The NOνA Experiment

(NuMI Off-Axis ν_e Appearance)

Jeff Nelson
College of William & Mary
Williamsburg, Virginia

NuFact05

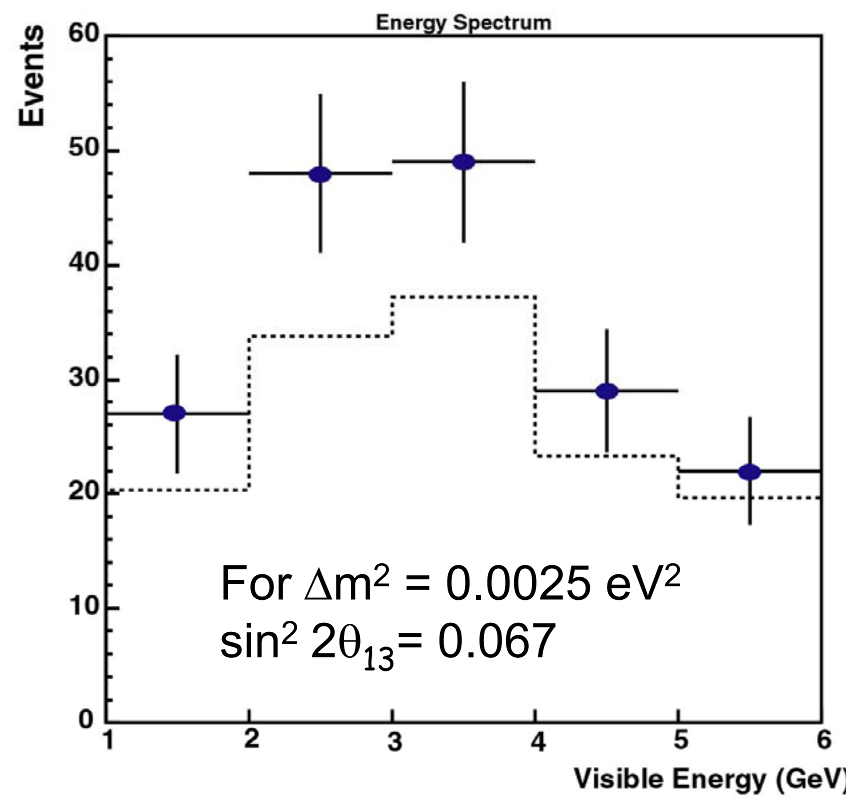
(For the Collaboration)

Outline for Talk

- Will largely gloss over motivation
- The NOνA detector
- Backgrounds & simulations
- Status & schedule
- Physics potential

MINOS & Electrons

- Will improve beyond the CHOOZ limit
  - 3σ sensitivity at half the CHOOZ limit



Observed number of events identified as coming from ν_e CC interactions with and without oscillations

Current Ideas & Goals

- Phase 1 (Extend $\nu_\mu \rightarrow \nu_e$ reach by order of magnitude; explore mass hierarchy & CPV)
  - NOvA
  - T2K
  - Reactors
- Phase 2 (Extend reach for mass hierarchy & CPV)
  - NOvA + PD (eventually 2^{nd} detector)
  - HK + PD
  - Brookhaven VLBL proposal
  - CERN PD + Mt H_2O detector
- Phase 3 (Significantly extend reach)
  - Neutrino factory
  - Beta beam

$P(\nu_\mu \rightarrow \nu_e)$ in Vacuum

$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

- $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
- $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
- $P_3 = J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
- $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

} Atmospheric-solar interference (P_3, P_4)

  - where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$
    $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

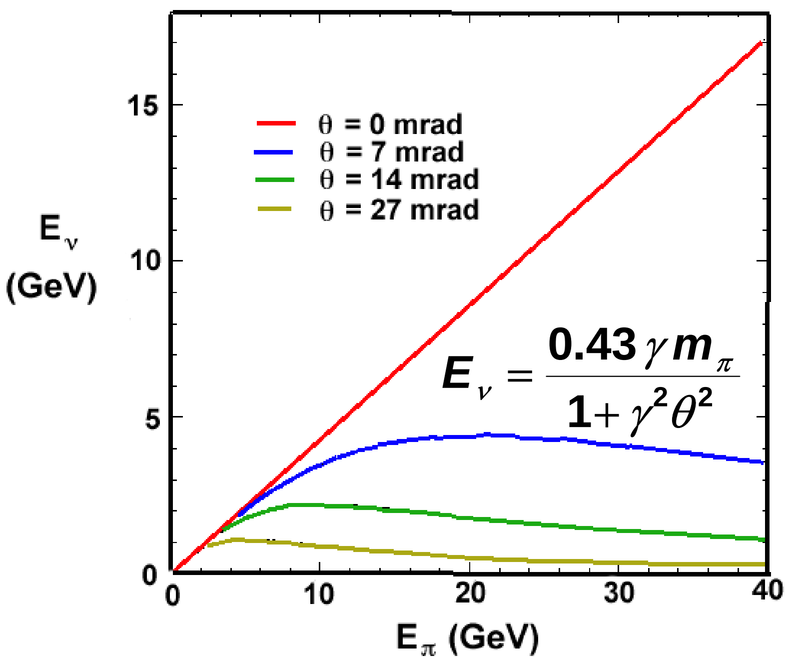
- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy

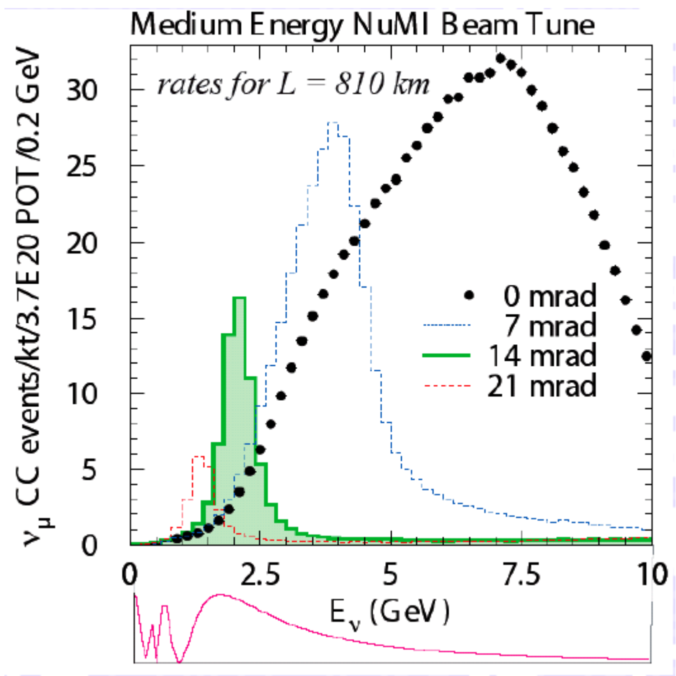
$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2}G_F\rho_e} \approx 11\,\text{GeV for the earthÕs crust.}$$

  - About ±30% effect for NuMI
  - About ±11% effect for T2K
- The effect is reduced for energies above the oscillation maximum & increased for energies below

NuMI Off-Axis

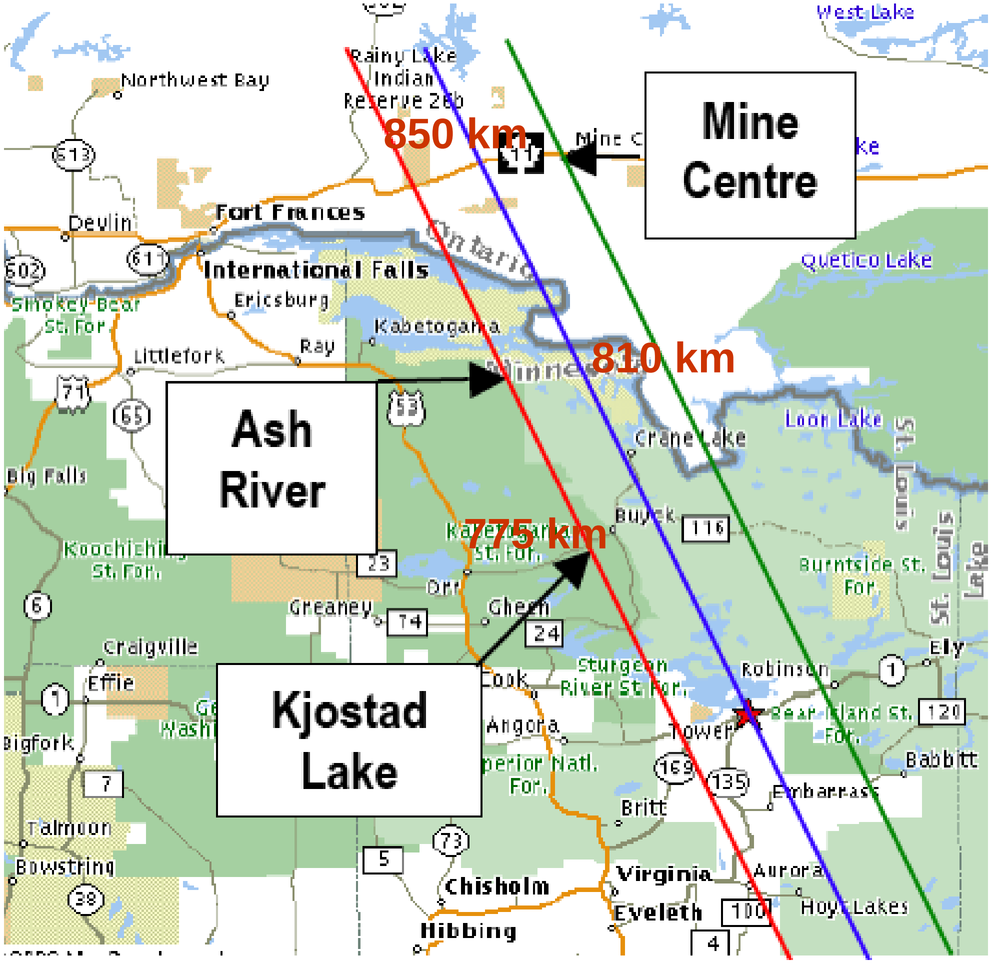
- 15 mrad off axis & 810 km from the source
- Yields a narrow band beam on oscillation maximum
- More flux & reduced backgrounds from the HE tails





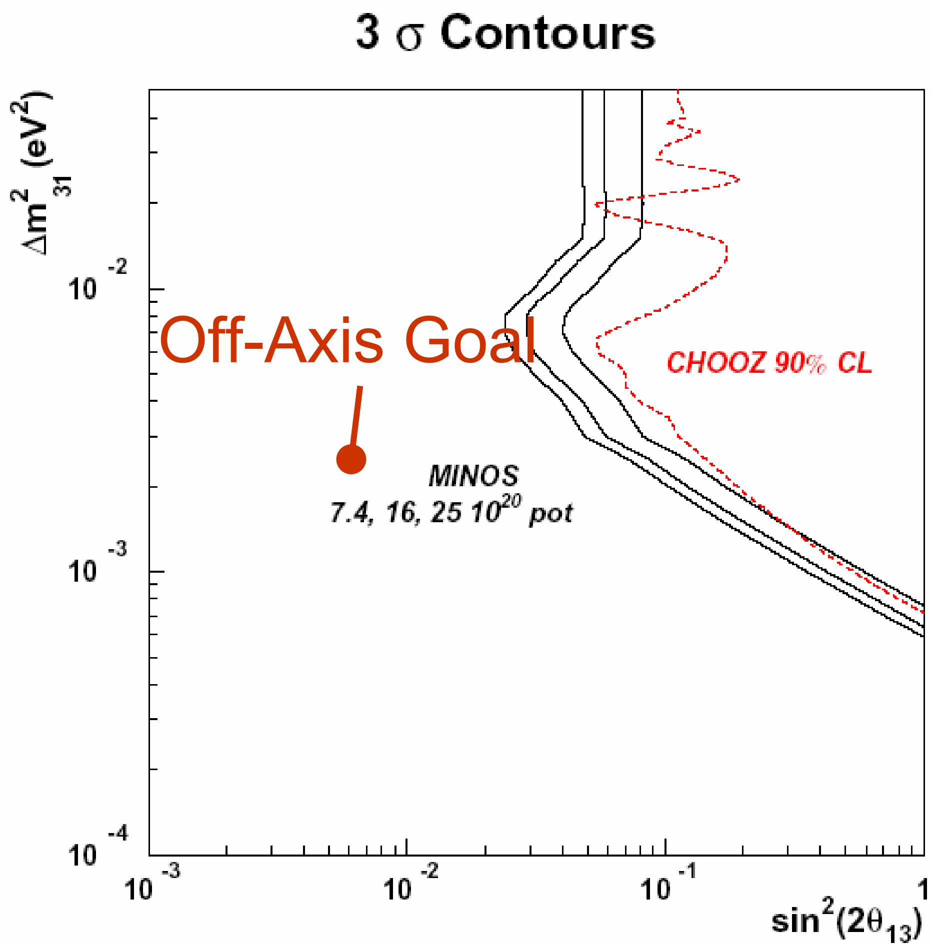
Far Detector Site

- Ash River
  - Baseline site
  - Can fly into International Falls (less in than hour drive to site)
  - Resort area
- Kjostad Lake
  - Orr-Buyck Rd
  - Good backup site
- Mine Centre
  - Must cross the US-Canada border (in a paper mill site) to get from airport to site
- Range of angles available at all sites



The NOνA Experiment

- NOνA is an approved Fermilab ν_e appearance experiment
  - Improve the MINOS $\nu_\mu \rightarrow \nu_e$ measurement by an order of magnitude
- Unique long baseline
  - Use matter effects to determine the neutrino mass hierarchy
  - Go long & exploit it!
- The NOνA far detector
  - New 3/05 proposal
  - 30 kT "totally active" liquid scintillator detector

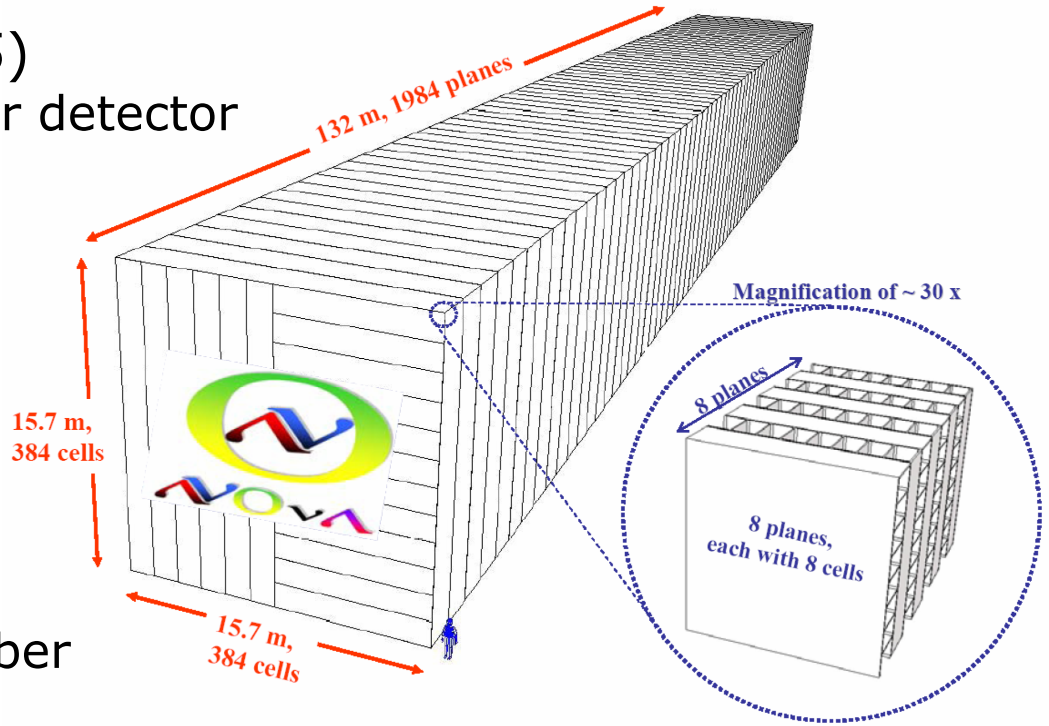


How Does NOνA Beat MINOS?

- Other than the off-axis beam…
  - Mass increased by a factor of 6
  - Improved energy resolution and e/π^0 discrimination
    - "Totally active scintillator detector" (TASD) instead of sampling calorimeter
    - Increase longitudinal sampling by a factor of 10 (1.5 X_0 to 0.15 X_0)
- All while reducing the cost/kiloton by a factor of 3 with respect to MINOS Far Detector

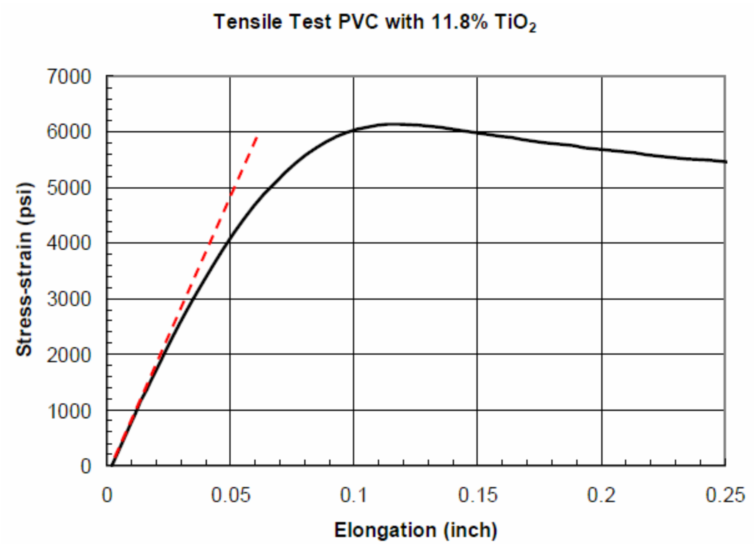
NOνA Far Detector

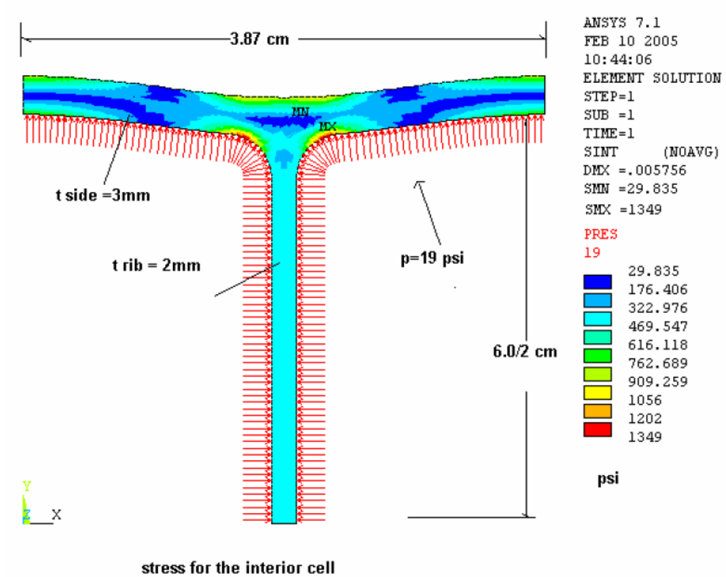
- Revised Proposal (April 05)
  - "Totally Active" scintillator detector
- Liquid scintillator cells
  - 3.9 cm x 6 cm x 15.7m
  - 0.15 X_0 sampling
  - 1984 planes of cells
- Cell walls
  - Extruded rigid PVC
  - 3 mm outer; 2 mm inner
- Readout
  - U-shaped 0.8 mm WLS fiber
  - APDs (80% QE)
- 30 kT
  - 24 kT liquid scintillator
  - 6 kT PVC



Structural Analysis

- Rigid PVC
  - ASTM D1784 "Standard Specification for Rigid PVC Compounds"
    - Defines 6 grades with allowable design stresses from 1000 PSI to 2000 PSI
  - NOvA design working limit of 1500 PSI
    - Well before creep onset
  - Good resistance to catastrophic failure
    - Creep before crack
- FEA model
  - Results baselined with bench tests
  - Maximum internal stress of 1400 PSI for vertical cell from hydrostatic pressure
  - Maximum transferred stress of 560 PSI for horizontal to vertical cells
    - 70 PSI in sheer
  - Safety factor of 2.9 for buckling
  - 10C temperature change
    - Force generated of 4.3 PSI
    - Length of detector increased by 9cm
    - Include expansion gaps between blocks

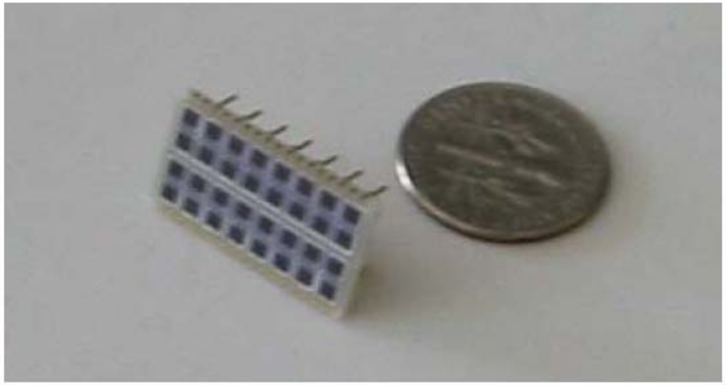




Half Block Prototype Being Built

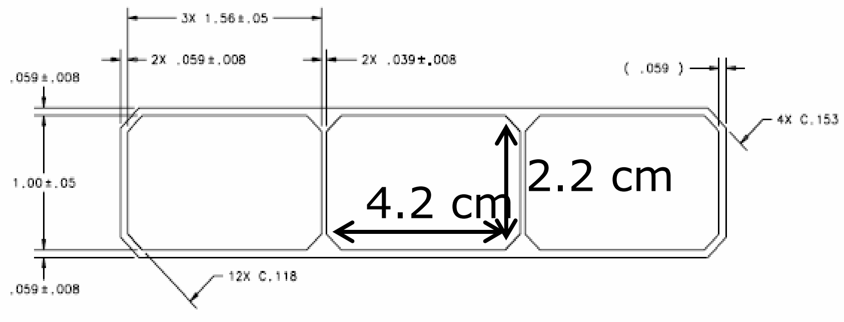
Initial Readout Tests

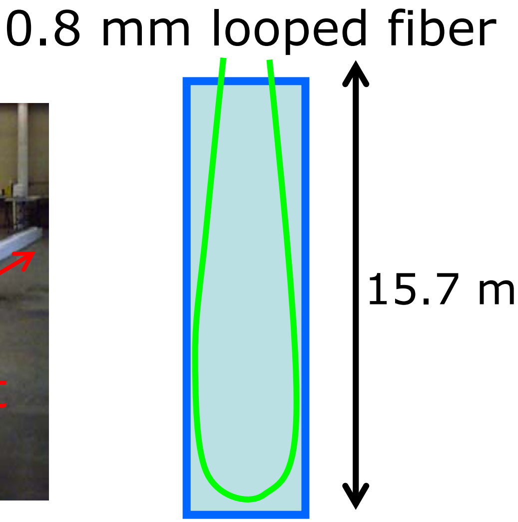
- Baseline APD readout
- Off the shelf extrusions
  - Different cell profile
  - Reflectivity not fully optimized
  - Working with pigment vendors to optimize the reflectivity (as in MINOS)

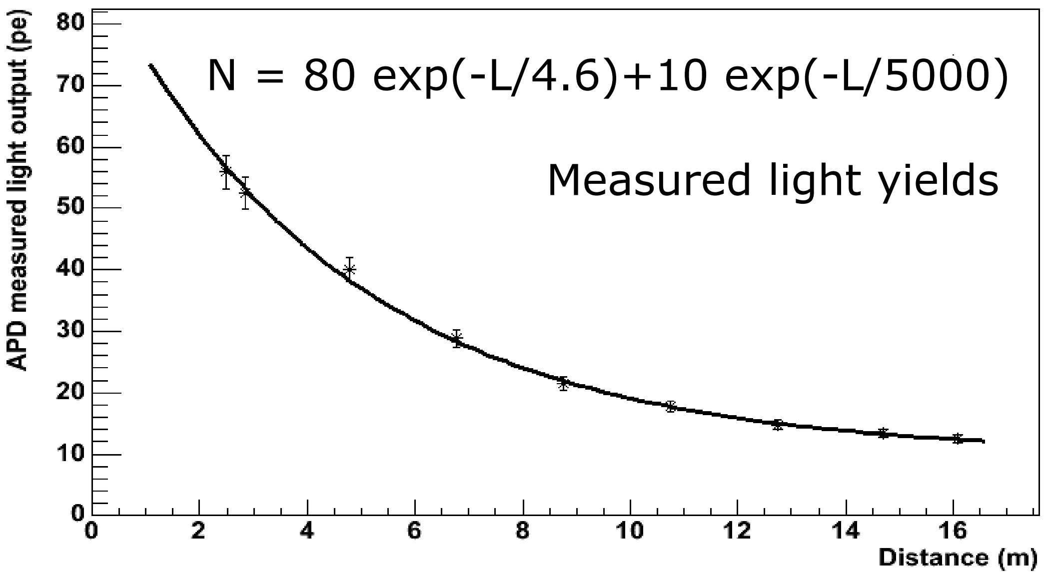


- Off the shelf ASIC (Fermilab's MASDA)
  - Capacitance known to be too high
  - Revised prototype front end being fabricated for testing
- Given these expected changes, the light yield meets specifications
  - 13 PEs per MIP -> 27 PEs per MIP
  - Will give 10:1 signal to noise for MIP

Initial Tests Using Extrusions from Existing Die





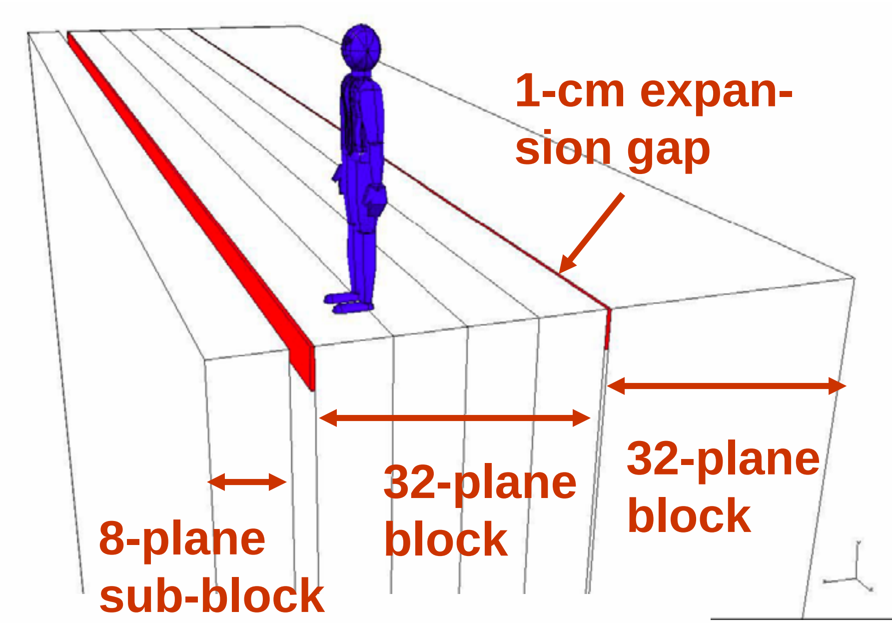


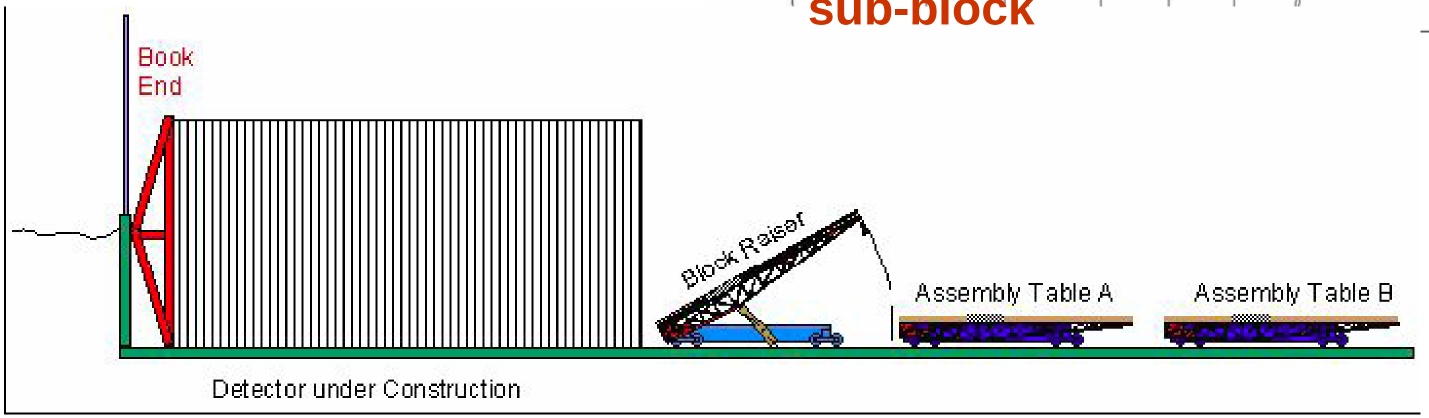
Geometry gives factor of 1.75
13 pe goes to 23 pe

Reflectivity gives factor of 1.2
23 pe goes to 27 pe

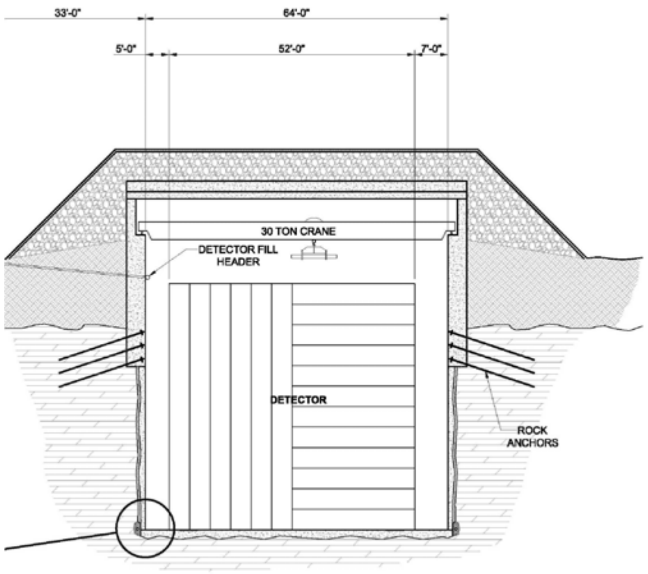
Far Detector Assembly

- One 8-plane sub-block assembled per day
- Detector has 248 sub-blocks
- Can fill with scintillator and run during construction
- 50% planes built & tested at Argonne

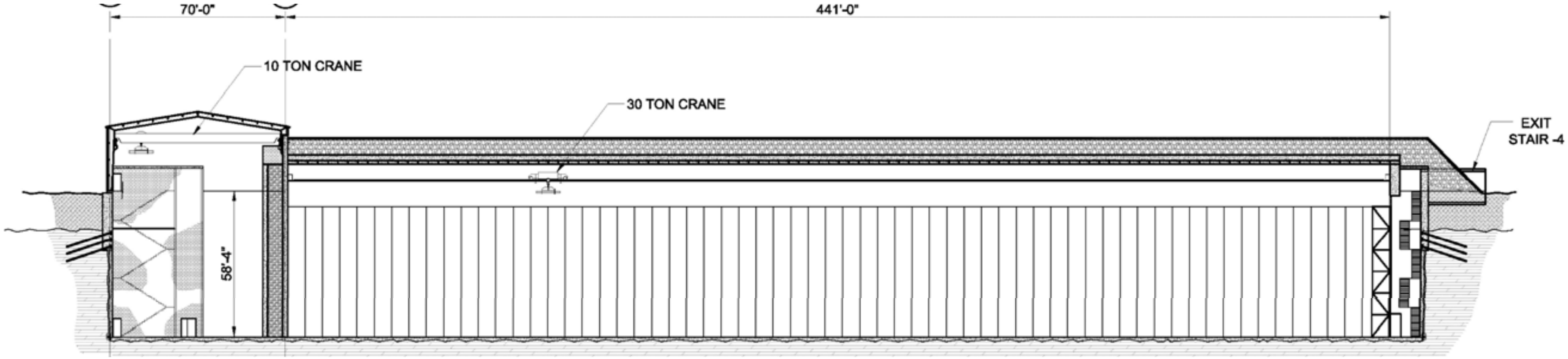




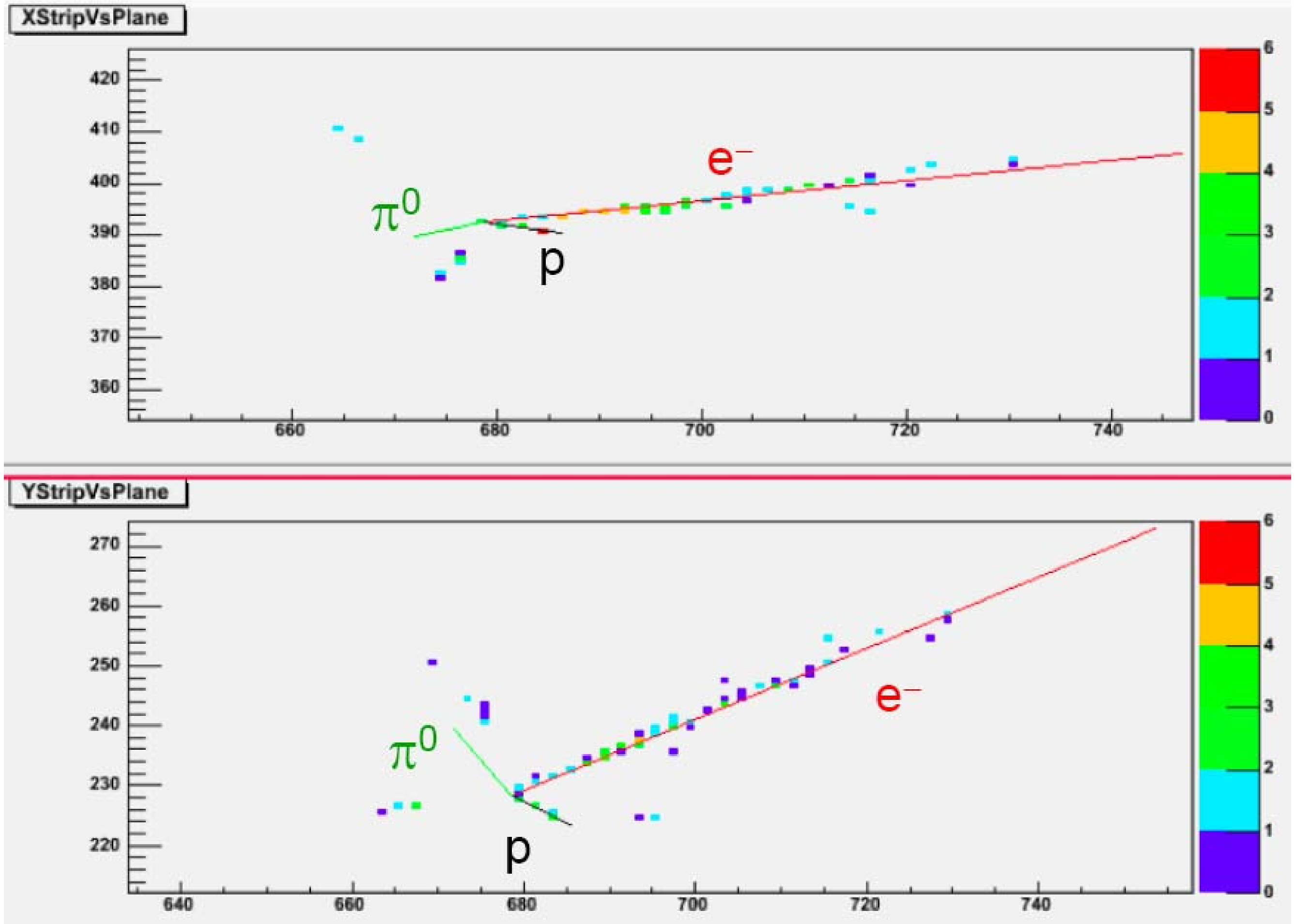
Far Detector Building Design with Overburden



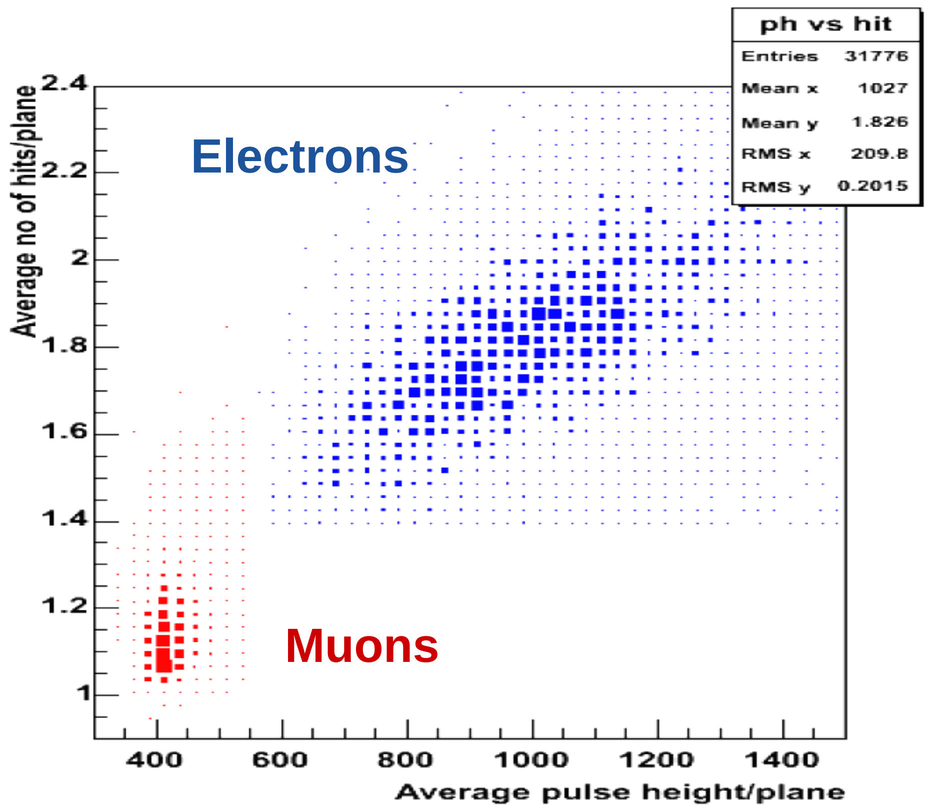
Overburden not in current baseline

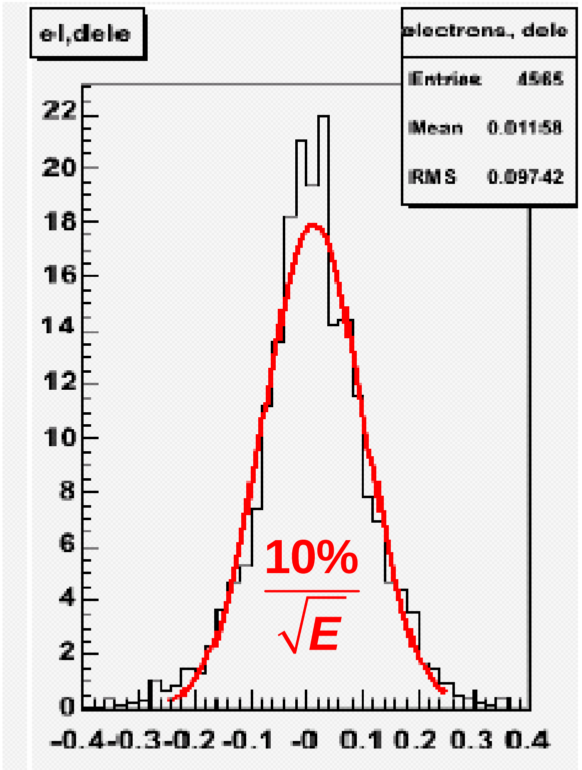


Example MC Event
1.65 GeV $\nu_e N \to e p \pi^0$



Electron ID & Energy Resolution

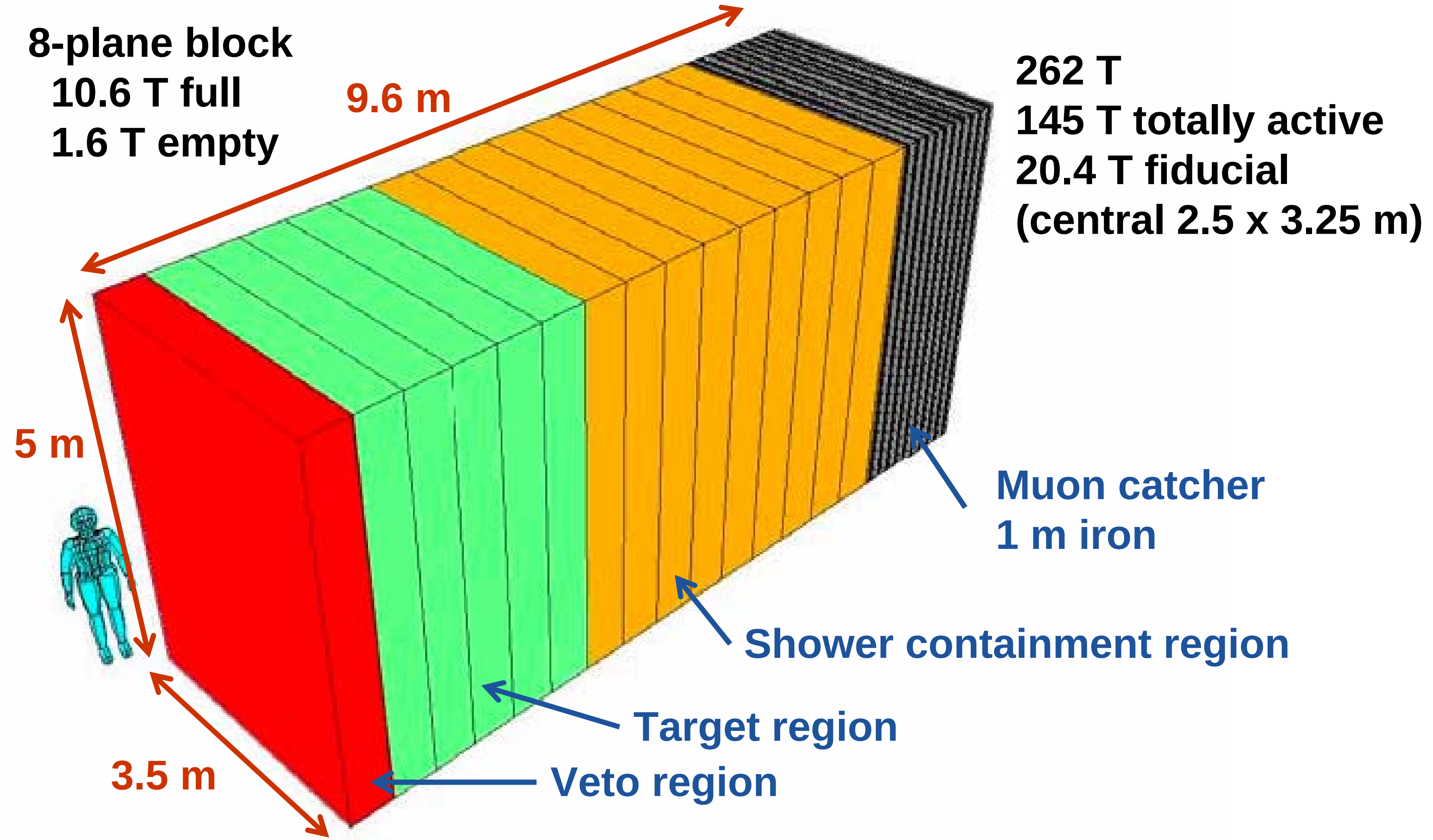




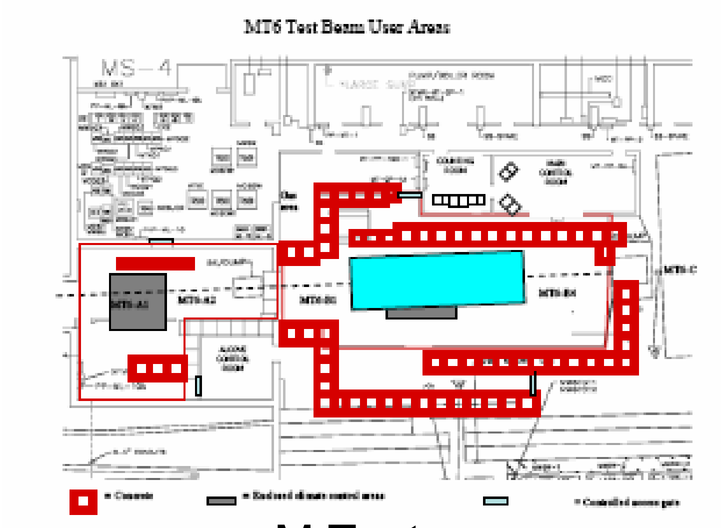
Electron resolution

Also use RMS of pulse height per plane, gaps & energy cuts

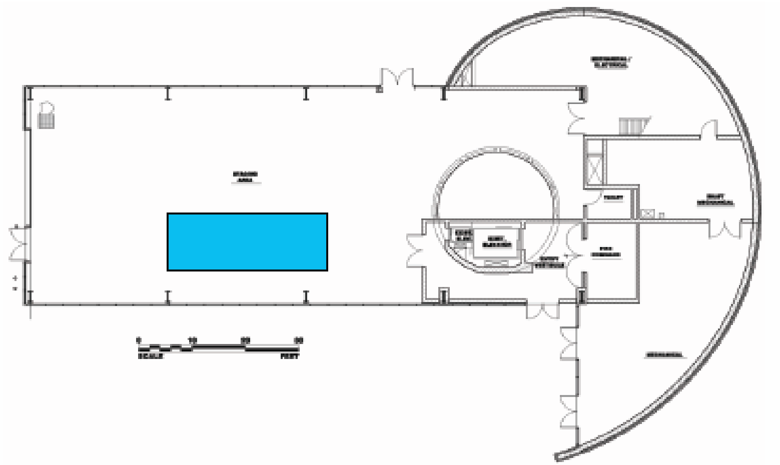
Near Detector



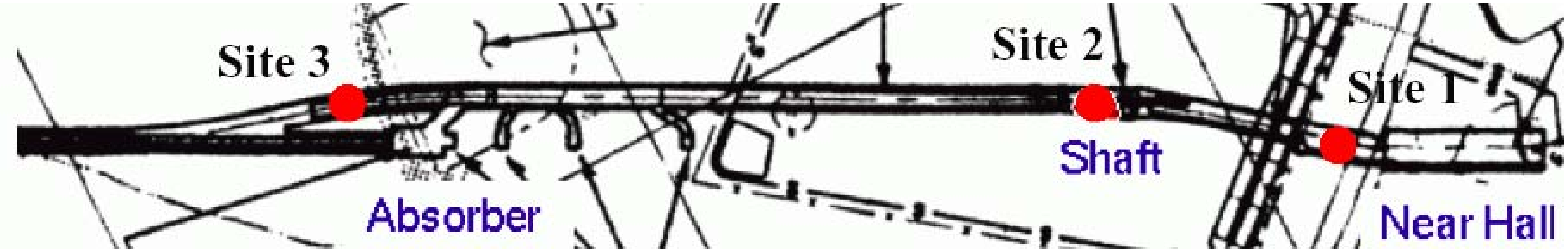
Near Detector: Modular & Mobile



M Test



MINOS Surface Building

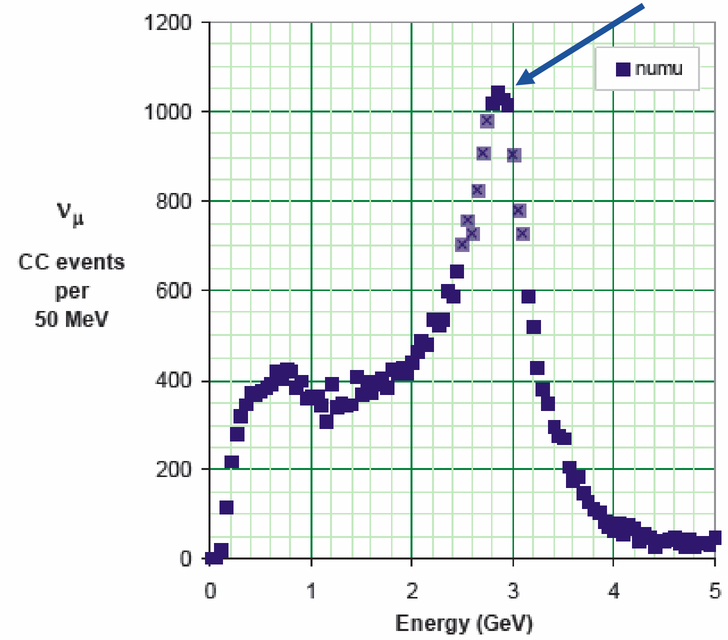


NuMI Access Tunnel

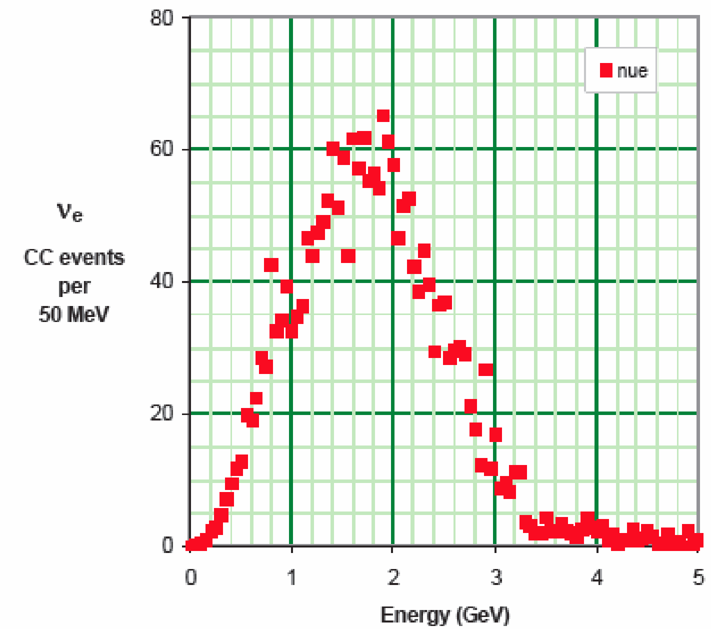
Near Detector in MINOS Surface Building

6.5 x 10^{20} pot in 75 mrad off-axis beam

Kaon peak

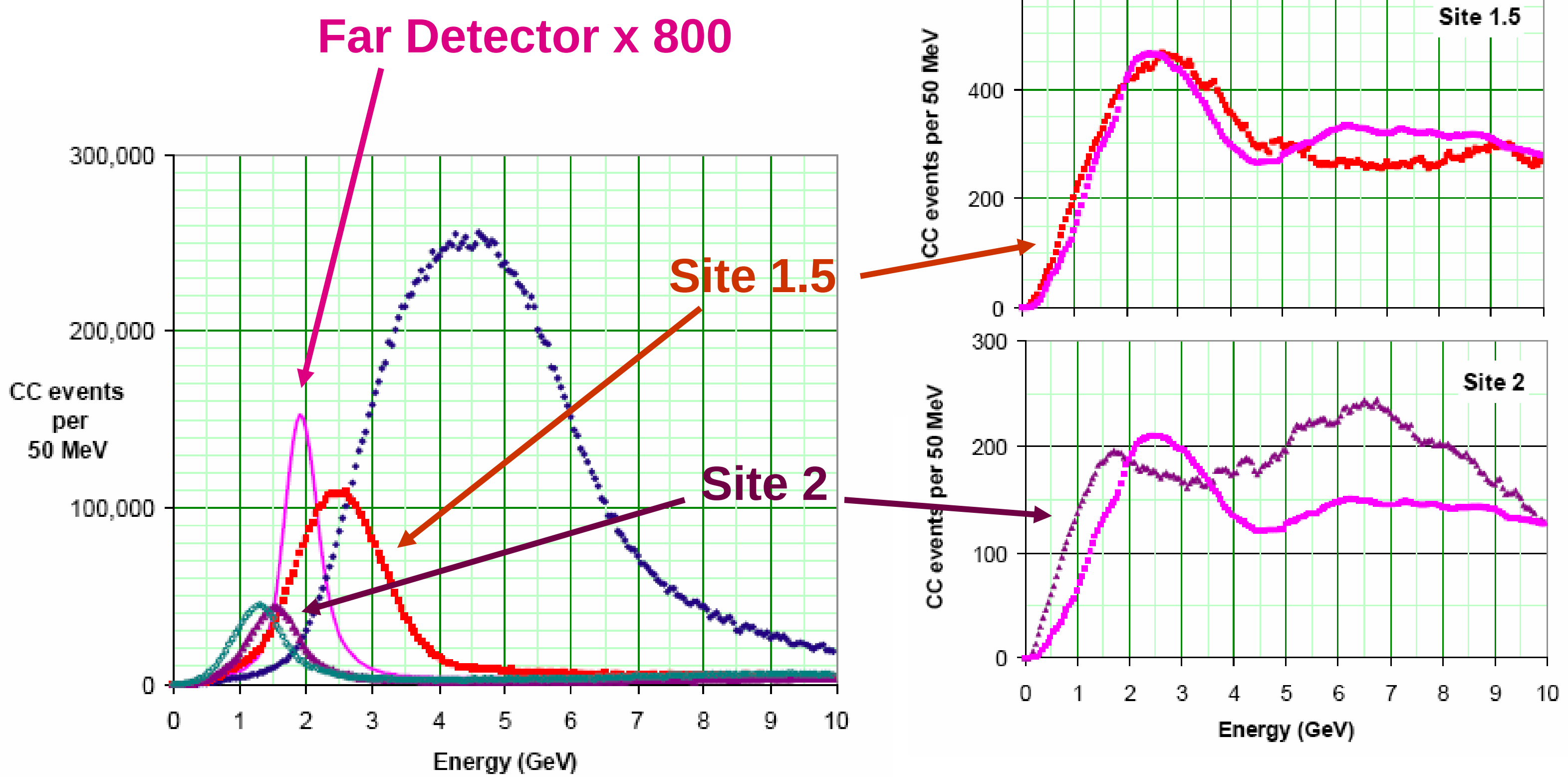


45,000 ν_μ CC events



2,200 ν_e CC events

Near Detector in the Access Tunnel



ν_μ CC events

ν_e CC events

NOνA Status

- Approved by Fermilab April 2005
- Letter from Mike Witherell
  - "The Committee found that NOνA …is the best approach to address the compelling neutrino physics questions ahead of us. They judged NOνA to be well designed, fully competitive, and complementary to other efforts. They also consider it to be the right platform for further steps in the evolving neutrino program worldwide. The Committee recommended Stage I approval."
  - "Organizing the best program of neutrino research with Fermilab's accelerators is critical to the strength of the particle physics program in the US and worldwide."
  - "I agree with the Committee's judgment that NOνA is the right experiment to anchor this program, and I agree that now is the time to act. I therefore grant Stage I approval to the NOνA experiment."

Change in NOνA Prospects

- The cancellation of the BTeV experiment caused a major change in the prospects for NOνA
  - Funds are available for medium size new initiatives
  - More protons are available
- DoE has signaled that it will prepare to put funds for NOνA in the FY07 budget
  - Pending NuSAG/P5 and OMB approval
- Strong Fermilab support
  - Only approved US experiment in post 2010 era

NOνA Project

- Fermilab Project Planning has set out a schedule of critical decisions and reviews that will allow a Oct 2006 construction start (see timeline)
- Fermilab has initiated a project management office for NOνA at Fermilab
  - NOνA cospokesperson John Cooper (Fermilab) will transition to Project Manager
  - Ron Ray will act as Deputy Project Manager

Cost

	Contingency	Total Cost M$
Far Detector		
Active detector	30%	80
Electronics and DAQ	55%	13
Shipping	21%	7
Installation	43%	14
Near Detector	44%	3
Building and outfitting	58%	29
Project management	25%	5
Additional contingency		14
Total	50%	165

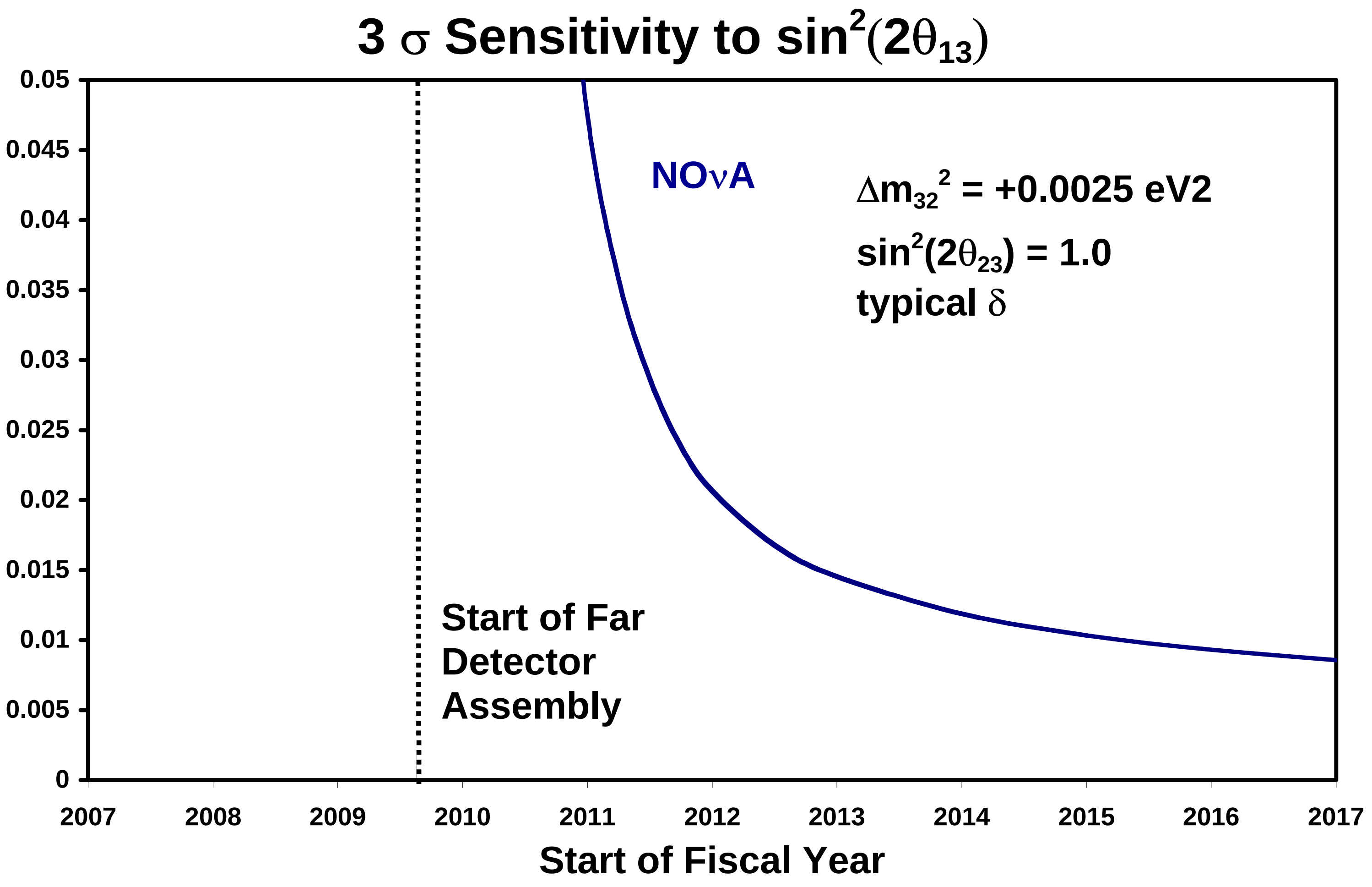
Schedule
(10 of 29 Milestones)

Project start	Oct 2006
R&D prototype Near Detector complete	Mar 2007
Start Far Detector Building construction	Jul 2007
Start receiving packaged APDs	Oct 2007
Start extrusion module factories	Oct 2007
Start construction of Near Detector	Dec 2007
Start operation of Near Detector	Jul 2008
Start Far Detector assembly	May 2009
First kiloton operational	Oct 2009
Full 30 kilotons operational	Jul 2011

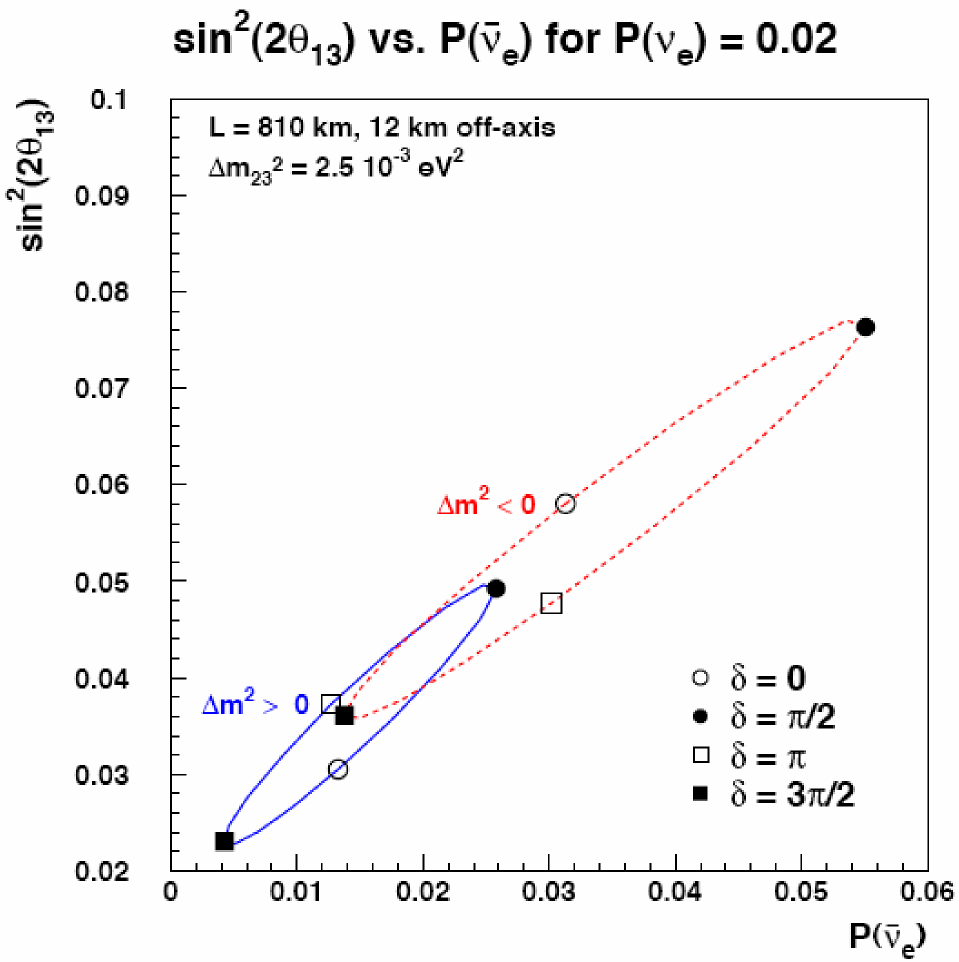
Post-Collider Proton Intensity

- NOνA gains more than a factor of 2 from not having to make antiprotons:
  - more Booster bunches available (9 to 11)
    - Factor of 1.22
  - Hide Booster filling time by filling the Recycler (2.2 s cycle time to 1.45s)
    - Factor of 1.50
  - Lost time from transferring antiprotons
    - Factor of 1.17
  - Total gain = (1.22)(1.50)(1.17) = 2.14
- Projected at 6.5 x 10^{20} pot/yr
  - 90% of available
- With a new Proton Driver, 25 x 10^{20} pot/yr

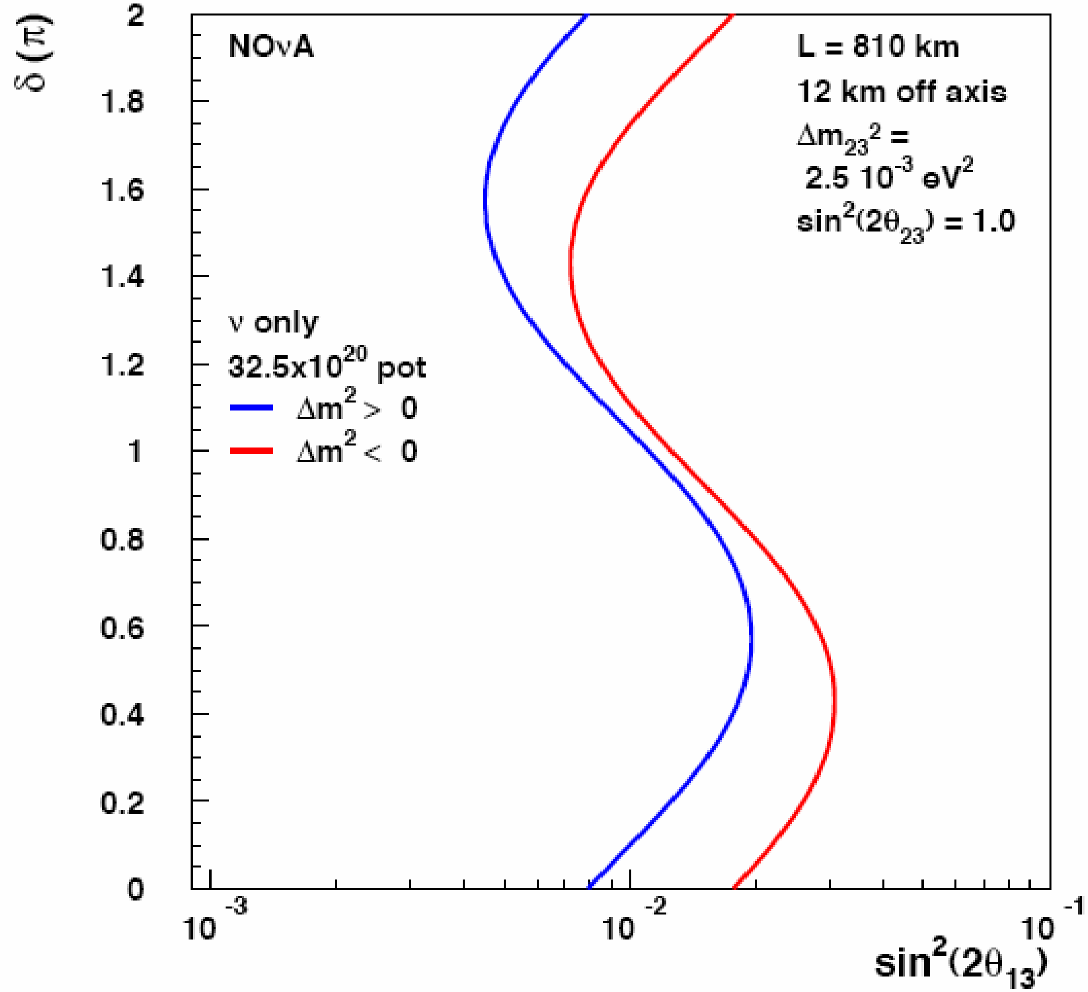
Sensitivity vs Time



Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation

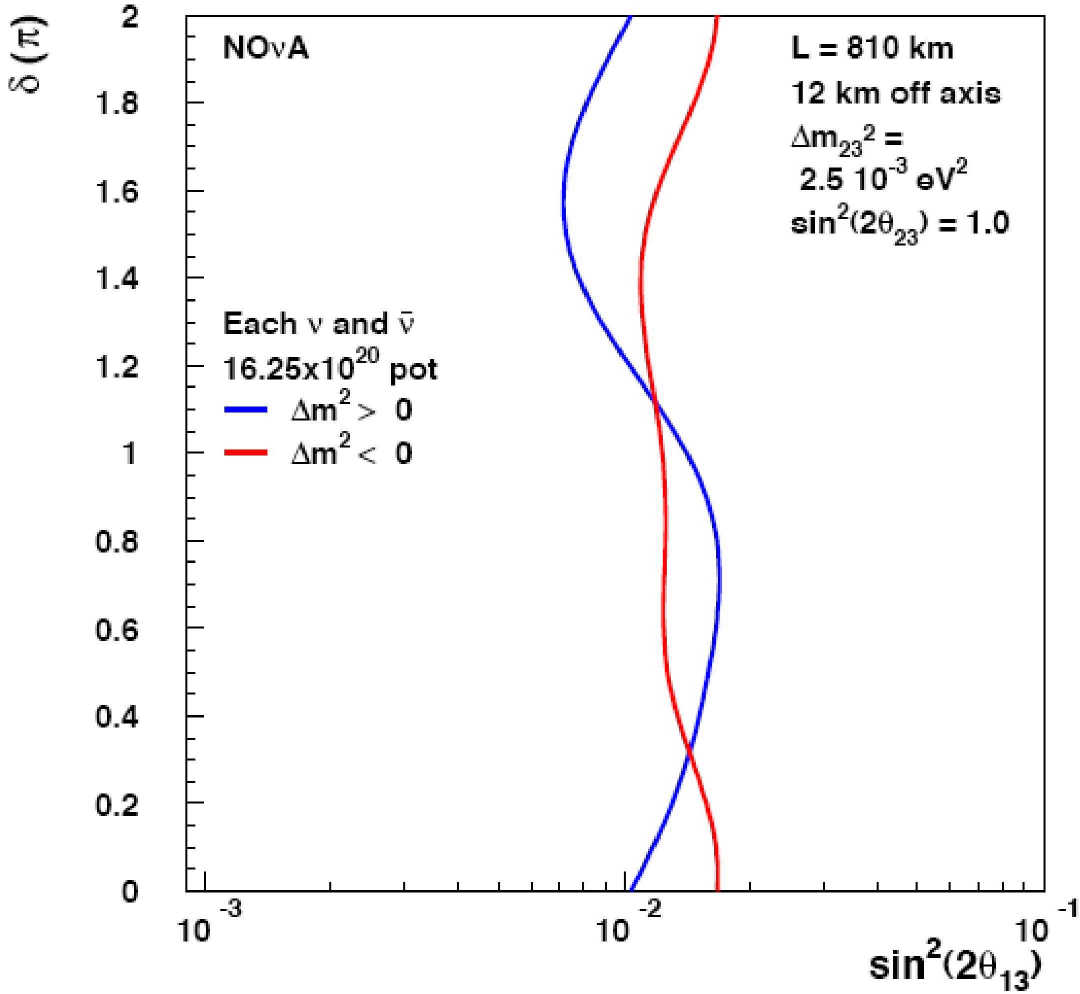


3 σ Sensitivity to $\theta_{13} \neq 0$



5 year
ν only run

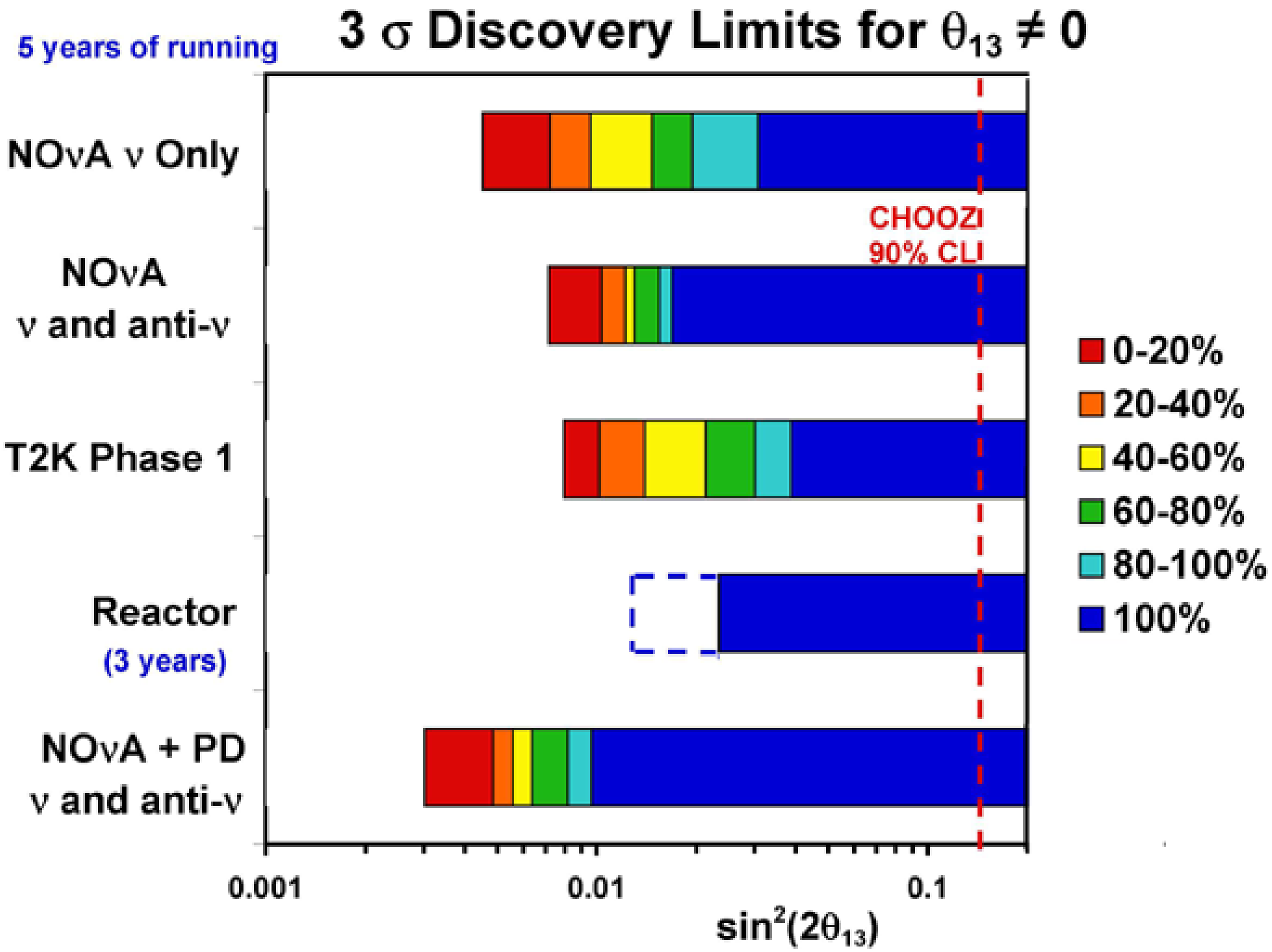
3 σ Sensitivity to $\theta_{13} \neq 0$



2.5 yr each

ν and $\bar{\nu}$ run

3 σ Sensitivity to $\theta_{13} \neq 0$



Fraction of δ covered

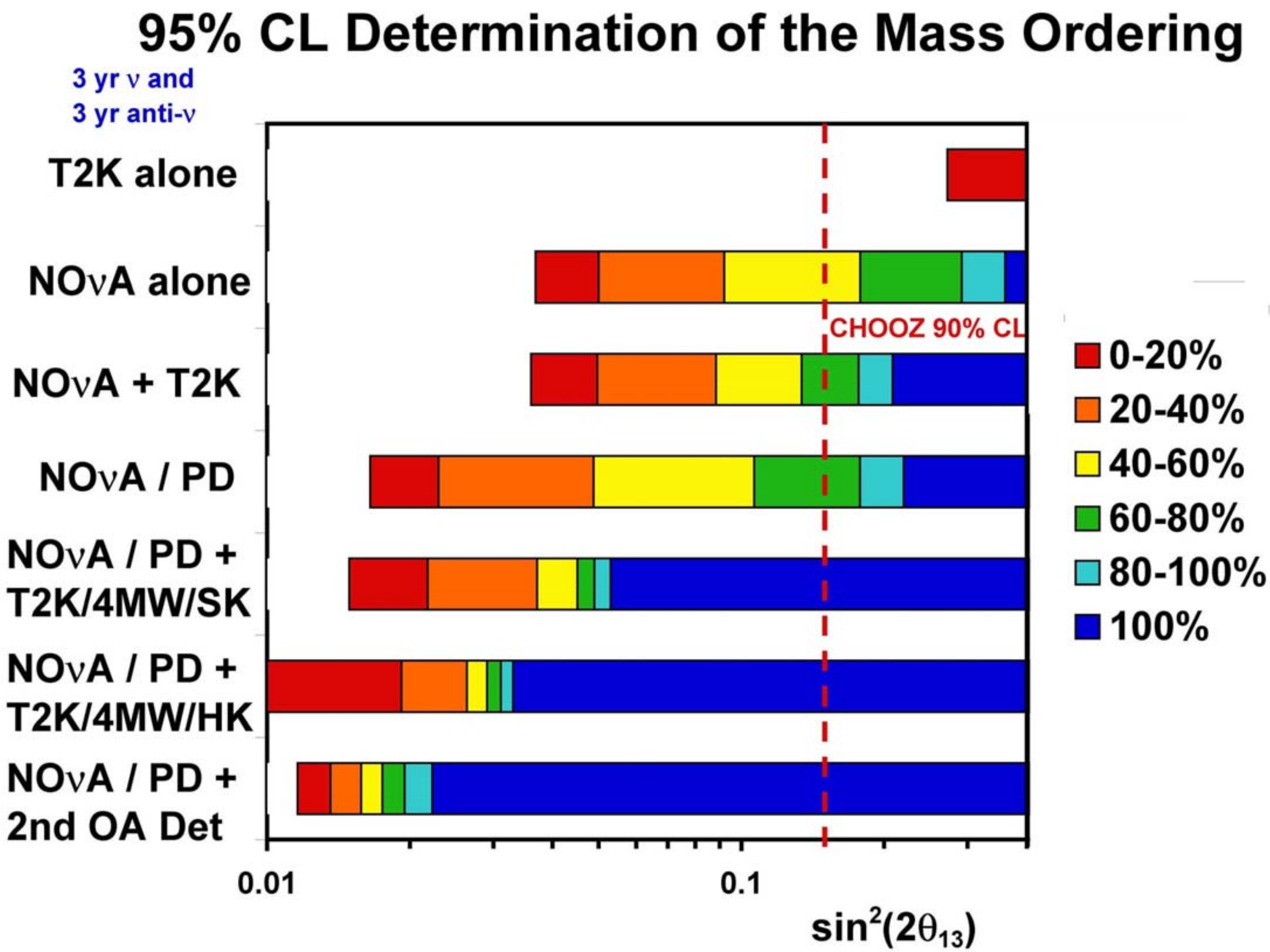
Importance of the Mass Ordering

- Window on very high energy scales
  - Grand unified theories (mostly) favor the normal mass ordering but other approaches favor the inverted ordering
- The next generation of neutrinoless double beta decay experiment care about the mass ordering
  - If inverted ordering, can decide if the neutrino is its own antiparticle
  - If normal ordering, a negative result is inconclusive
- For CPV measurement we need to resolve the mass ordering
  - Matter effects contributes an apparent CP violation that must be corrected

Role of NOνA in Resolving the Mass Ordering

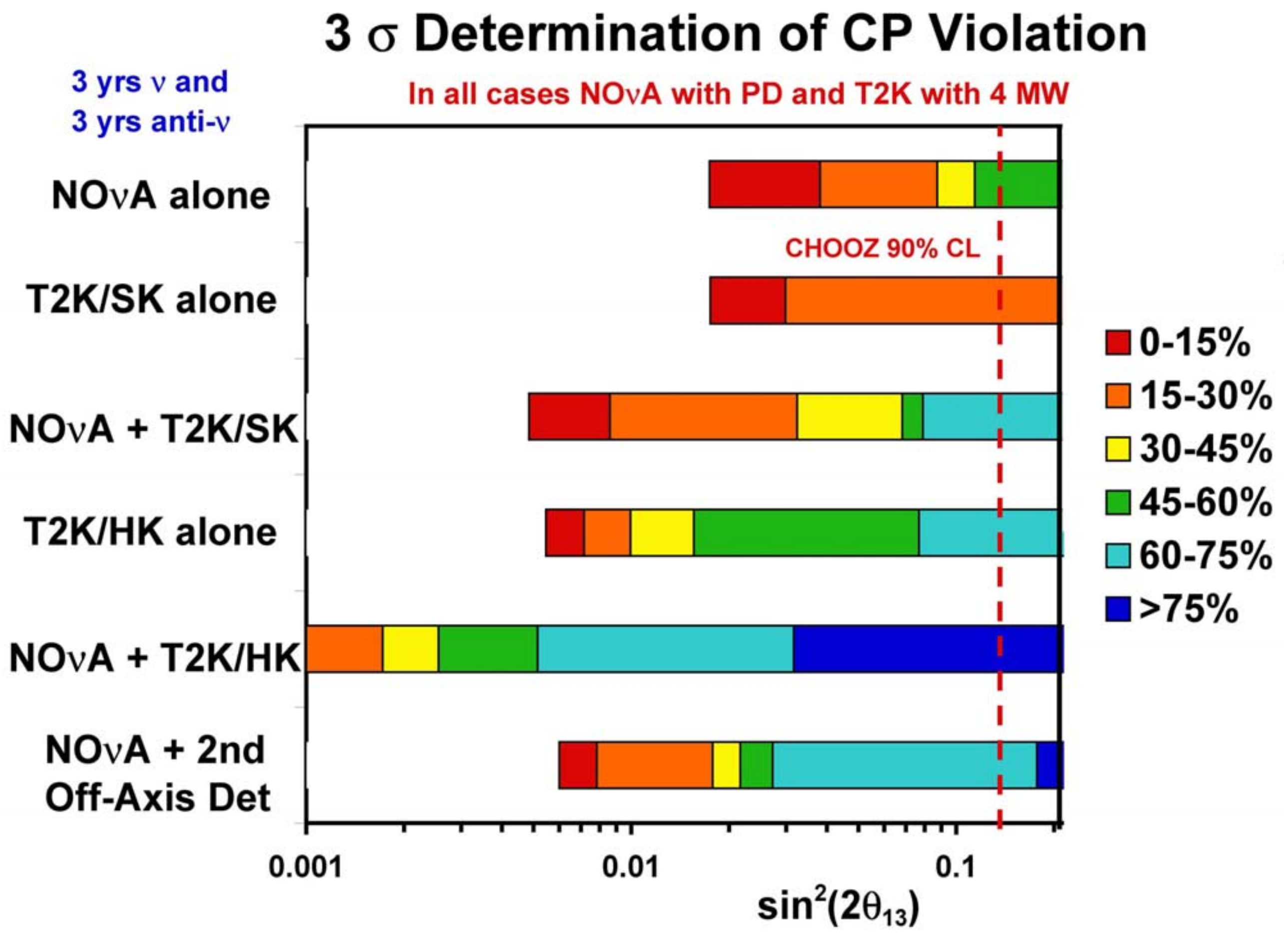
- The mass ordering can be resolved only by matter effects in the earth over long baselines
- NOνA is the only proposed experiment with a sufficiently long baseline to resolve the mass ordering
- The siting of NOνA is optimized for this measurement
- NOνA is the first step in a step-by-step program that can resolve the mass ordering in the region accessible to conventional neutrino beams

95% CL Resolution of the Mass Ordering



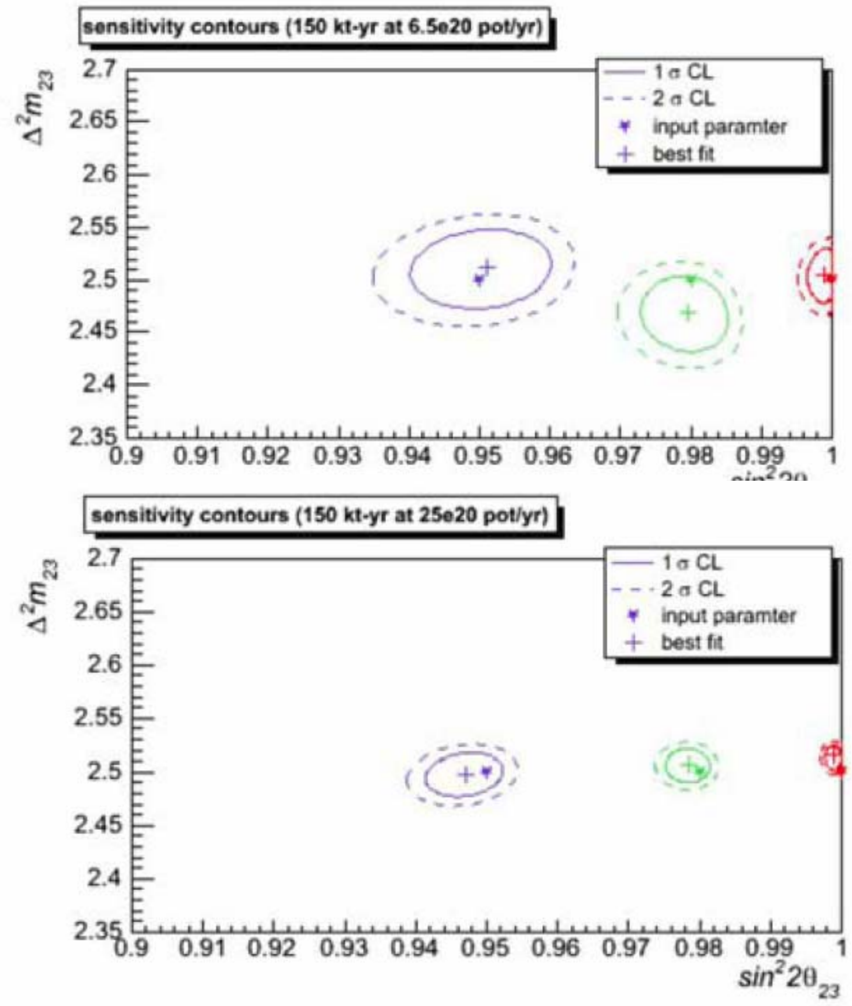
Fraction of δ covered

3 σ Determination of CP Violation



Fraction of δ covered

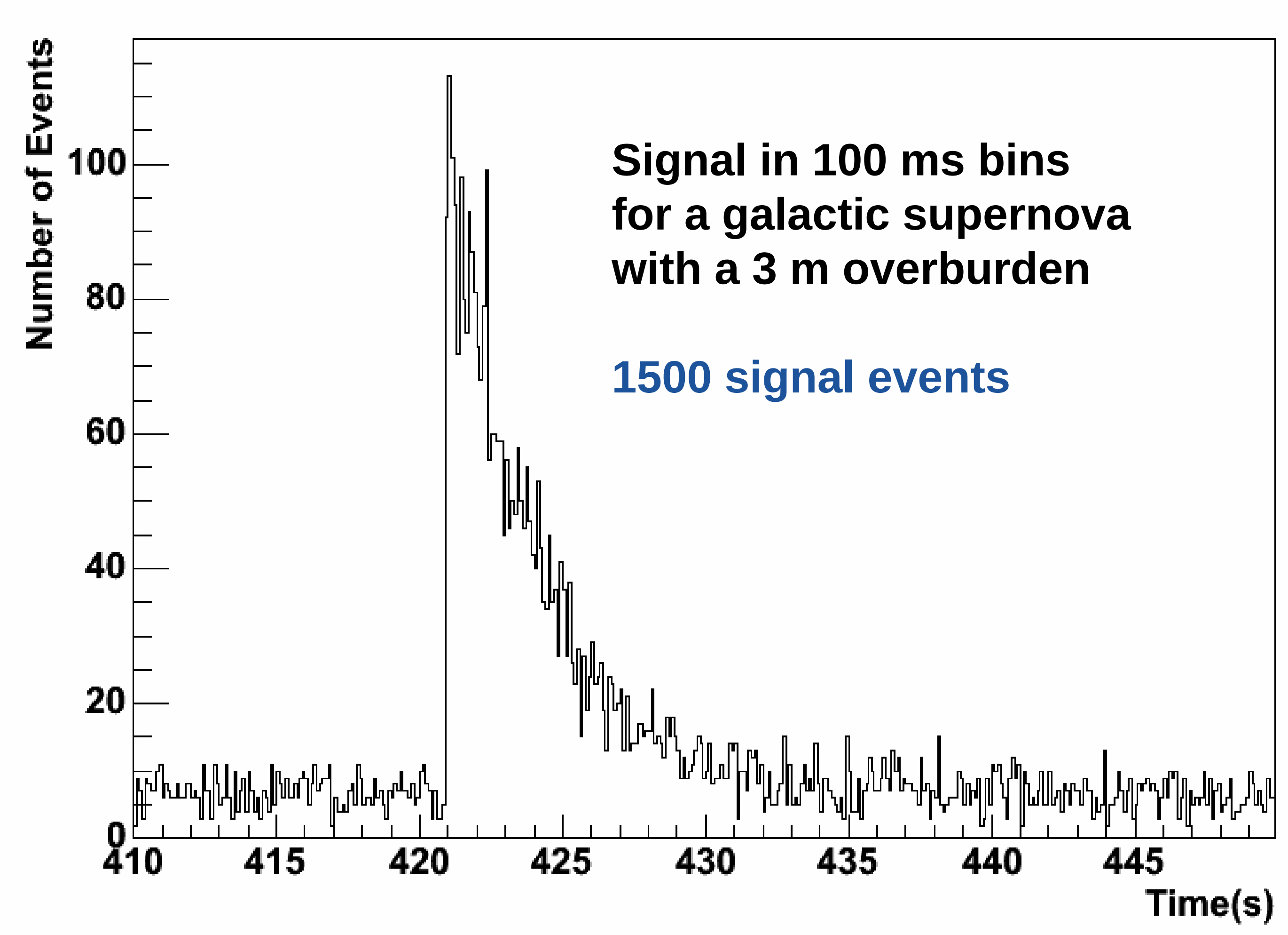
Other Topics: Δm_{32}^2 & θ_{23}



5-year ν run

5-year ν run
with Proton Driver

Galactic Supernova

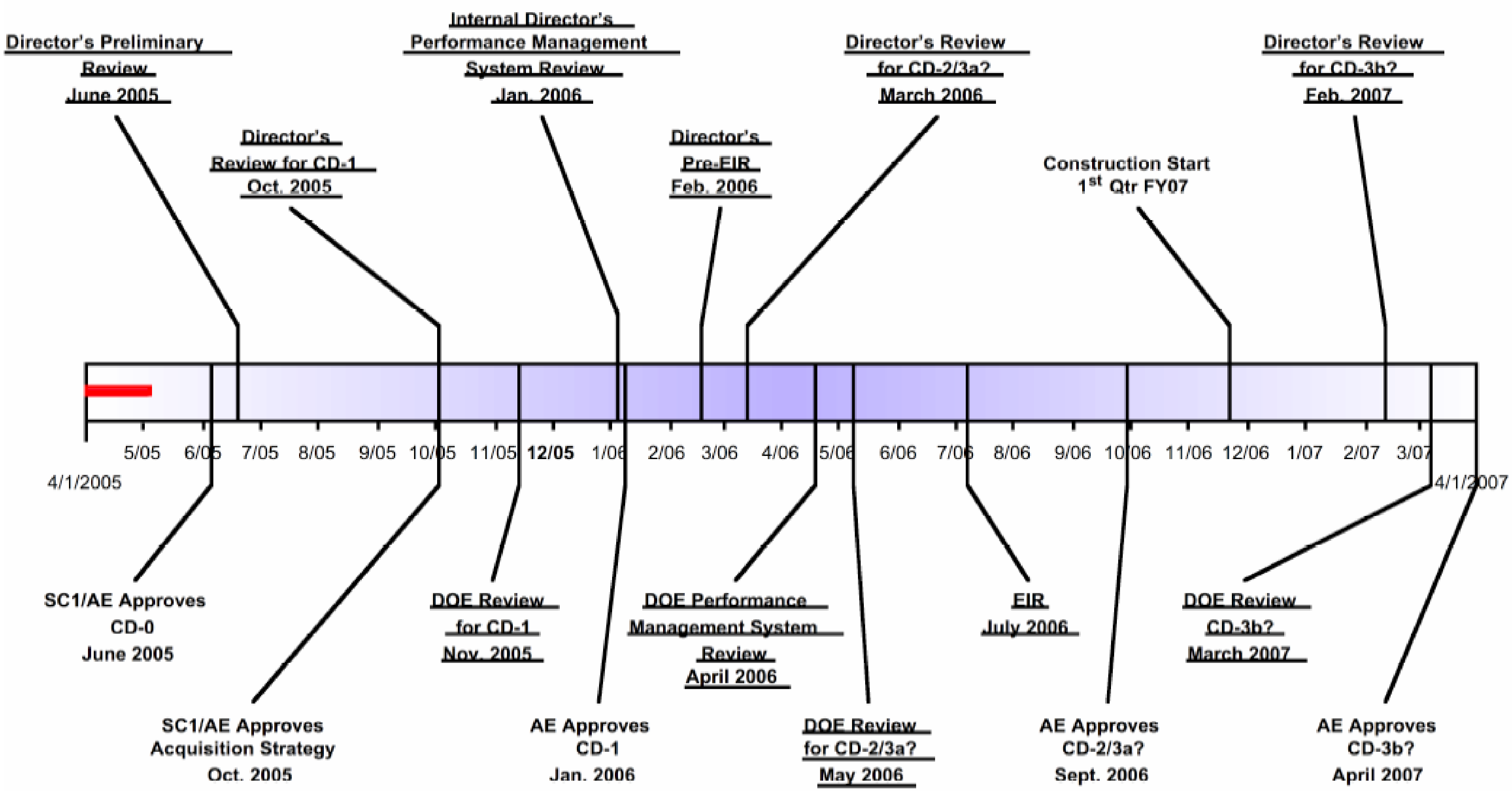


Summary

- NOνA provides a flexible approach to studying all of the parameters of neutrino oscillations
  - NOνA baseline is crucial in the context of the global program
  - NOνA is the first stage of a flexible program
    - Each stage can be planned according to what has been learned in previous stages
  - The NOνA physics reach is greater than other experiments being contemplated for the next few years
    - Reach faster than J2K official schedule presented here
  - The full range of the NOνA/NuMI program is comparable to that of other conventional approaches
  - NOνA is the size project that can be started now

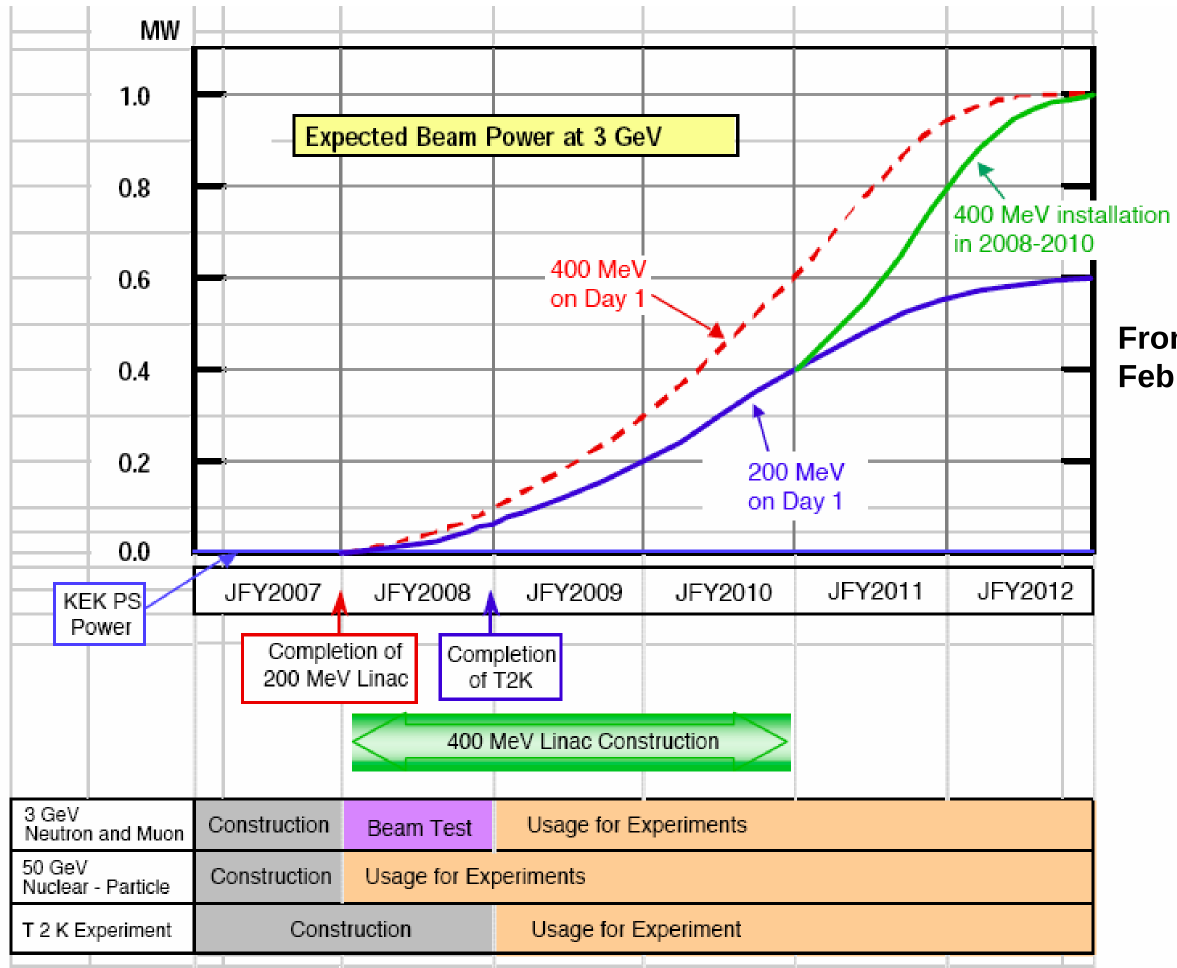
Back up slides

Ed Temple's Timeline of Critical Decisions & Reviews



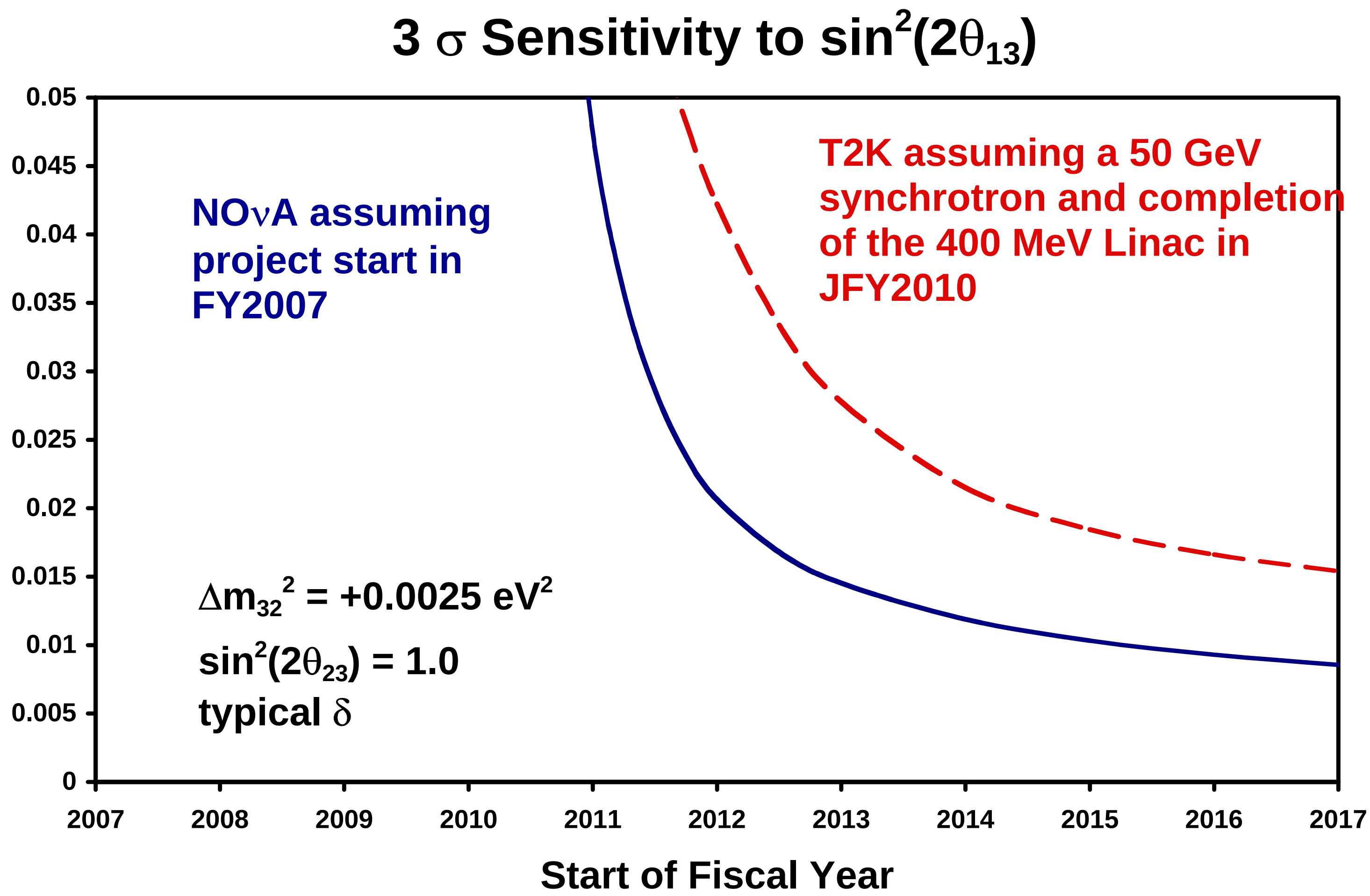
11 reviews in 22 months exclusive of NuSAG, P5, and the PAC

Assumed T2K Beam Power vs. Time

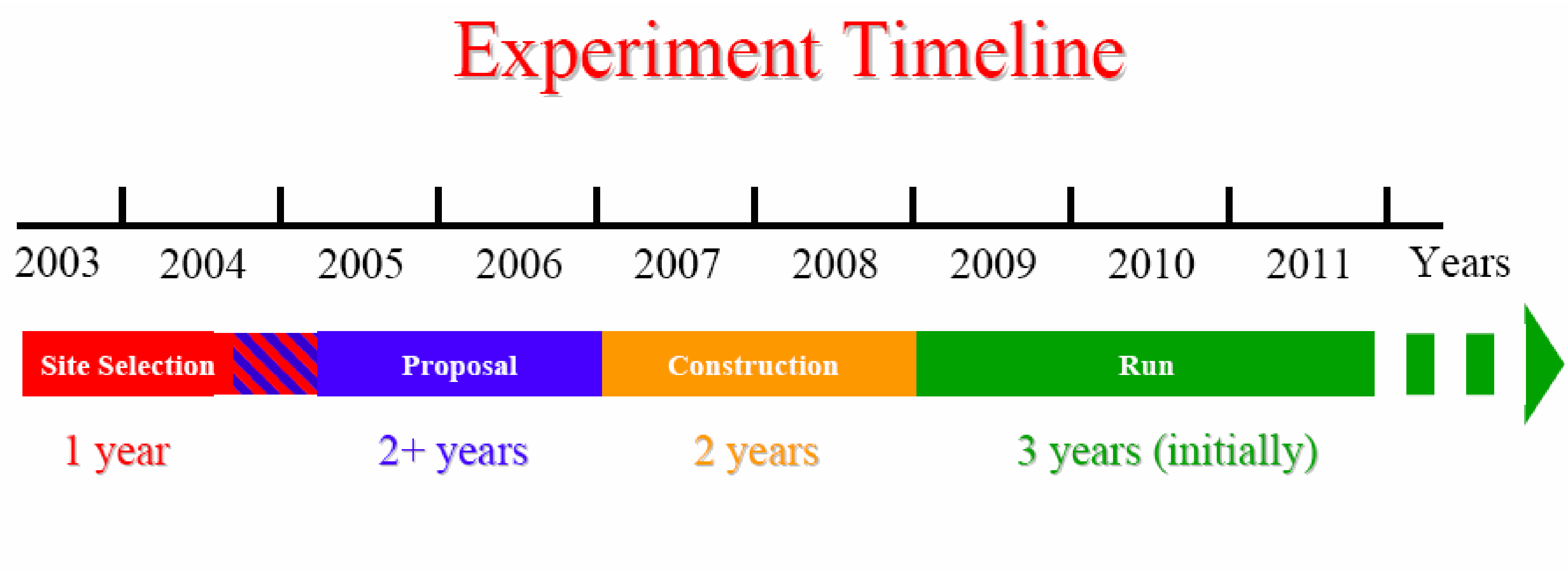


From S. Nagamiya, Feb 2005

Sensitivity vs. Time
Comparison to T2K

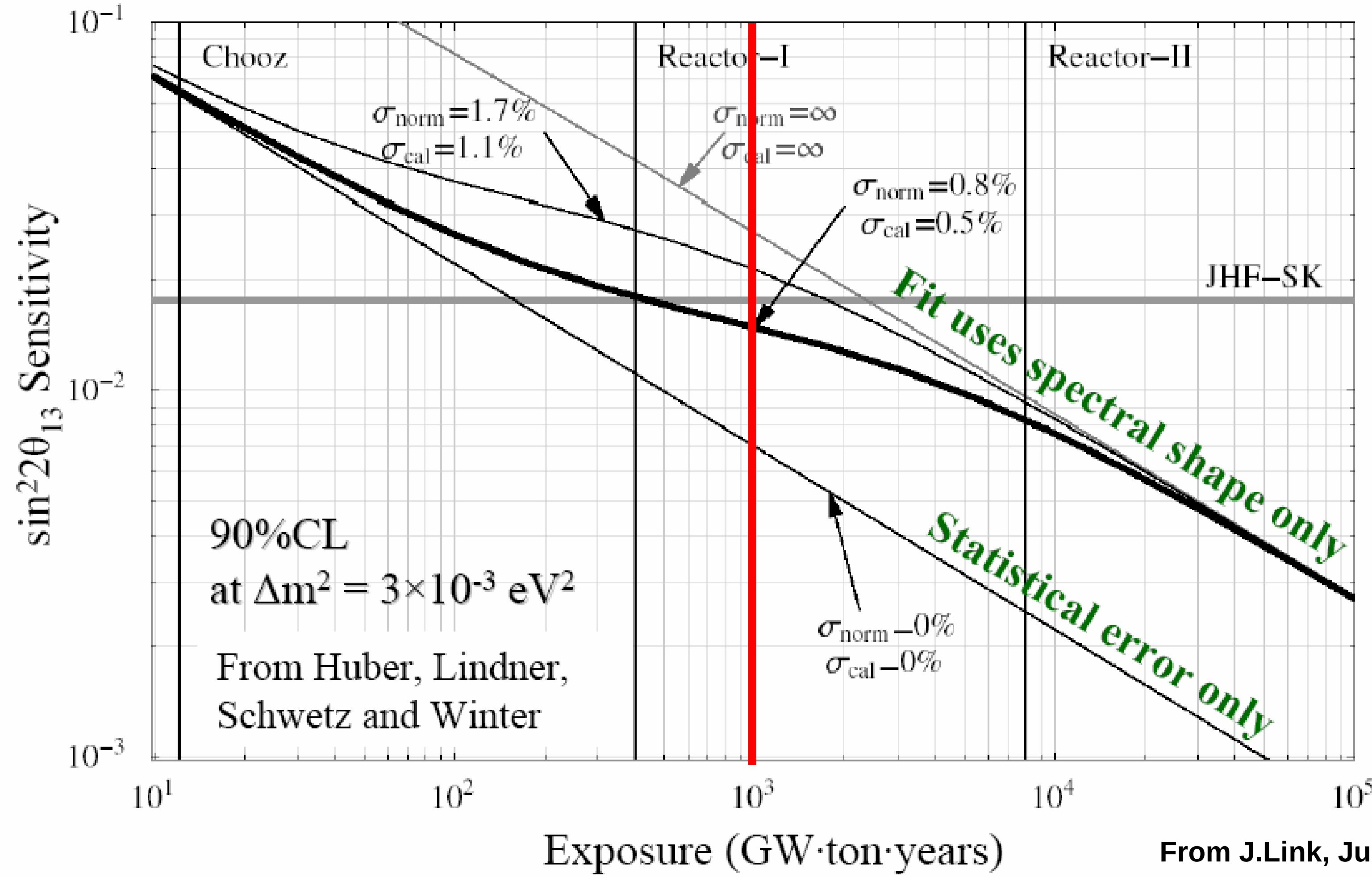


Assumed Reactor Timeline



From J.Link, June 2004

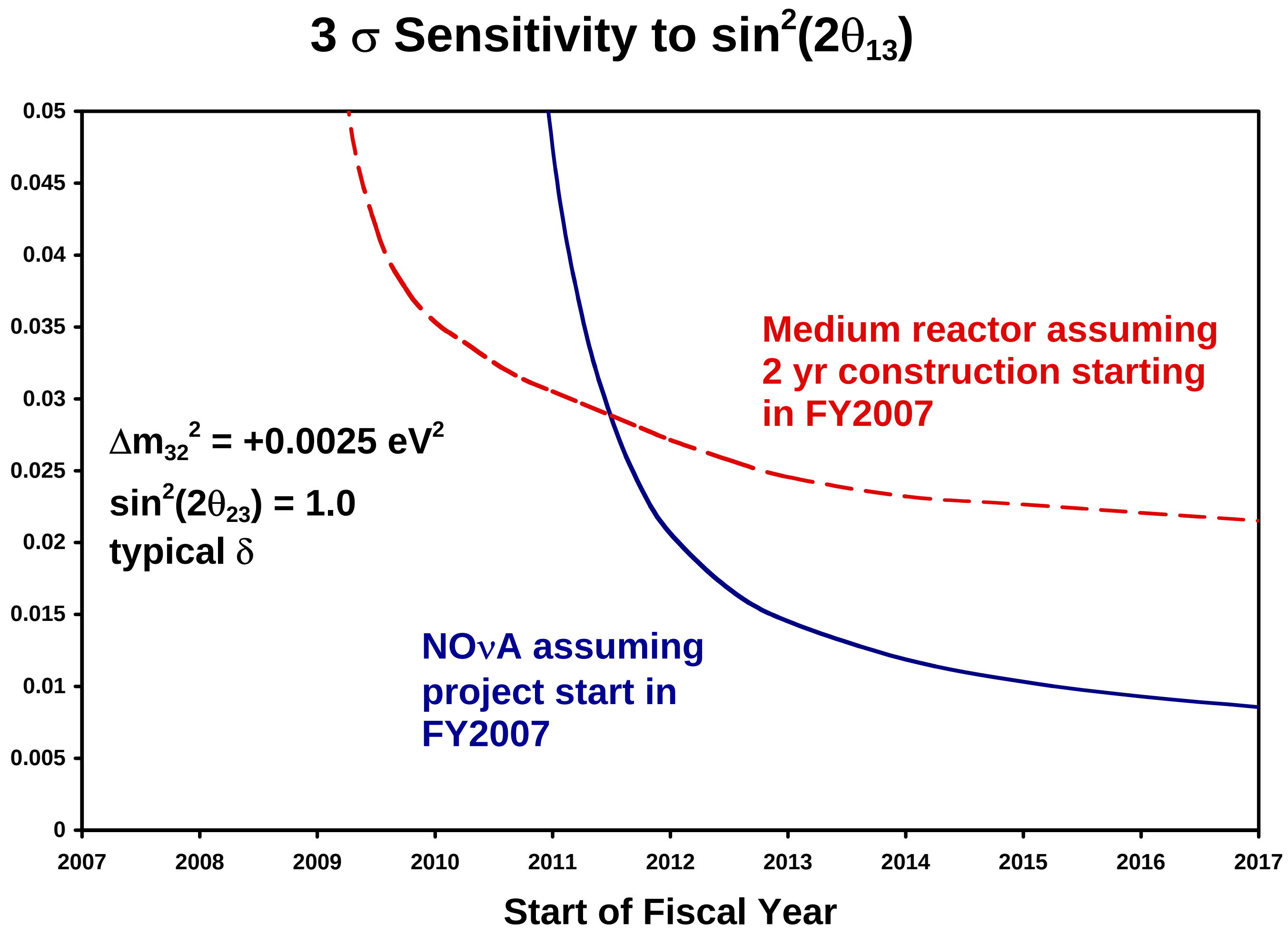
Reactor Sensitivity Model with 900 GW tons/yr



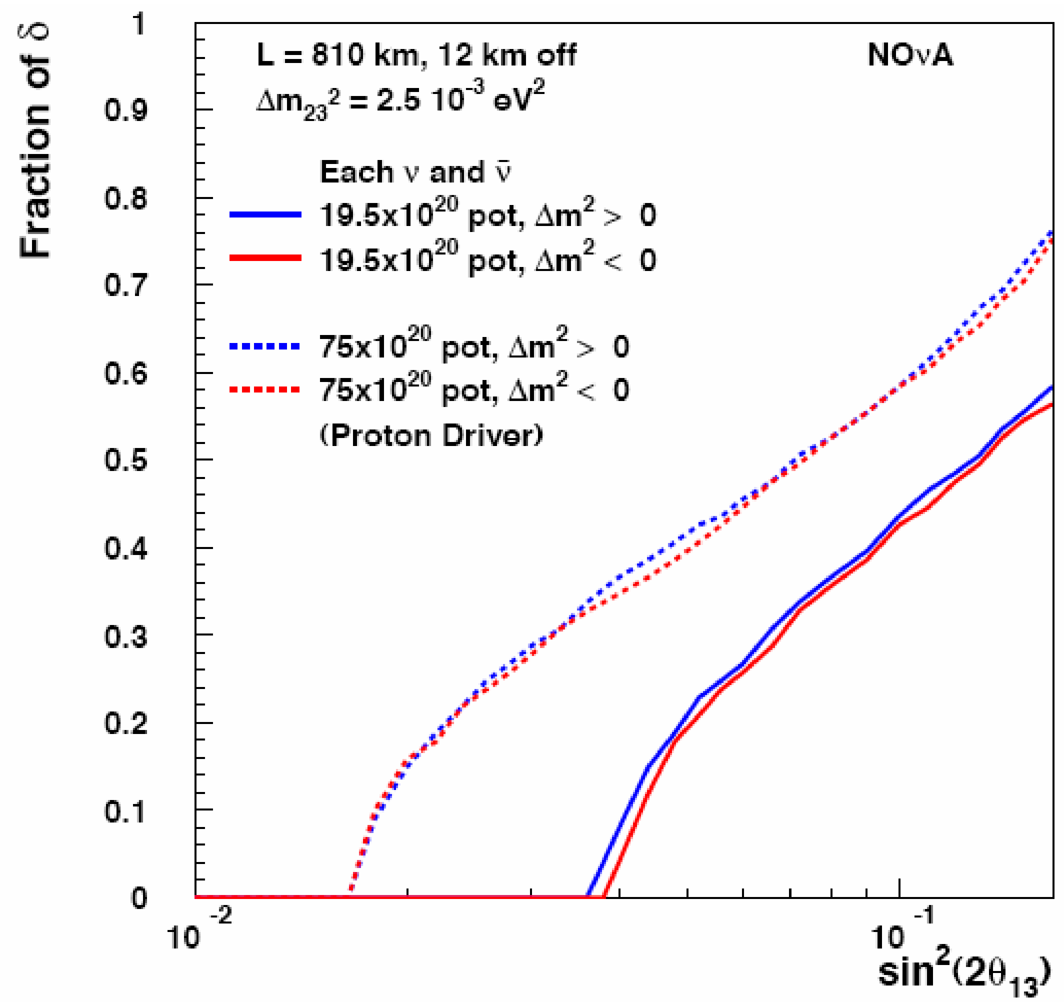
From J.Link, June 2004

Sensitivity vs. Time

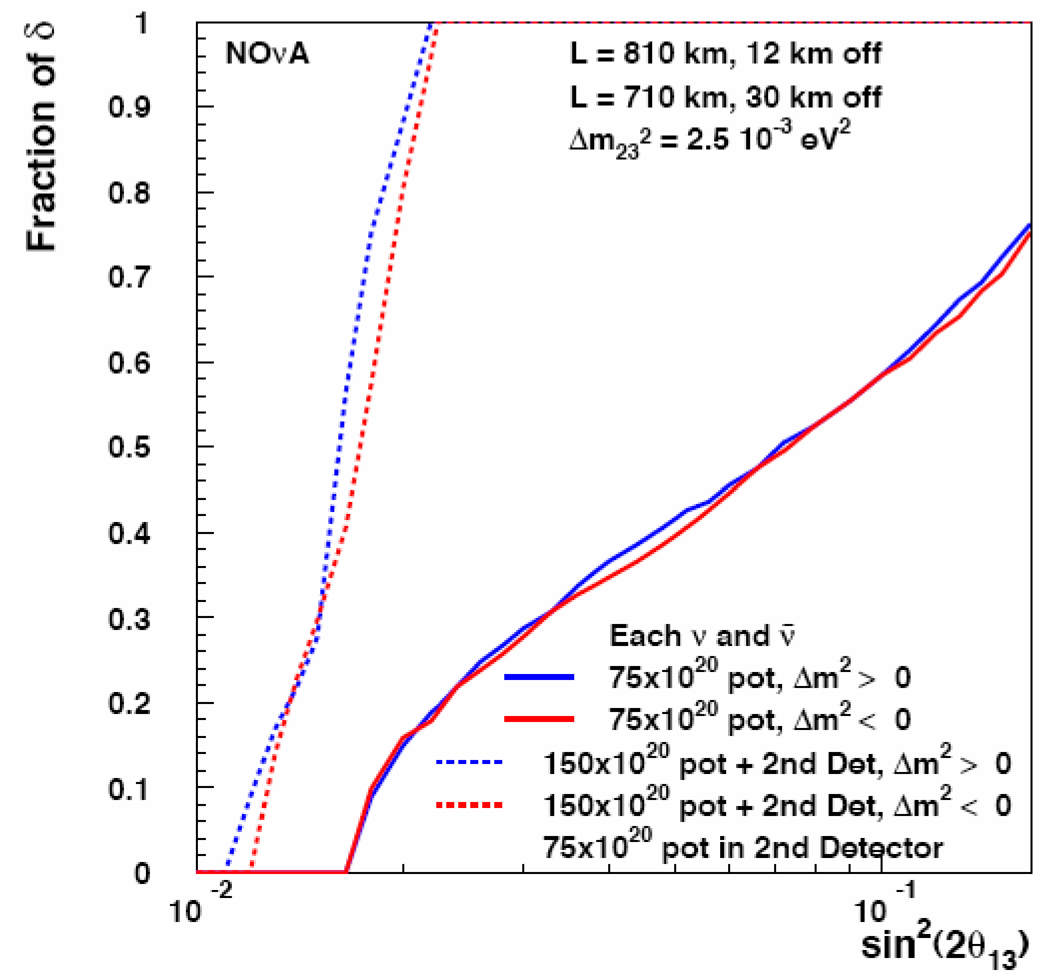
Comparison to a reactor experiment



95% CL Resolution of the Mass Ordering

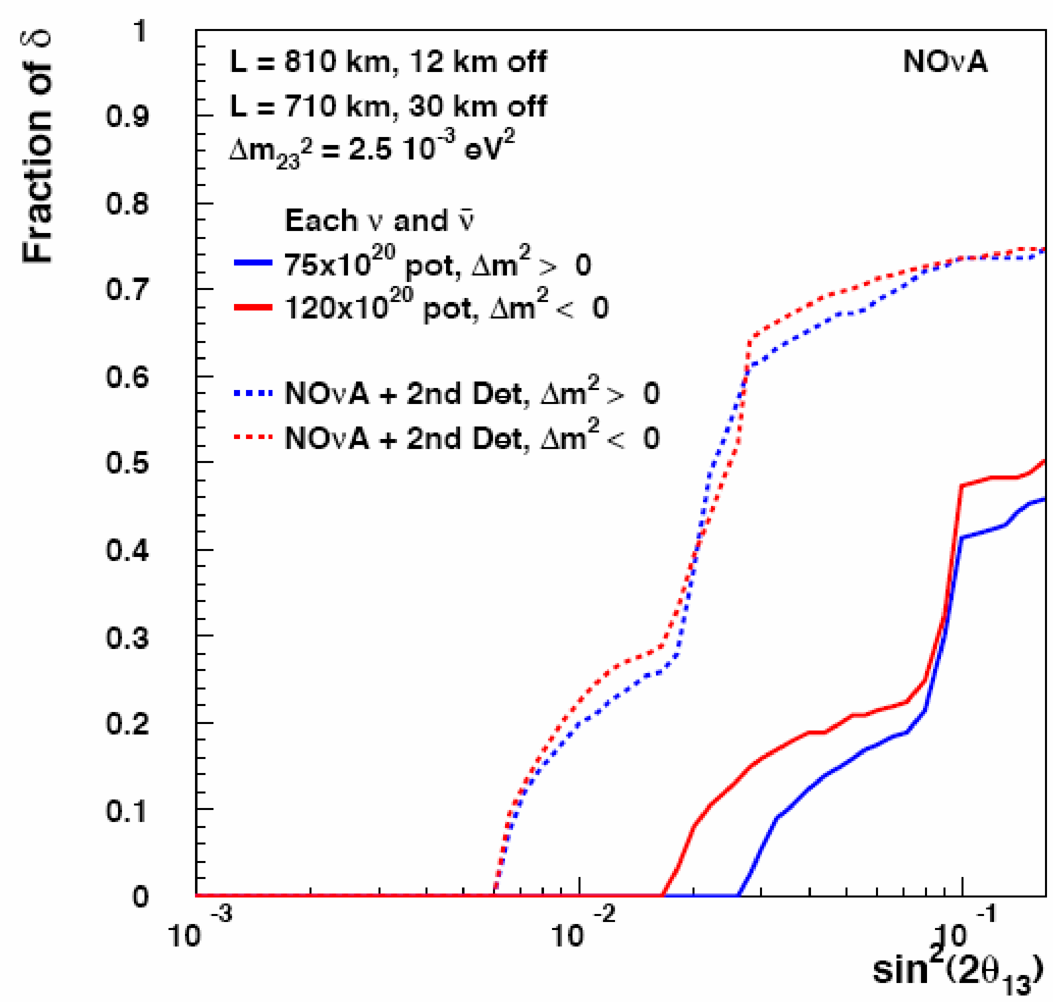


95% CL Resolution of the Mass Ordering

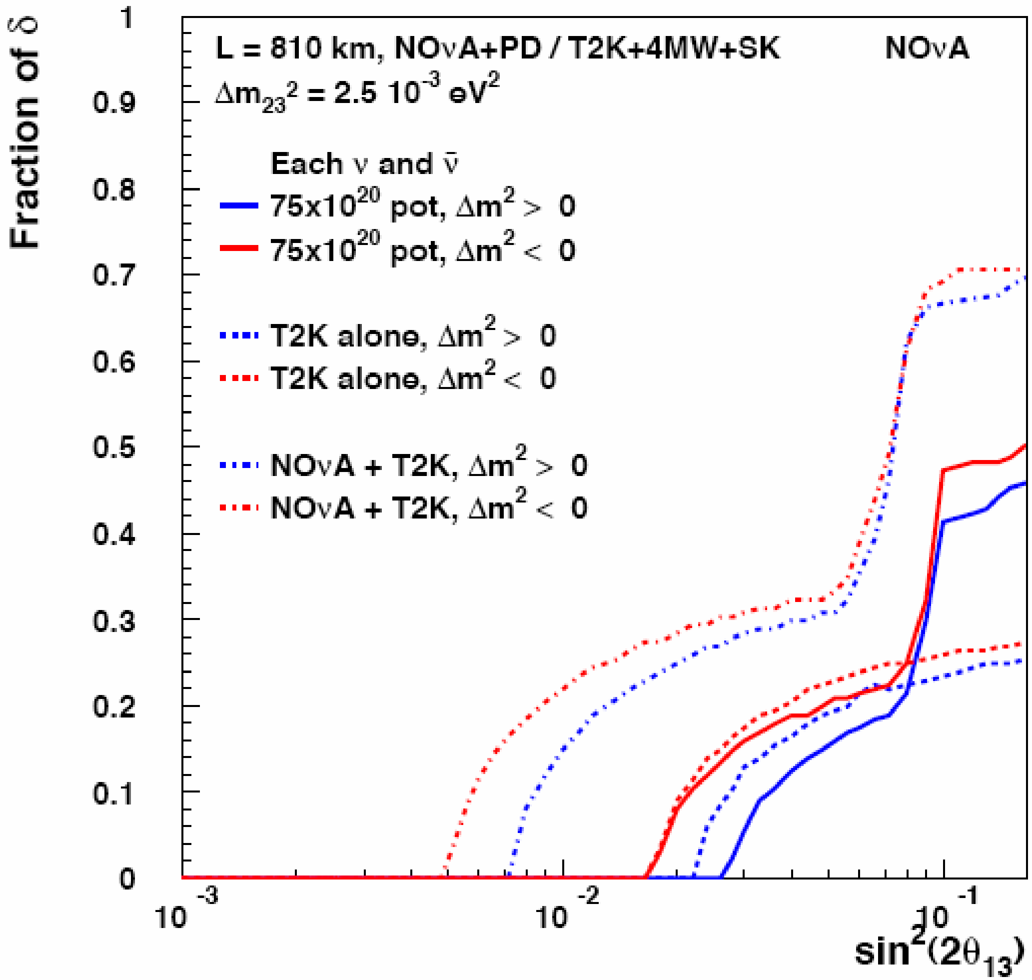


- Staged scenario
  - 2 years into the PD run, realize the need for the 2nd off-axis detector
  - Build in 4 years
  - Run for 6 years
  - Thus, 12 years running of NOvA with PD
  - 6 years of running the 2ND detector
- Several technologies possible for the 2nd Detector
  - Using SK as a model for the calculation

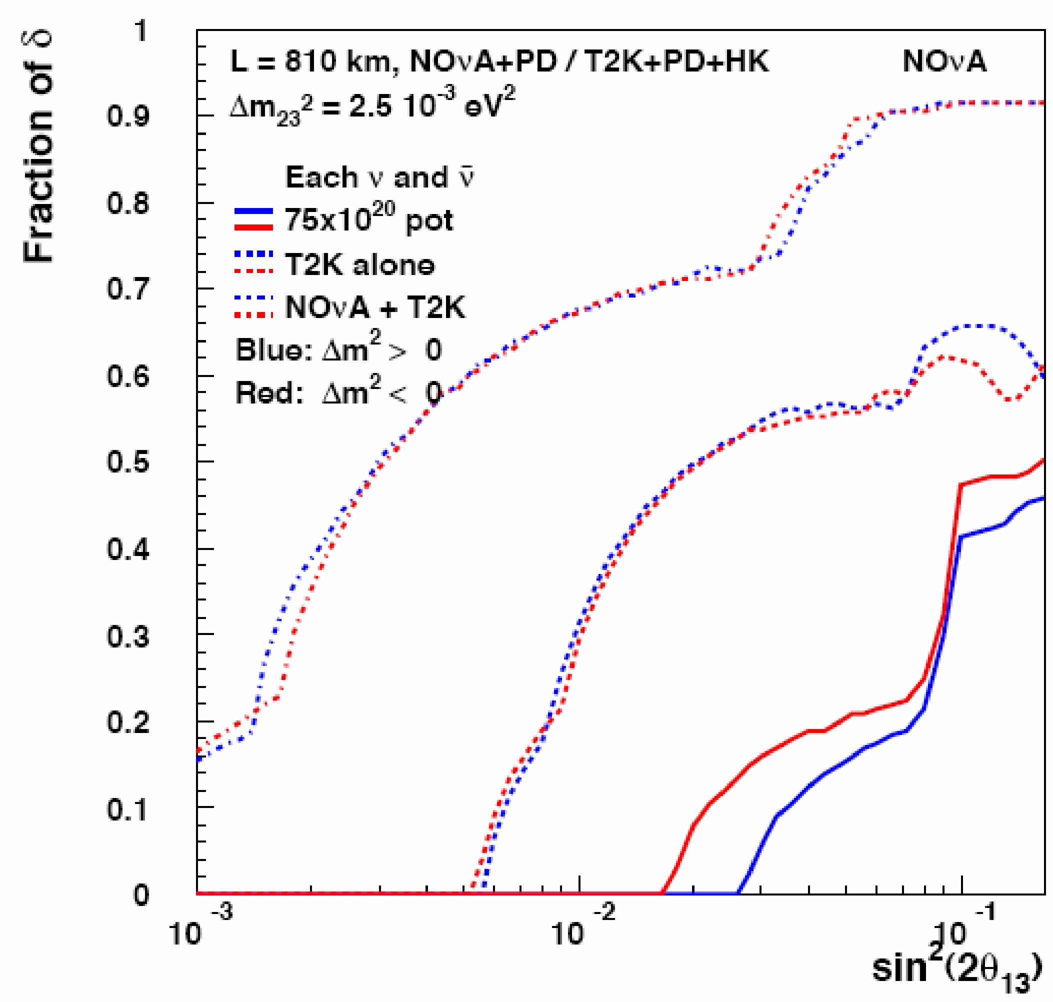
3 σ Determination of CP Violation



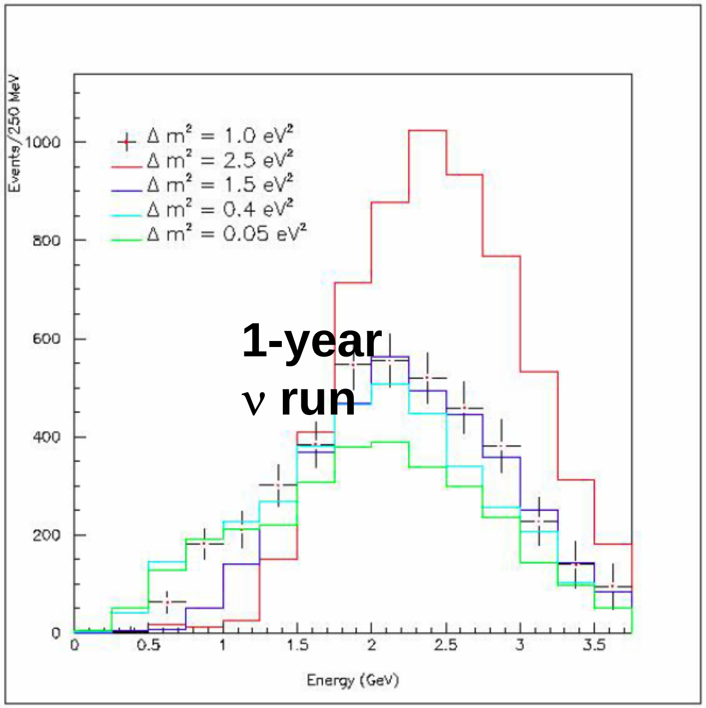
3 σ Determination of CP Violation

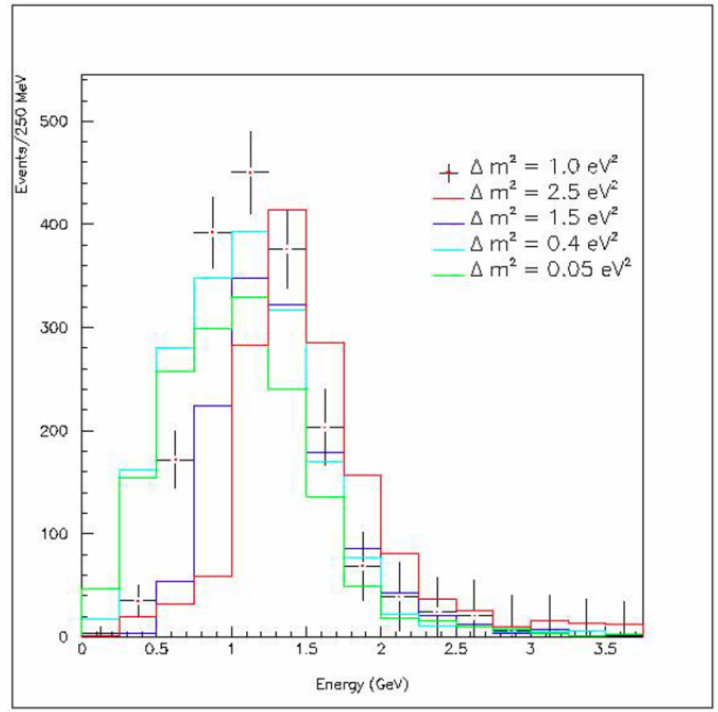


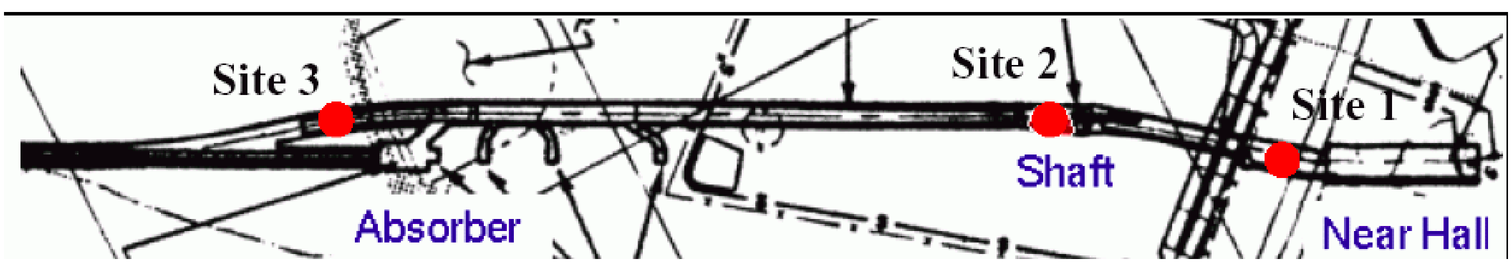
3 σ Determination of CP Violation



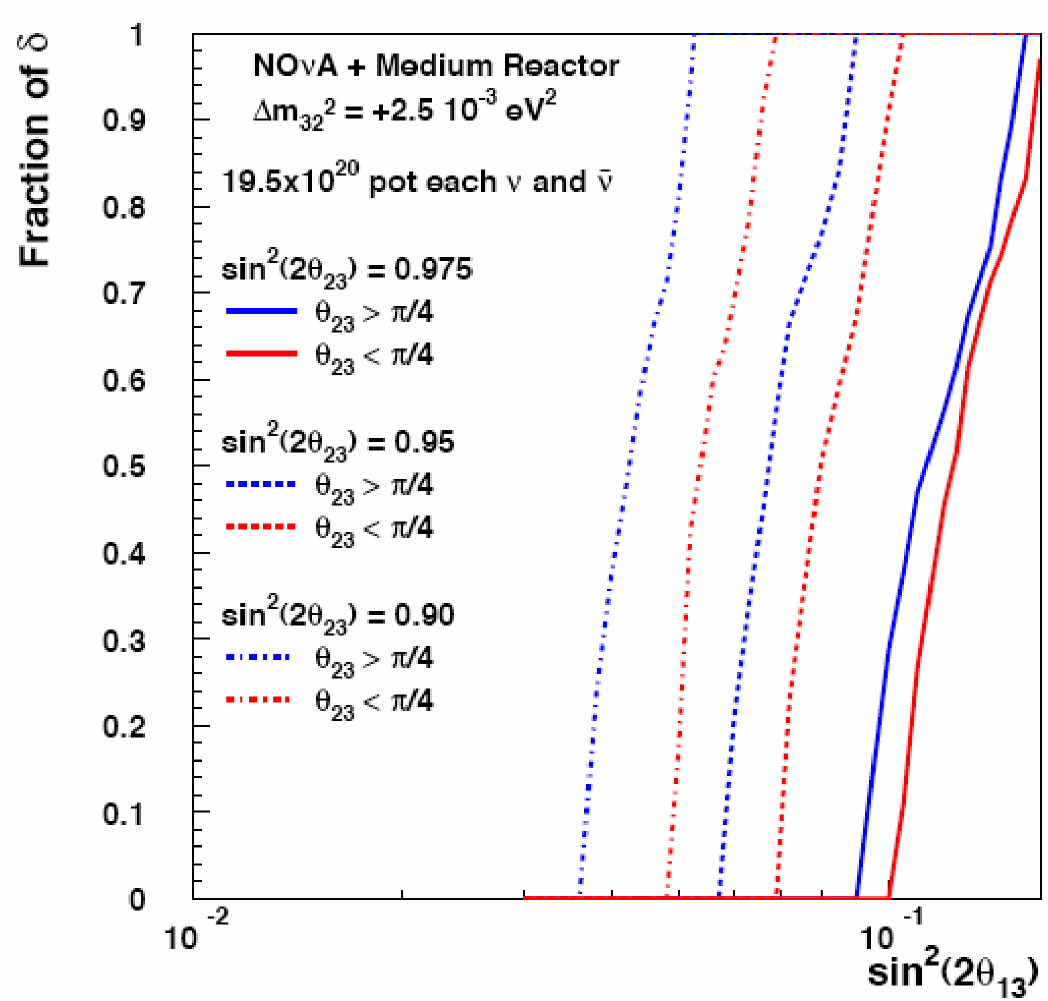
Study MiniBooNE Signal



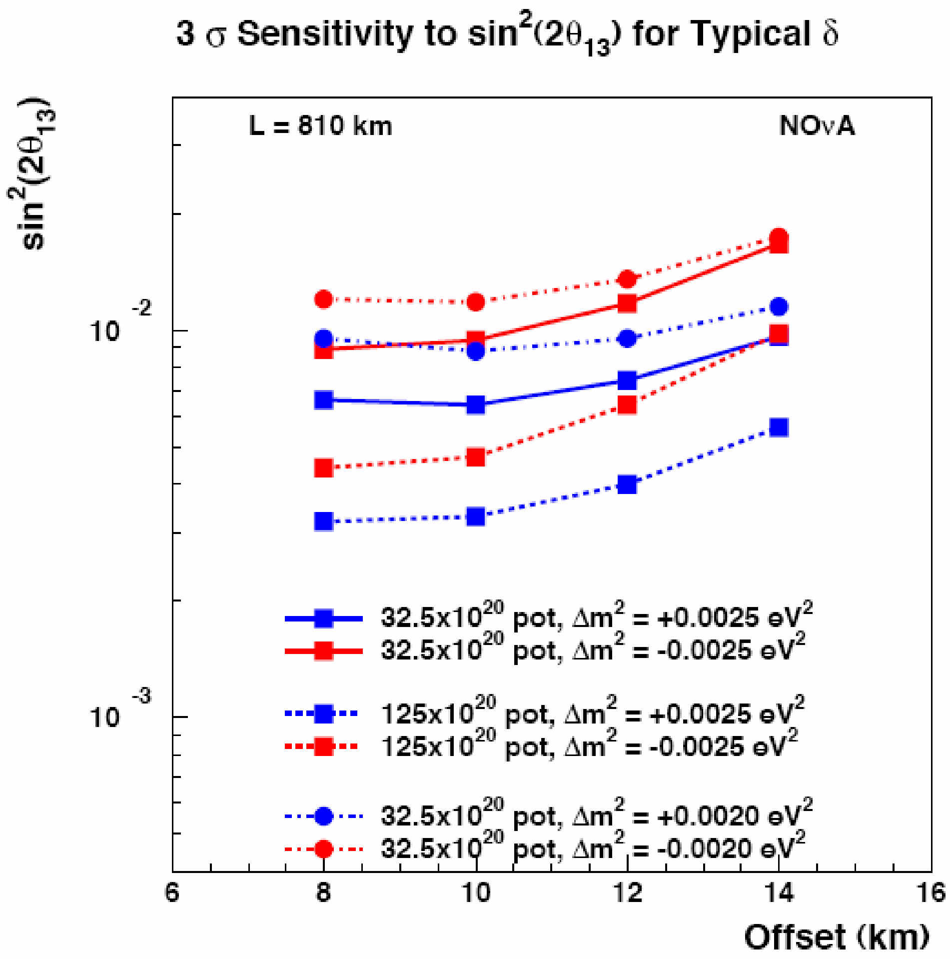




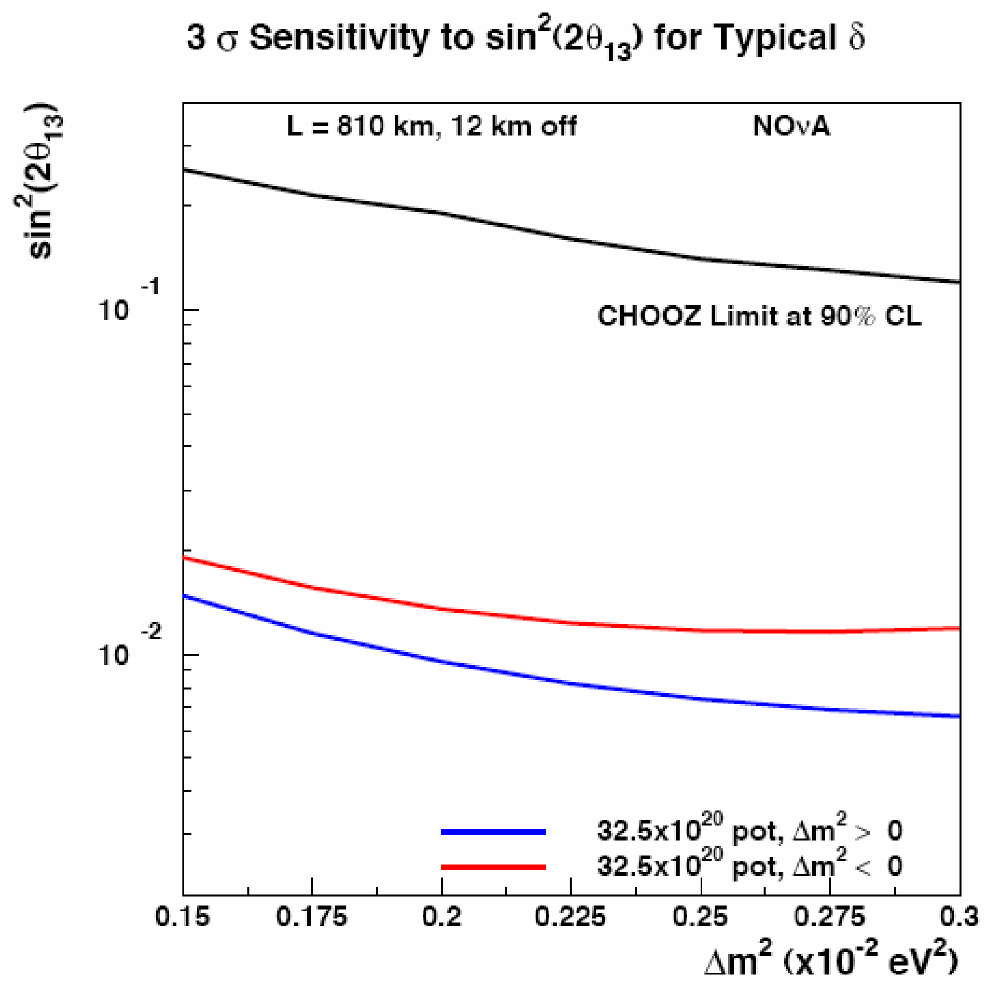
95% CL Resolution of the θ_{23} Ambiguity



Sensitivity to $\nu_\mu \rightarrow \nu_e$ Vs. Off-Axis Distance



Fixed-Site Sensitivity to $\nu_\mu \to \nu_e$ vs Δm^2_{23}



Mass Ordering vs Off-Axis Distance