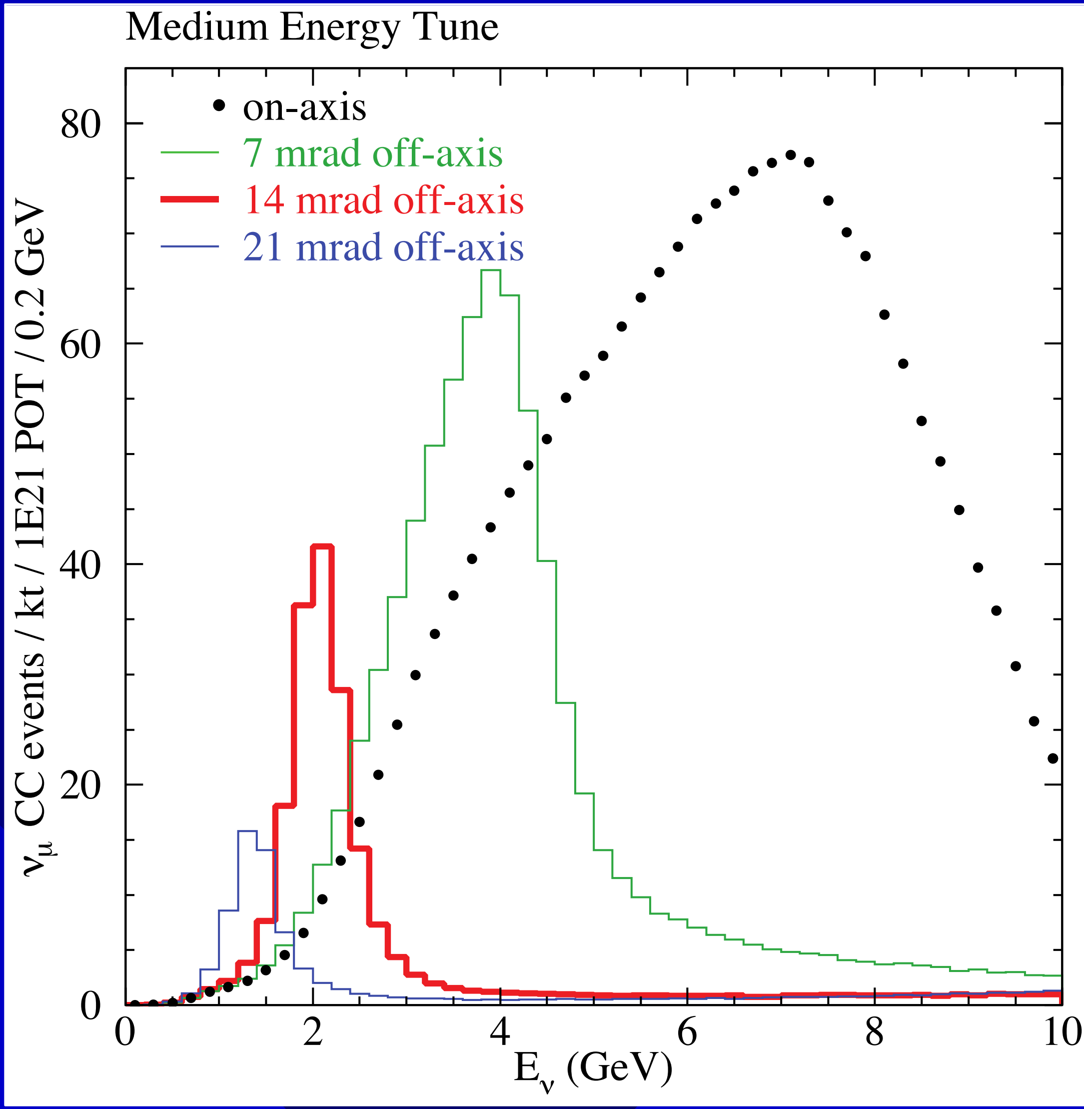


The Far Detector



Off Axis Location

- Near and Far Detectors are located 14 mrad away from the beam axis
  - At this angle, the neutrino beam has a narrow energy distribution with a peak around 2 GeV
    - Reduces the background
- The transition probability for $\nu_\mu \rightarrow \nu_e$ is expected to be close to its maximum
  - at this energy (2 GeV) and
  - at this location (810 km away from the neutrino source)
- The neutrino beam goes through the Earth so that we can make use of the matter effects



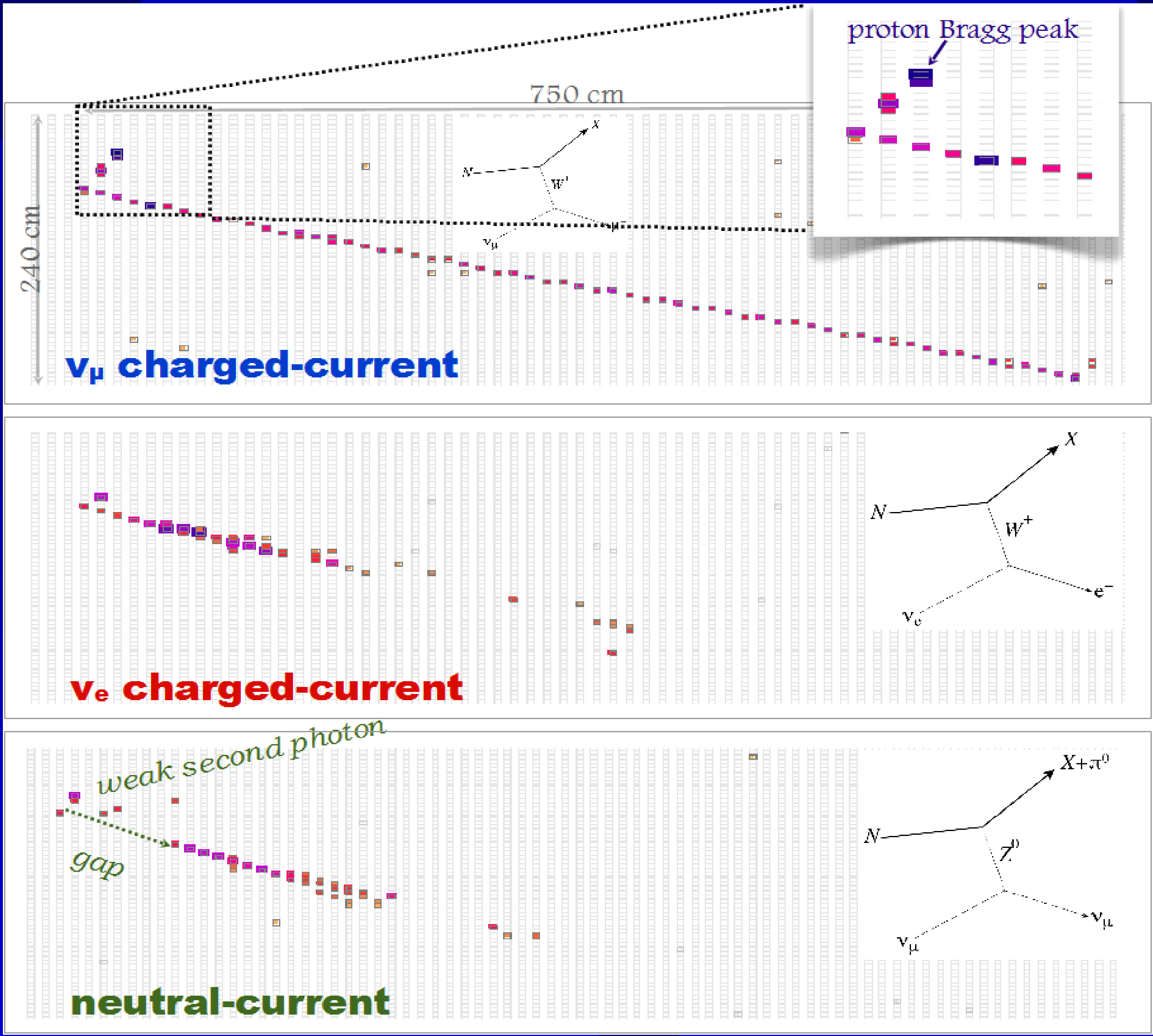
Neutrino Detection

Typical (simulated) events

- Long μ tracks
- Short proton track at the vertex may be visible

- Short electron tracks with EM cascades along the track
- Short proton track at the vertex may be visible

- $\pi^0 \rightarrow \gamma\gamma$
- Identified by gap b/w beginning and end of the γ tracks



Neutrino Mixing Parameters

Global status of neutrino oscillation parameters after recent reactor measurements

from arXiv:1205.4018 v2 [hep-ph] 21 May 2012

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	7.62 ± 0.19	7.27–8.01	7.12–8.20
Δm^2_{31} [10^{-3}eV^2]	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41–0.62 0.42–0.62	0.39–0.64
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	0.019–0.033 0.020–0.034	0.015–0.036 0.016–0.037
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	$0 - 2\pi$	$0 - 2\pi$

We don't know the sign, since we don't know the mass hierarchy

Is $sin^2(2\theta_{23}) = 1.0$, i.e. $\theta_{23} = 45°$?

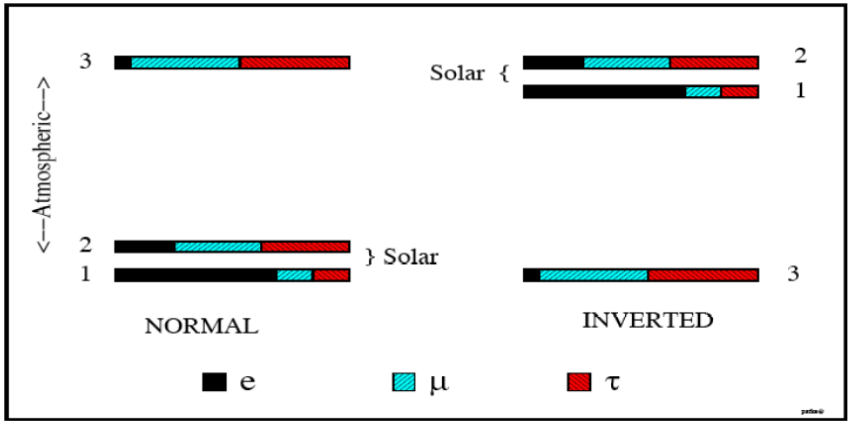
$\theta_{13} \approx 9°$

In other words: unknown

TABLE I: Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, and δ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy.

Neutrino Mixing Parameters

- We measure the appearance of ν_e and $\bar{\nu}_e$ i.e. $P(\nu_\mu \longrightarrow \nu_e)$ and $P(\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$ which are functions of
  - mixing angles $\theta_{13}, \theta_{23}, \theta_{12}$
  - the CP violating phase δ
  - the mass hierarchy, i.e. normal or inverted
  - mass squared differences $\Delta m^2_{31}, \Delta m^2_{21}, \Delta m^2_{32}$
  - neutrino energy (2 GeV)
  - oscillation distance (810 km)
  - matter effects



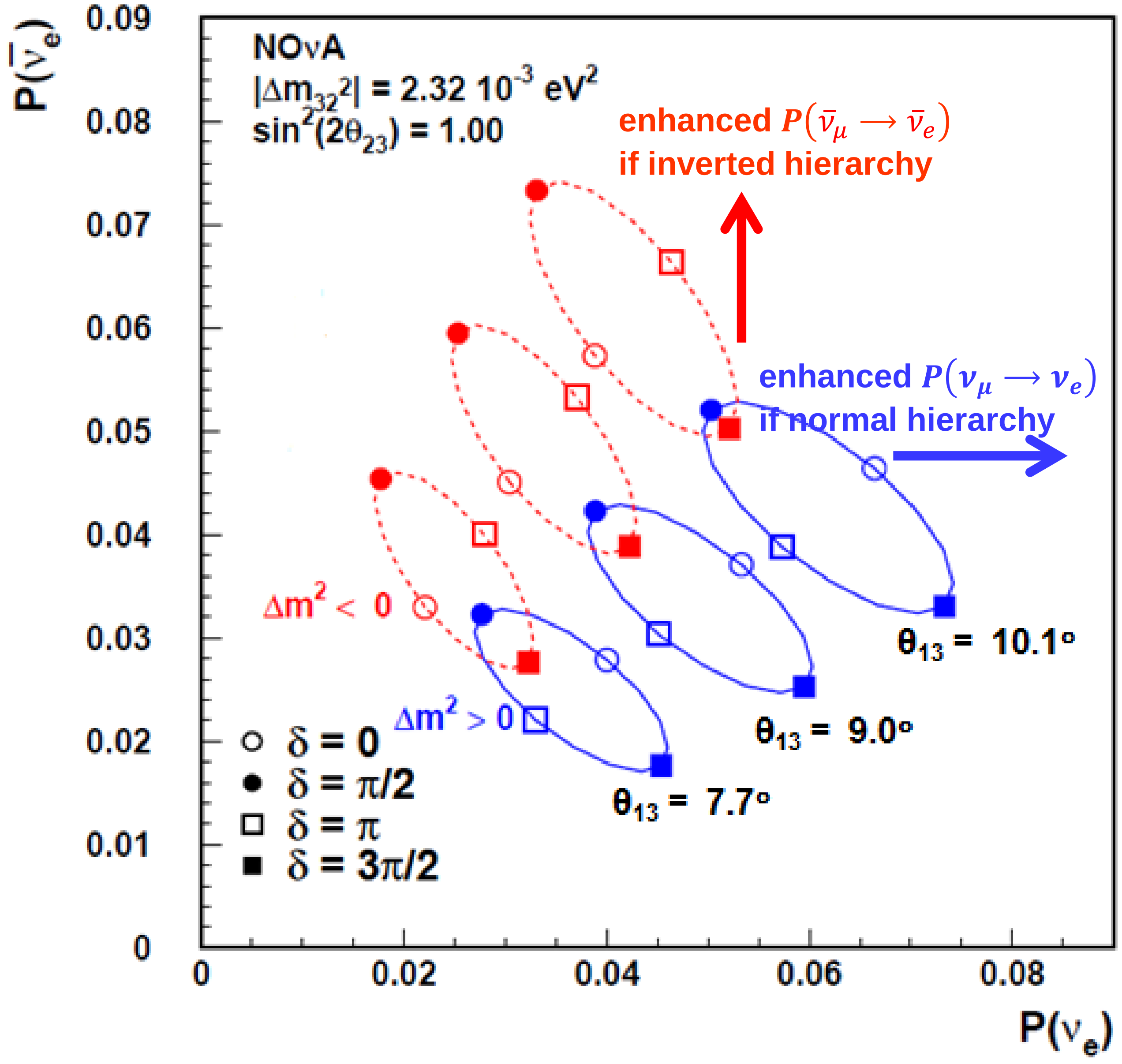
mass hierarchy

- Approximated probability function
  - $P_{vac}\binom{\nu_\mu \to \nu_e}{\bar{\nu}_\mu \to \bar{\nu}_e} \approx sin^2(\theta_{23})sin^2(2\theta_{13})sin^2(\Delta_{31})$
    $+cos^2(\theta_{13})cos^2(\theta_{23})sin^2(2\theta_{12})sin^2(\Delta_{21})$
    $+Jsin(\Delta_{21})sin(\Delta_{31})[cos(\Delta_{32})cos(\boldsymbol{\delta}) \mp sin(\Delta_{32})sin(\boldsymbol{\delta})]$
  - with $\Delta_{ij} = 1.27\frac{\Delta m^2_{ij}L}{E}$ and Δm_{ij} in eV^2, L in km, and E in GeV
  - and $J = cos(\theta_{13})sin(\theta_{12})sin(\theta_{13})sin(\theta_{23})$
  - matter effect $P_{matter}\binom{\nu_\mu \to \nu_e}{\bar{\nu}_\mu \to \bar{\nu}_e} \approx \left(1 \pm \frac{E}{6\mathrm{Gev}}\right) P_{vac}\binom{\nu_\mu \to \nu_e}{\bar{\nu}_\mu \to \bar{\nu}_e}$

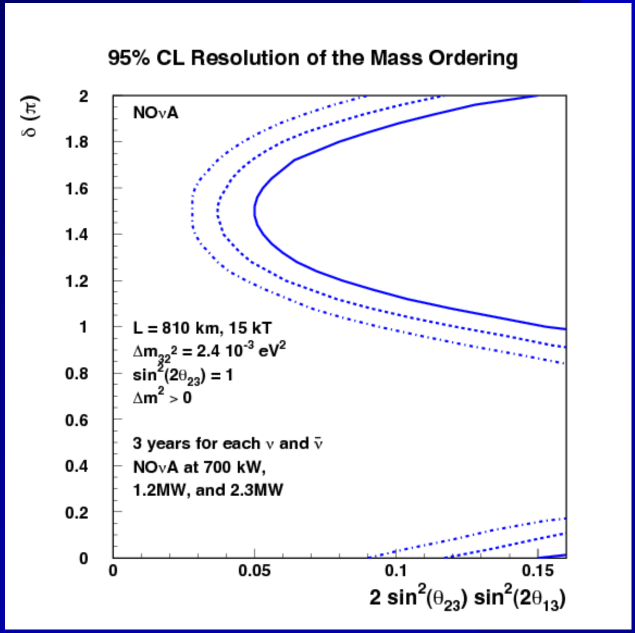
Reversed for inverted mass hierarchy

Neutrino Mixing Parameters

- NOvA measures the appearance probabilities for ν_e and $\bar{\nu}_e$
- The plot show how one may be able to extract θ_{13}, the mass hierarchy and the CP violating phase δ
  - This becomes more difficult for smaller values of θ_{13} due to overlaps of both ellipses
  - Fortunately, θ_{13} may be large according to the latest results
- The plot will look differently if $sin(2\theta_{23}) < 1$

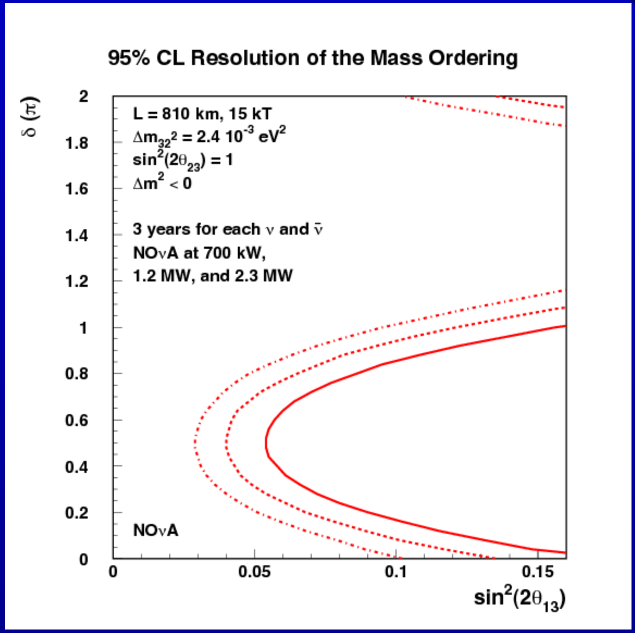


Neutrino Mixing Parameters



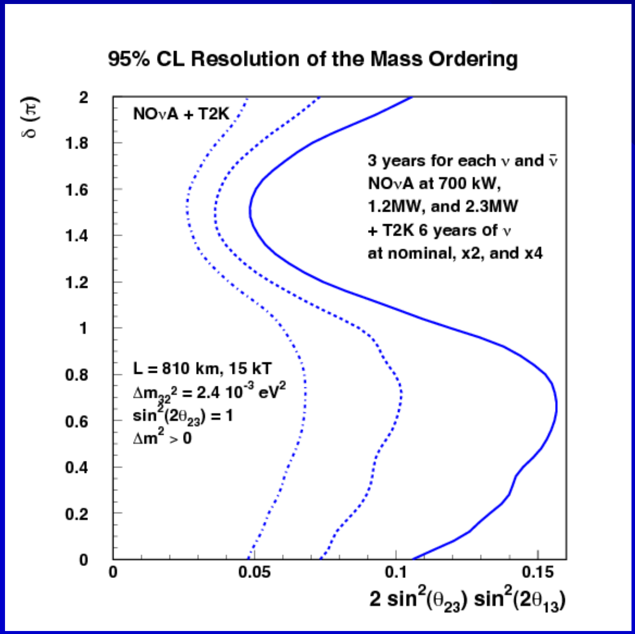
normal hierarchy

inverted hierarchy



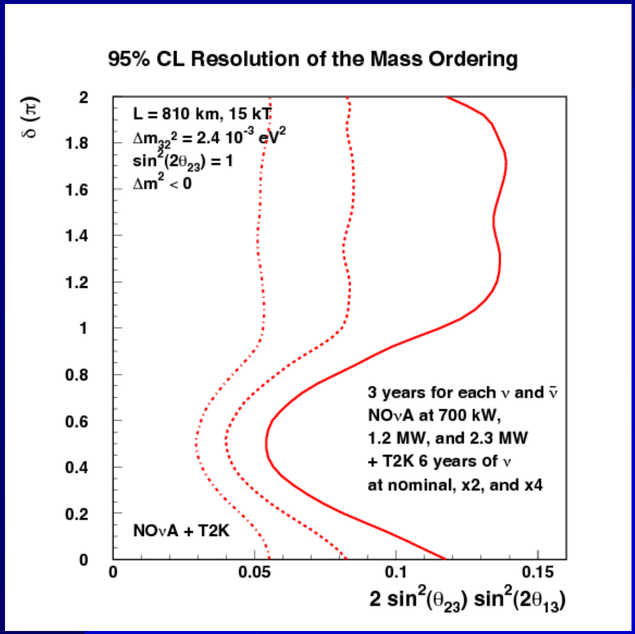
NOvA

The mass hierarchy can be resolved with better than 95% C.L. for values to the right of the curves.



normal hierarchy

inverted hierarchy



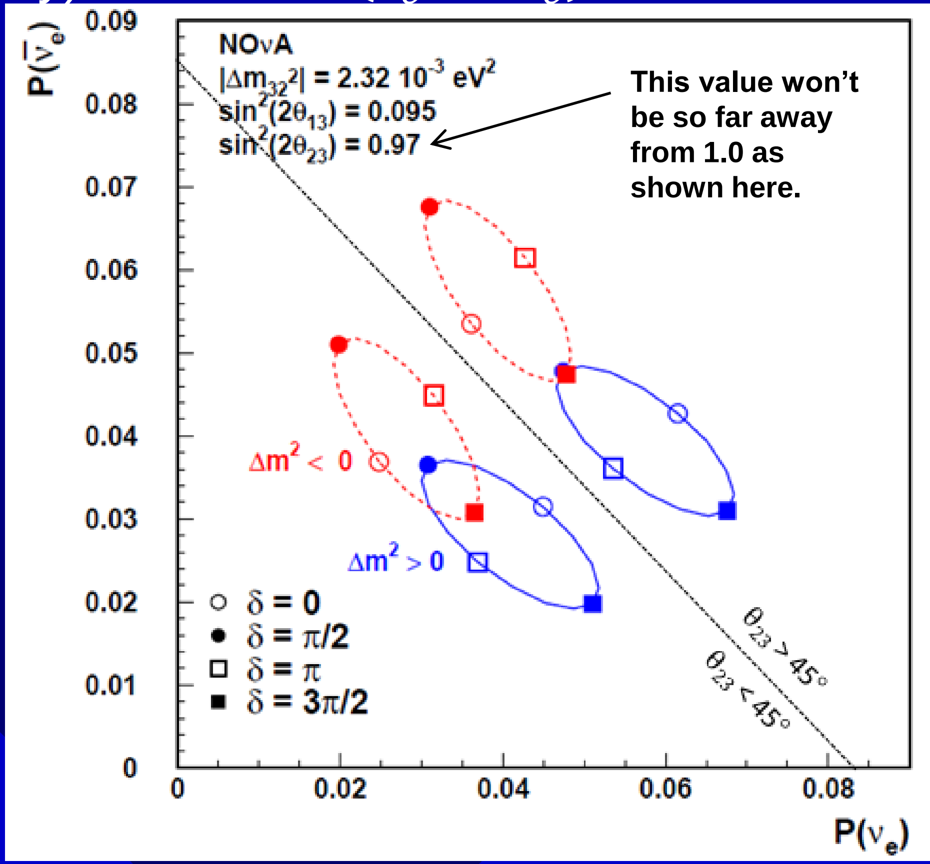
NOvA + T2K

Neutrino Mixing Parameters

- θ_{23} and Δm_{32}^2 can be determined by looking at the ν_μ survival probability
  $P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - sin^2(2\theta_{23})sin^2(\Delta_{32})$
  with $\Delta_{ij} = 1.27 \frac{\Delta m_{ij}^2 L}{E}$ and Δm_{ij} in eV^2, L in km, and E in GeV
  - This approximation assumes that the ν_μ disappearance is mainly caused by $\nu_\mu \rightarrow \nu_\tau$ (see arXiv:0711.0769v1 [hep-ex])
  - P depends on θ_{23}, Δm_{32}^2, L, E
  - P can be determined as a function of E
    by comparing the ν_μ energy spectrum at the ND and FD
    - Since L is known, this leaves the two unknown variables θ_{23} and Δm_{32}^2 which can be fitted to P to obtain their values
      - However, we only get $sin^2(2\theta_{23})$ and cannot distinguish whether $\theta_{23} > 45°$ or $\theta_{23} < 45°$
    - Requires an excellent energy resolution for muons (as a product of the CC ν_μ reaction)

Neutrino Mixing Parameters

- If $sin^2(2\theta_{23}) < 1$ → $\theta_{23} \neq 45°$
  - We need to determine whether θ_{23} is less or greater than 45º
  - The $P(\nu_e)$ -$P(\bar{\nu}_e)$ map will look differently
  - Reactor experiments (e.g. Daya Bay) measure $P(\bar{\nu}_e \longrightarrow \bar{\nu}_e)$ which depends on $sin^2(2\theta_{13})$
    - unlike NOvA which depends on $sin^2(\theta_{23})sin^2(2\theta_{13})$
    - Comparison can be used to determine whether θ_{23} is less or greater than 45º



Other Physics Opportunities

- Magnetic monopoles
  - can be identified as highly ionizing and/or very slow moving particles going through the entire detector
- Supernova neutrinos
  - the detector will be subjected to a larger amount of neutrinos coinciding with a supernova
- Solar WIMPs
  - would result in high energetic neutrino events coming from the direction of the sun

Summary

- Many physics goals can be reached
  - Measuring the neutrino mixing angles θ_{13}, θ_{23}
  - Measuring the mass squared difference Δm^2_{32}
  - Determining the CP violating complex phase δ
  - Determining the mass hierarchy

- Recent θ_{13} results show that it is large, which helps us to reach our physics goals

- The Prototype Near Detector at the surface
  - Has already been running successfully
  - Has provided us with valuable information about the detector construction

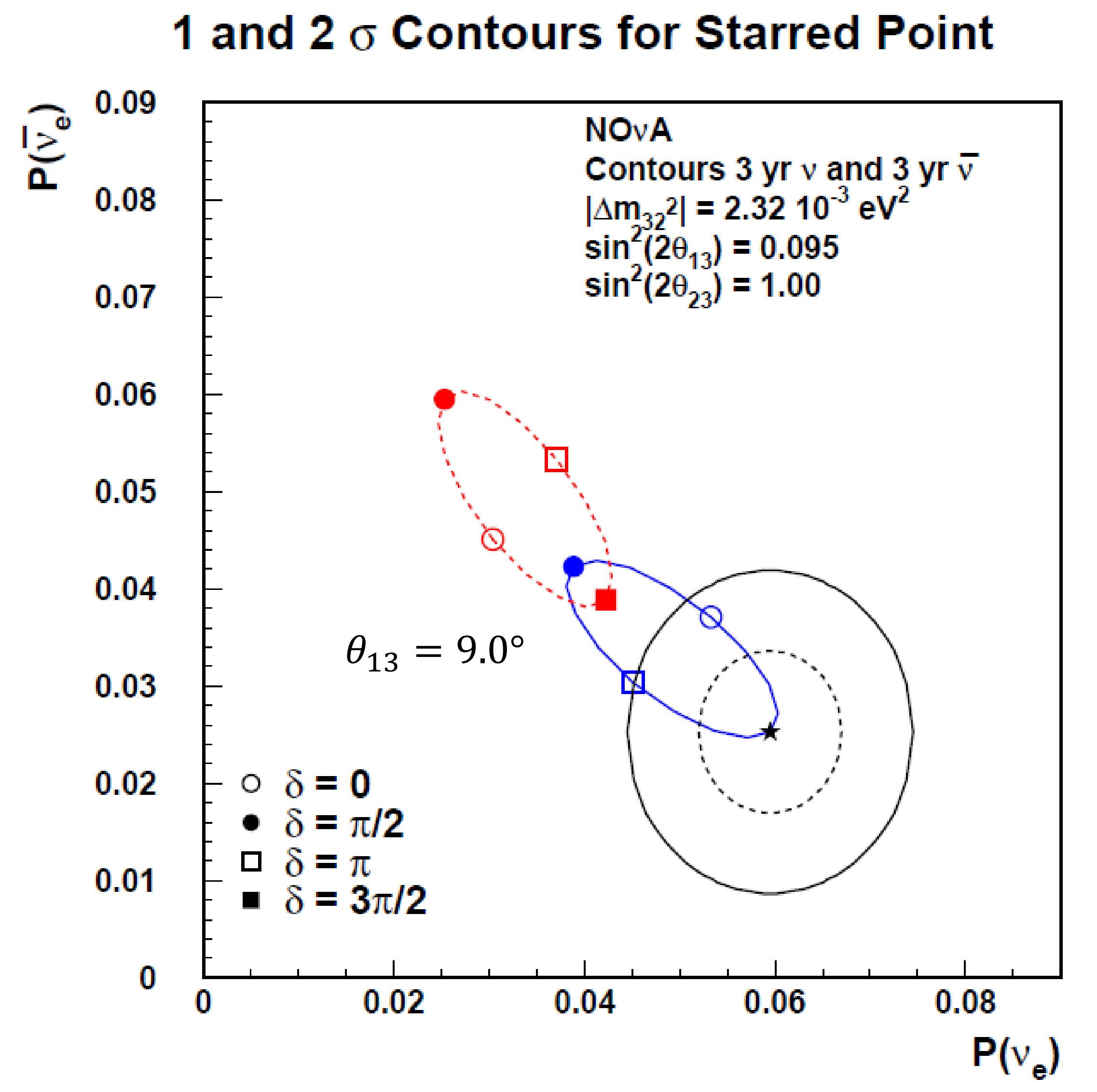
- Far Detector construction will begin this summer
  - First events can be recorded as soon as the first block is installed
  - First oscillation events can be observed as soon as the neutrino beam gets turned on in April 2013


Thank You

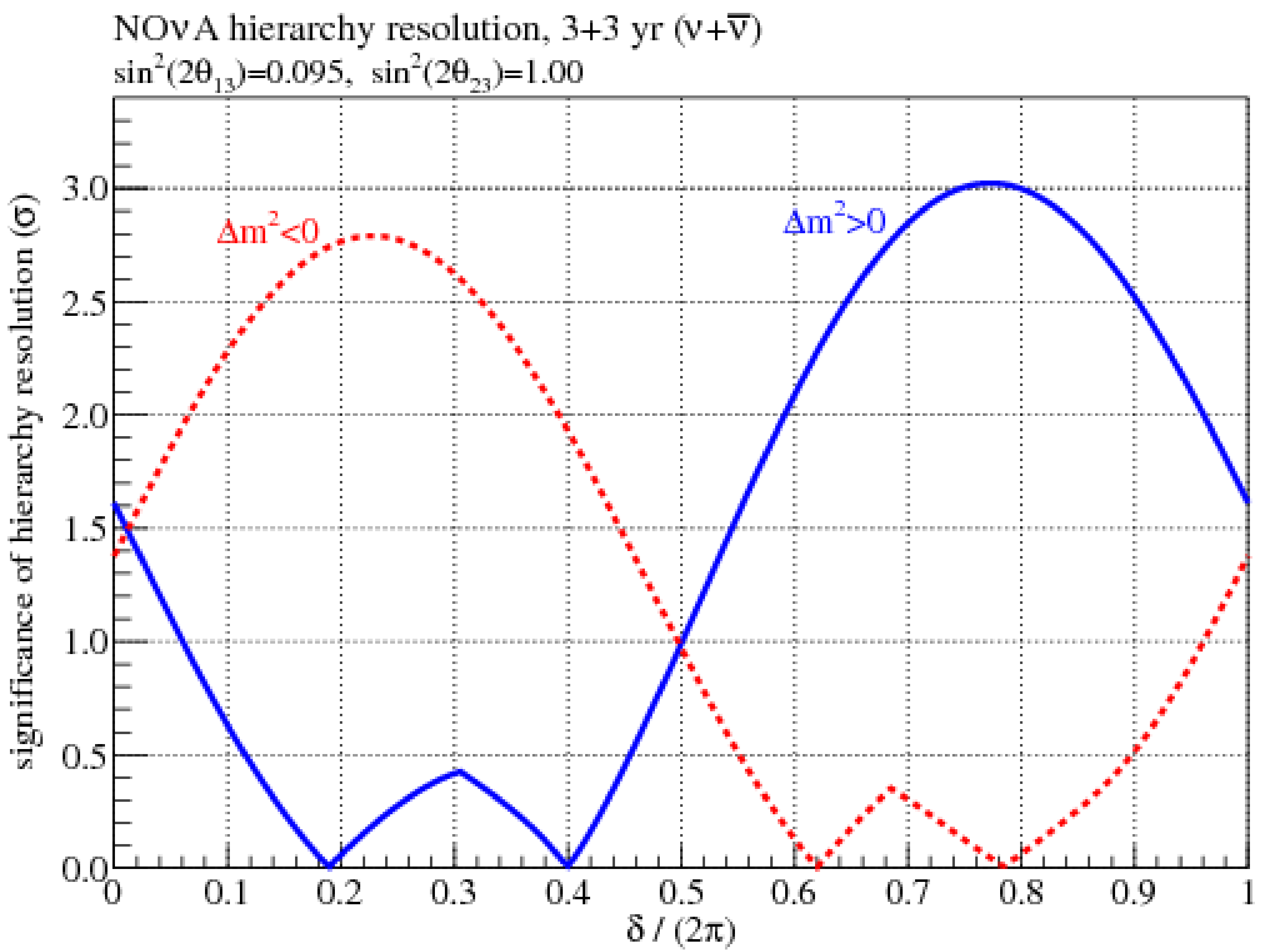
Backup Slides

Neutrino Mixing Parameters

- Example:
  - Assume we measure
    $P(\nu_\mu \longrightarrow \nu_e) = 0.025$
    $P(\overline{\nu_\mu} \longrightarrow \overline{\nu_e}) = 0.060$
  - 3 years in neutrino mode and 3 years in anti-neutrino mode



Neutrino Mixing Parameters



Neutrino Mixing Parameters