Physics Potential Of NOνA

Fermilab PAC
Fermilab
7 April 2005

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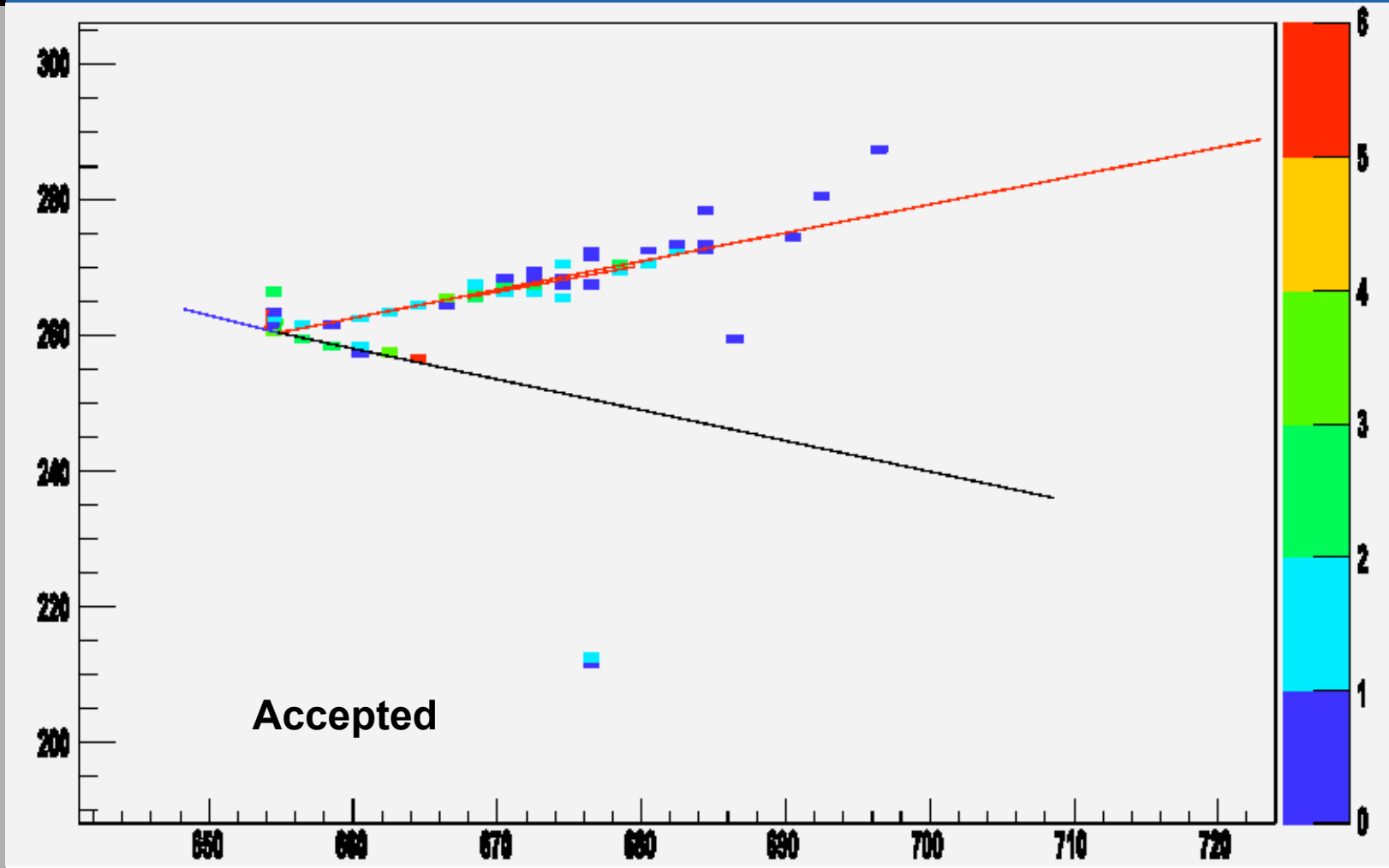
Technology Decision

- A 30 kT totally active detector gave about the same FoM (signal/√background) for $\nu_\mu \rightarrow \nu_e$ as a 50 kT sandwich detector and cost about the same.
- Advantages of a totally active detector:
  - Finer longitudinal segmentation, better energy resolution, and higher signal/background, leading to
    - Improvement with more sophisticated analysis
    - Better understanding of beam backgrounds
    - Reduction of cosmic ray backgrounds
    - Increased precision for measuring $\sin^2(2\theta_{23})$
    - Possible supernovae detection
  - Faster detector assembly

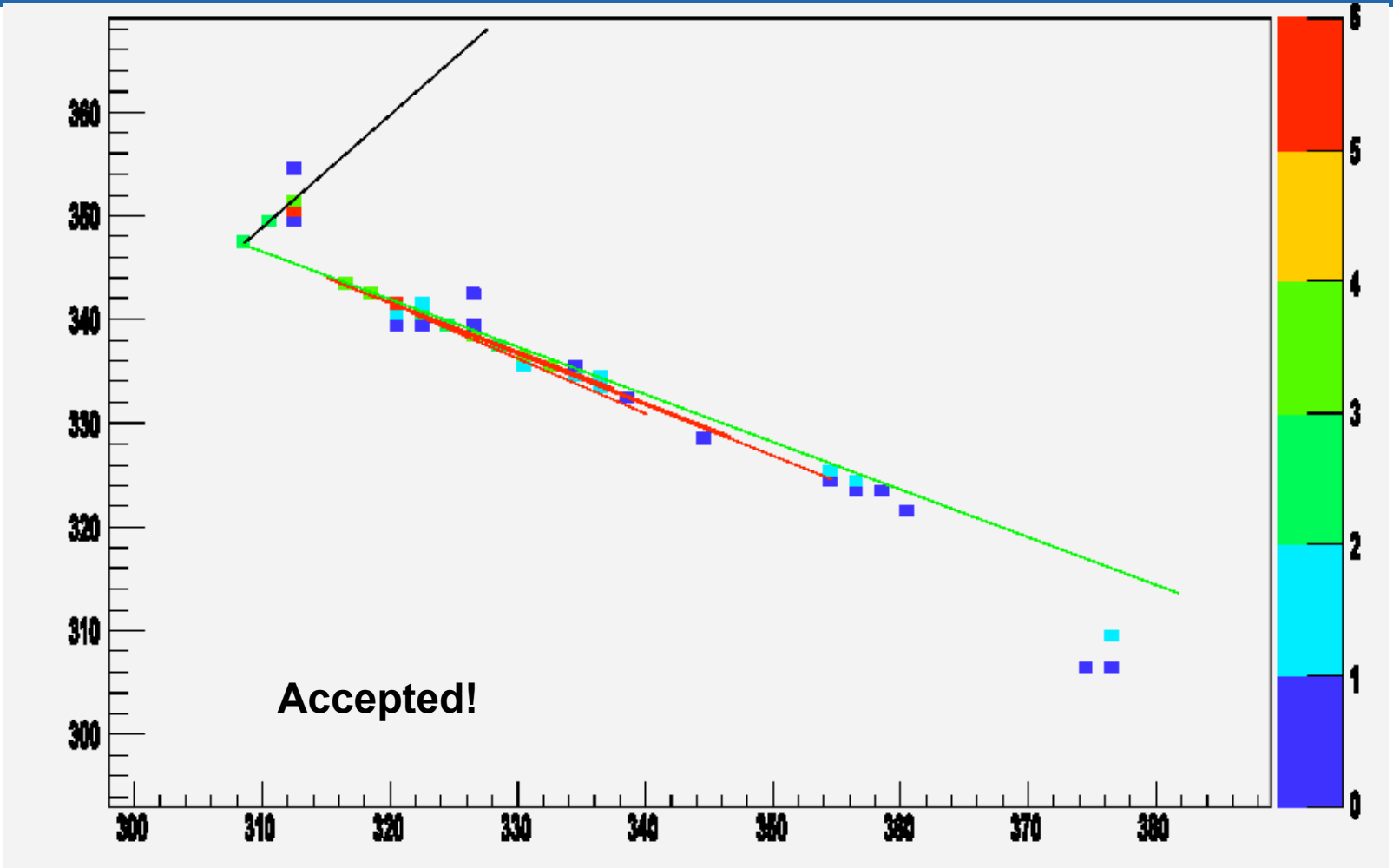
Simulations

- **Full simulations using modifications of MINOS software**
  - **Generation of neutrino interaction event**
  - **Calculation of detector response → raw signals**
  - **Reconstruction: track finding and fitting, particle ID for each track, interaction vertex**
  - **Preliminary event identification**
  - **Maximum likelihood analysis**
- **Not as sophisticated as present MINOS analyses, but a floor on possible detector capability**

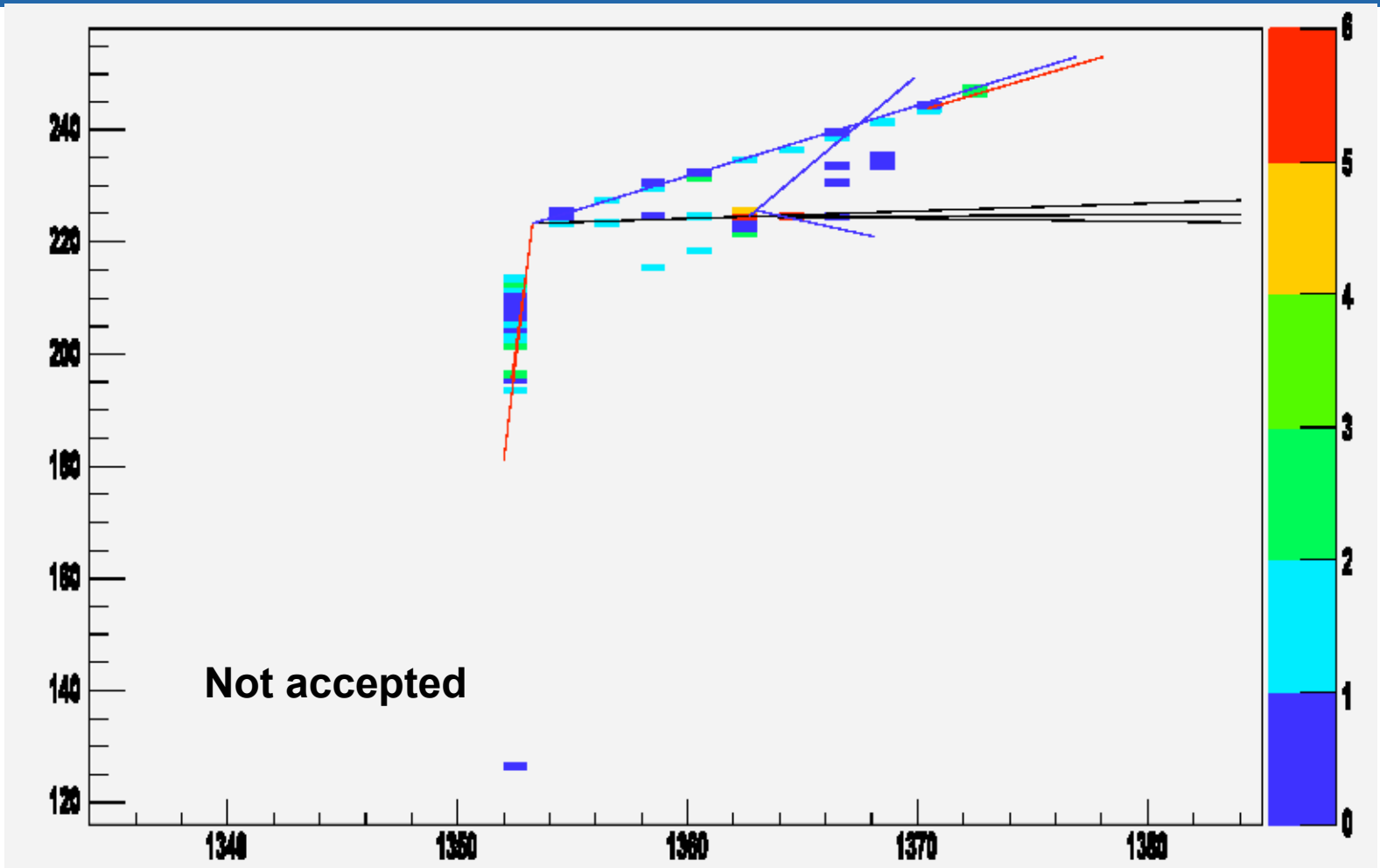
1.87 GeV $\nu_e N \rightarrow e p \pi^+ \pi^0$ x-z View



2.11 GeV $\nu_\mu N \rightarrow \nu_\mu p \pi^0$ x-z View



1.86 GeV $\nu_e N \rightarrow ep\pi^+$ x-z View



Post-Collider Proton Plan

- Proton Plan with Collider
  - 9/11 Slip-stacked Booster batches at 5.5×10^{12} p/batch
  - Repetition rate = 0.8 s (Booster) + 1.4 s (Ramp) = 2.2 s
  - 10% for Collider shot setup + 5% for antiproton transfer
  - $\Rightarrow$ 3.4 $\times10^{20}$ protons/yr
- Post-Collider Proton Plan
  - 11 batches for neutrinos $\Rightarrow$ 11/9 = 1.22 factor
  - Hide Booster filling time in Recycler $\Rightarrow$ 0.8 s $\rightarrow$ 0.067 s
    $\Rightarrow$ 2.2 s $\rightarrow$ 1.467 s = 1.50 factor
  - Save 10% shot setup and 5% antiproton transfer = 1.17 factor
  - $\Rightarrow$ (3.4 $\times10^{20}$ protons/yr)(1.22)(1.50)(1.17) = (7.3 $\times10^{20}$ protons/yr)
- Negotiated rate is 90% of this: (6.5×10^{20} protons/yr)
- Proton Driver rate taken as 25×10^{20} protons/yr

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

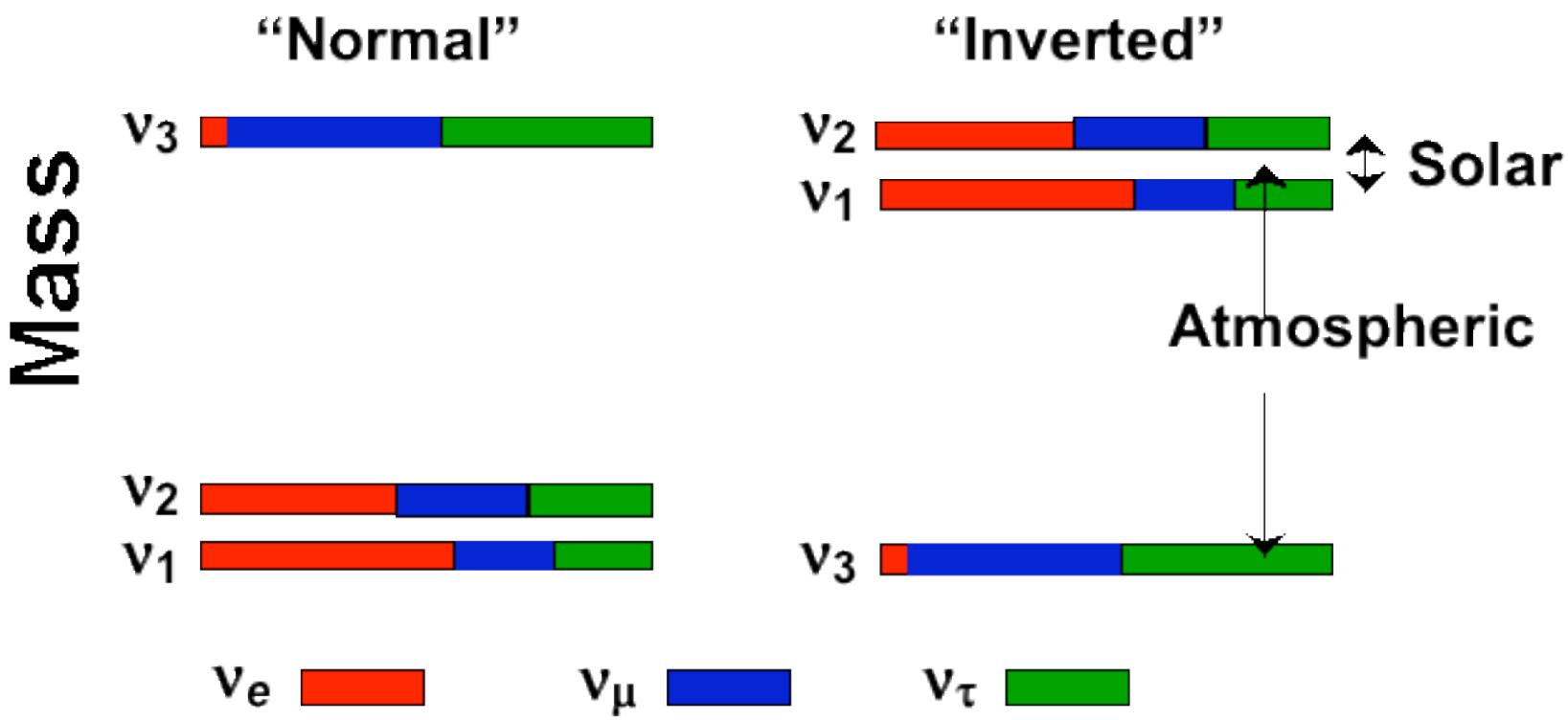
- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta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

  } Atmospheric-solar interference

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})$ x

$\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

Mass Ordering



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

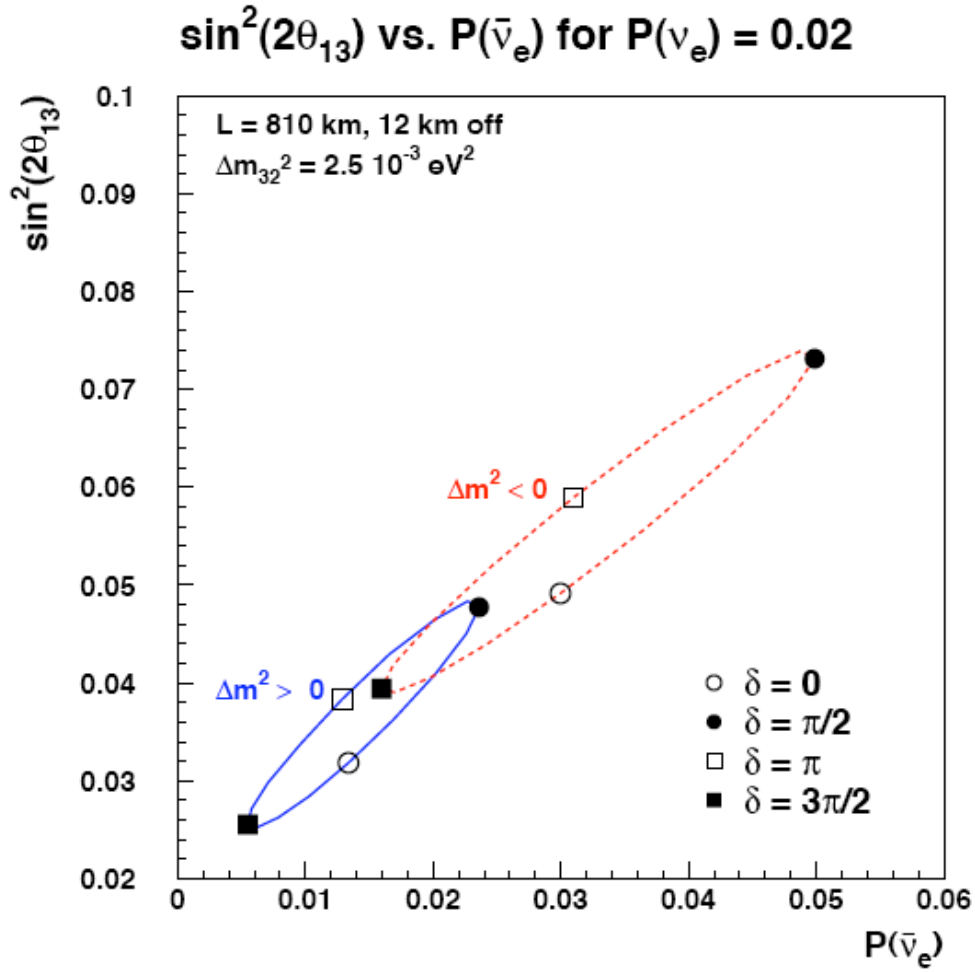
- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m_{13}^2}{2\sqrt{2}G_F\rho_e} \approx 11\,\text{GeV for the earth's crust.}$$

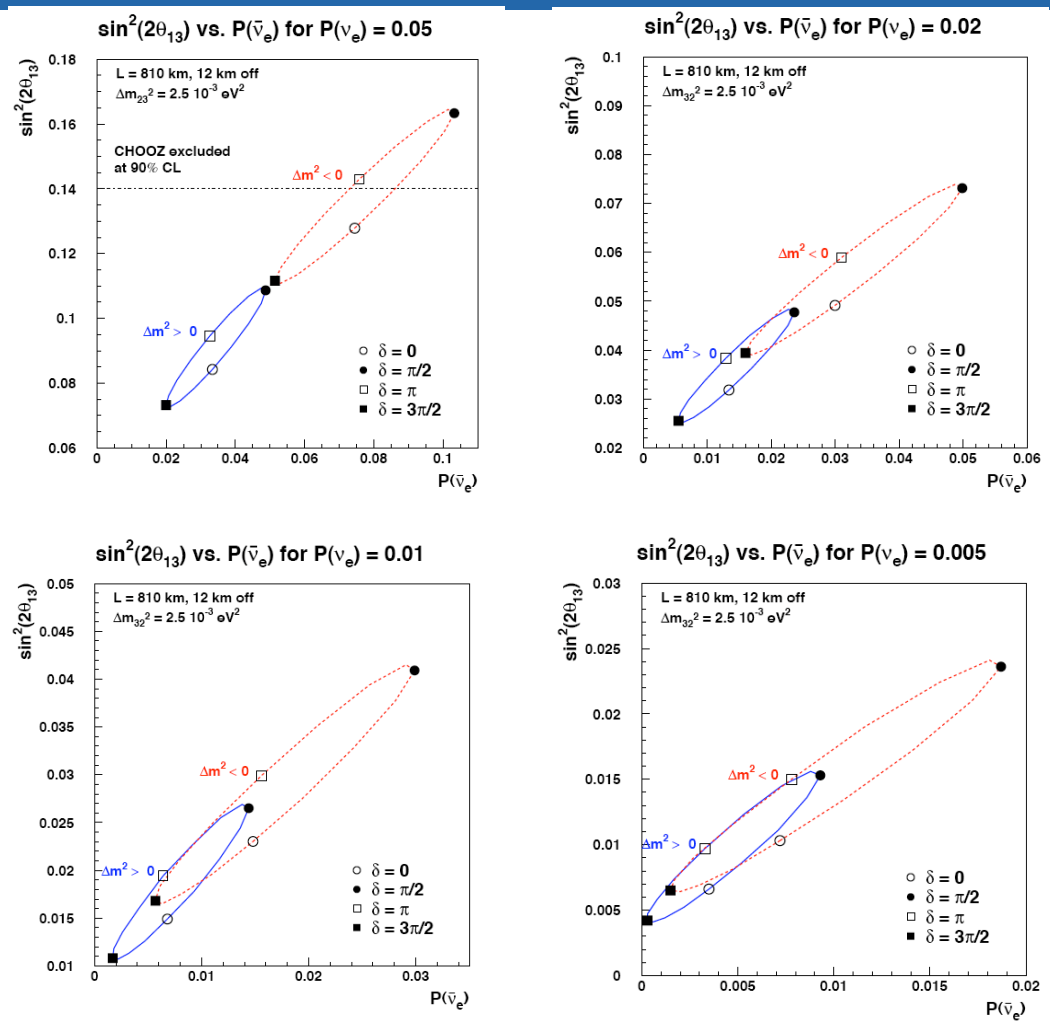
About a ±30% effect for NuMI, but only a ±11% effect for JPARC .

However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

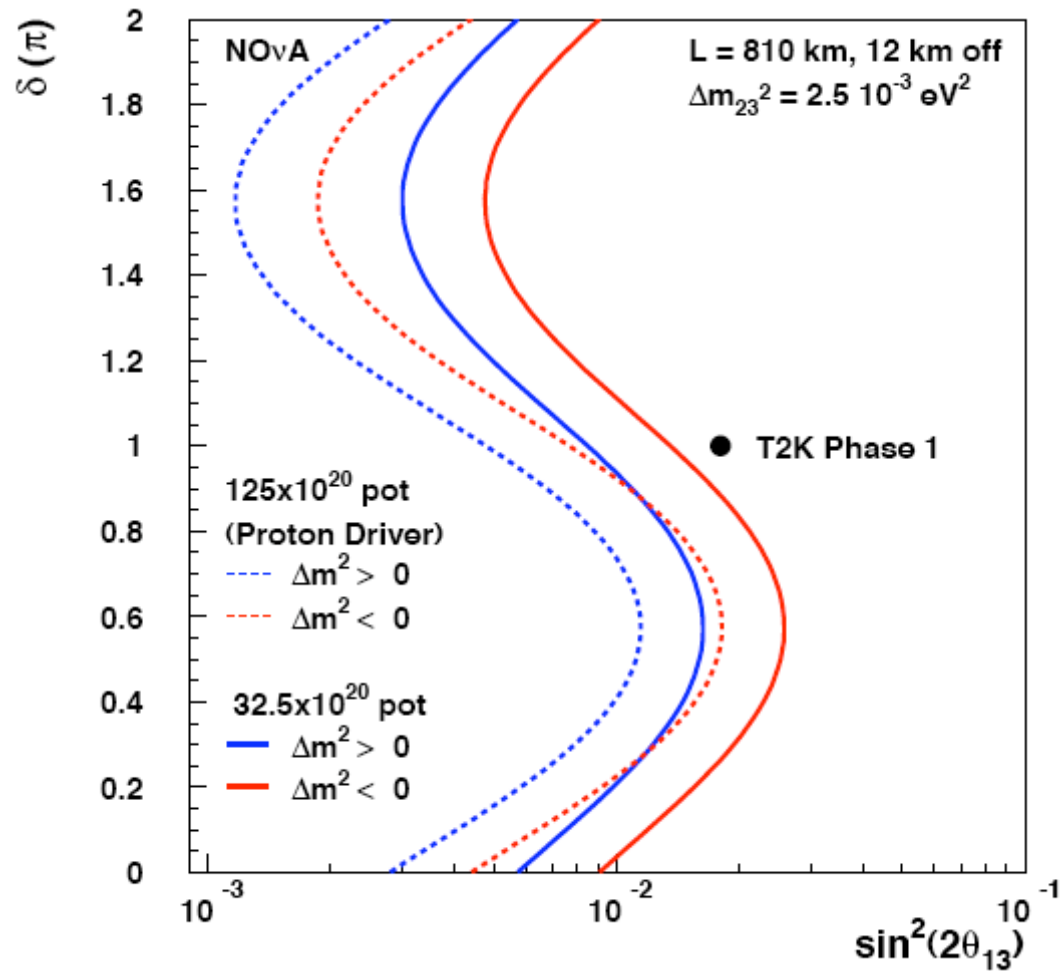
Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation



Parameters Consistent with Other Oscillation Probabilities

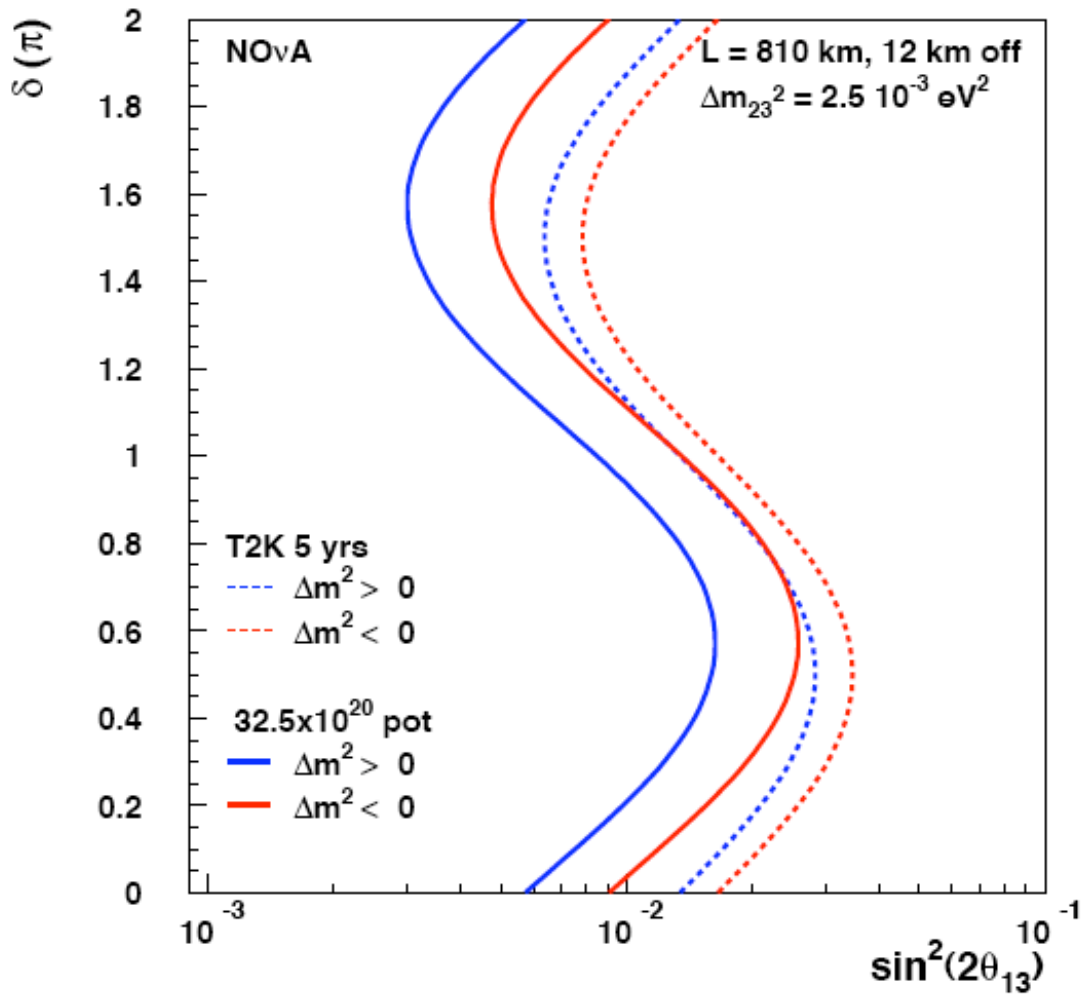


3 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$



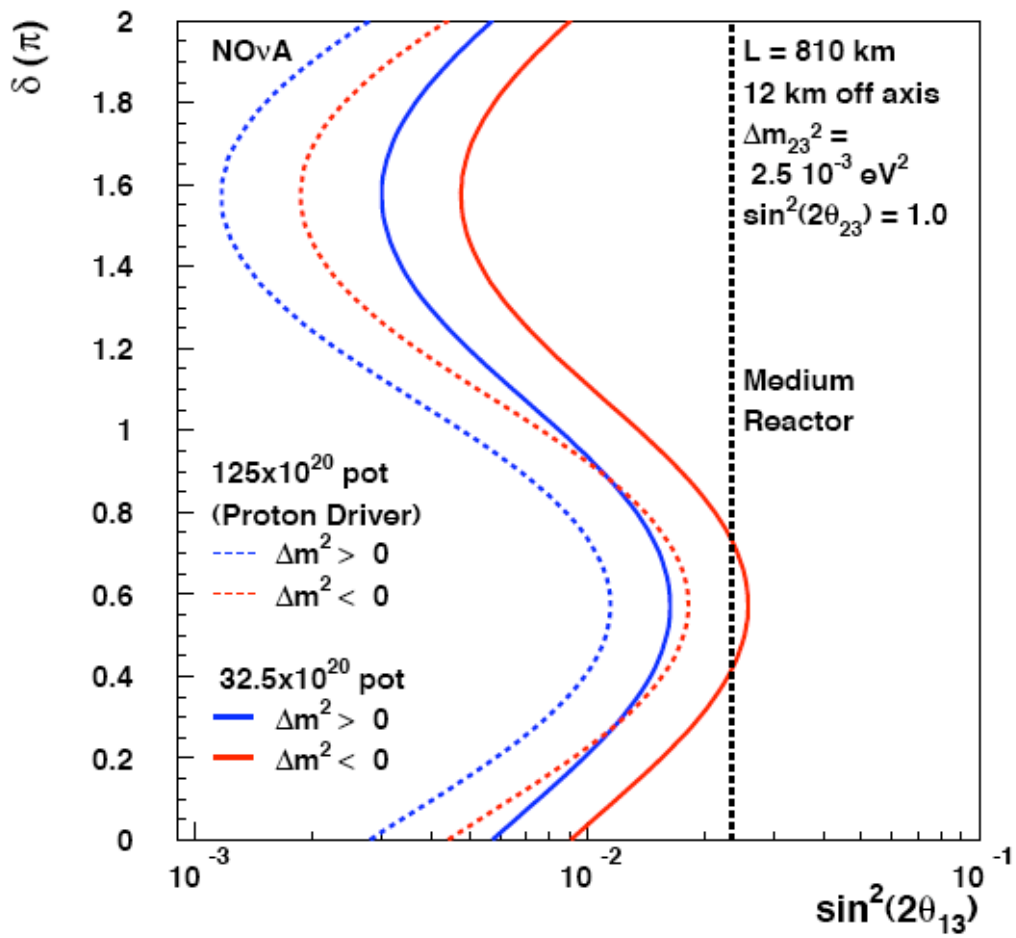
5 year ν run

3 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$ Comparison to T2K



NOνA's sensitivity is greater than T2K's by
1.6 to 2.4 for $\Delta m^2 > 0$
1.2 to 1.8 for $\Delta m^2 < 0$

3 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$ Comparison to Reactors



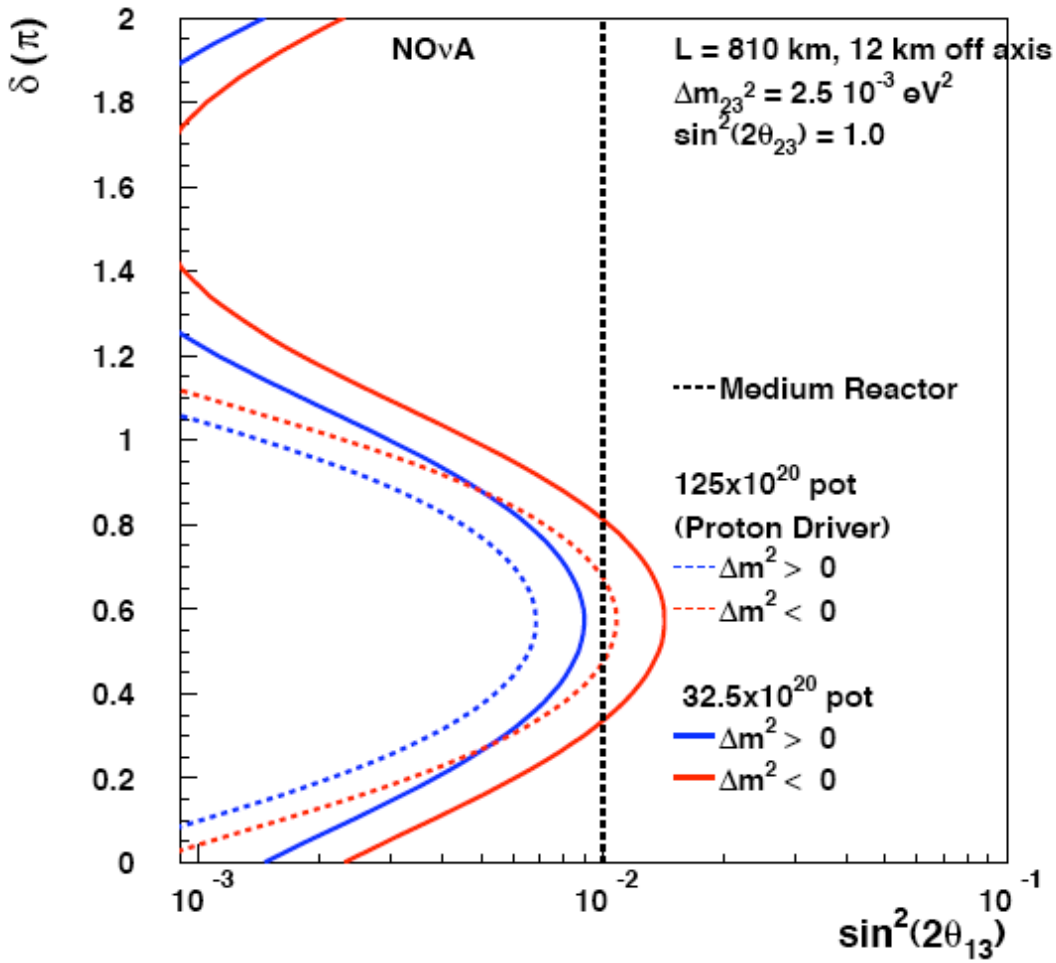
"Medium Reactor" is a Braidwood or Daya Bay class experiment (1% sensitivity at 1.28 σ ("90% CL")

NOνA's sensitivity is greater than that of a medium reactor by

1.4 to 7.8 for $\Delta m^2 > 0$

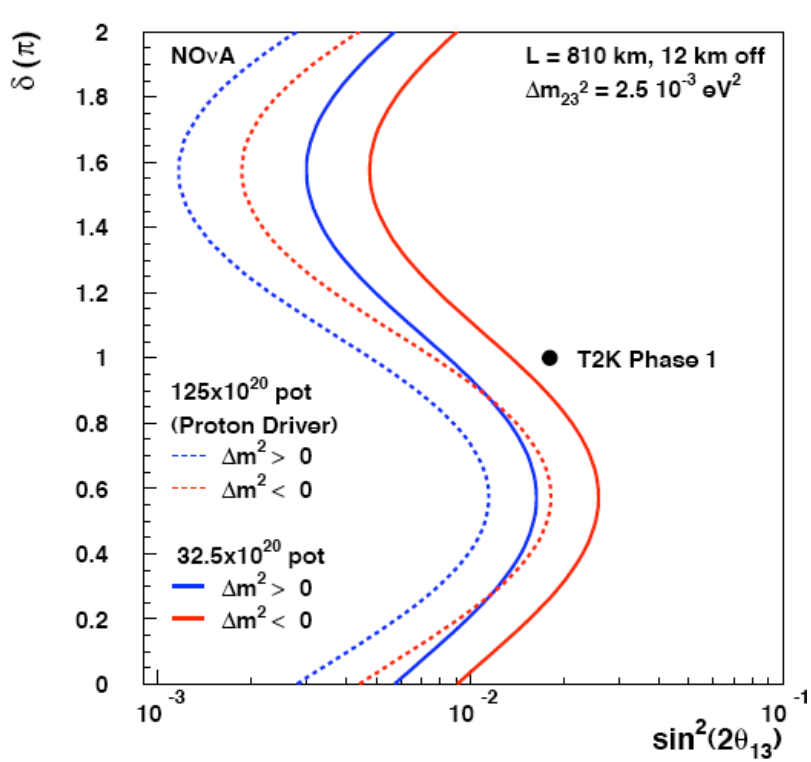
0.9 to 4.9 for $\Delta m^2 < 0$

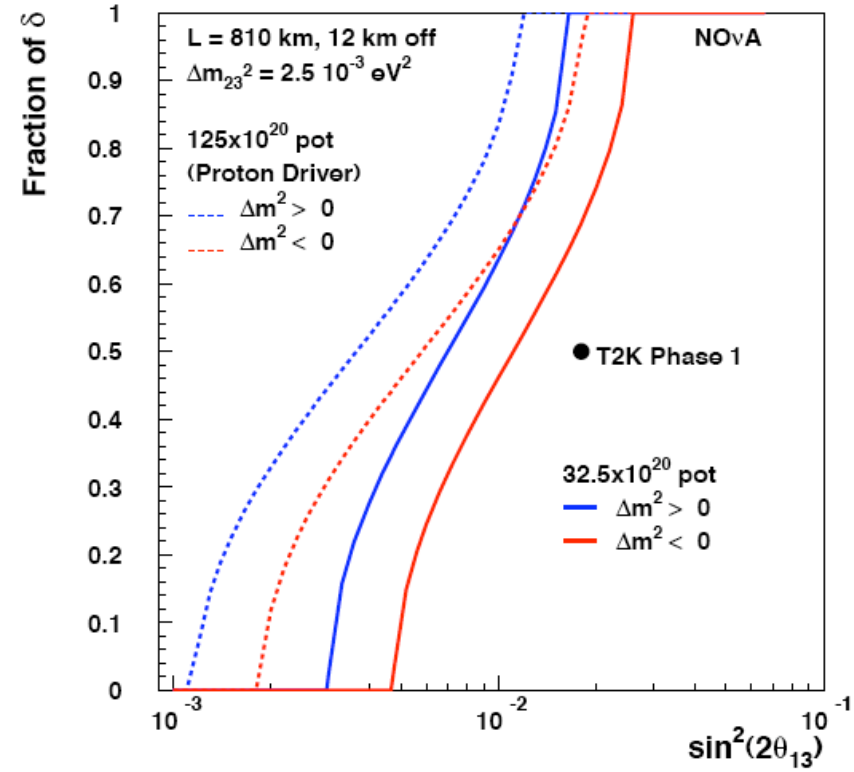
1.28 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$ Comparison to Reactors



"90% CL"

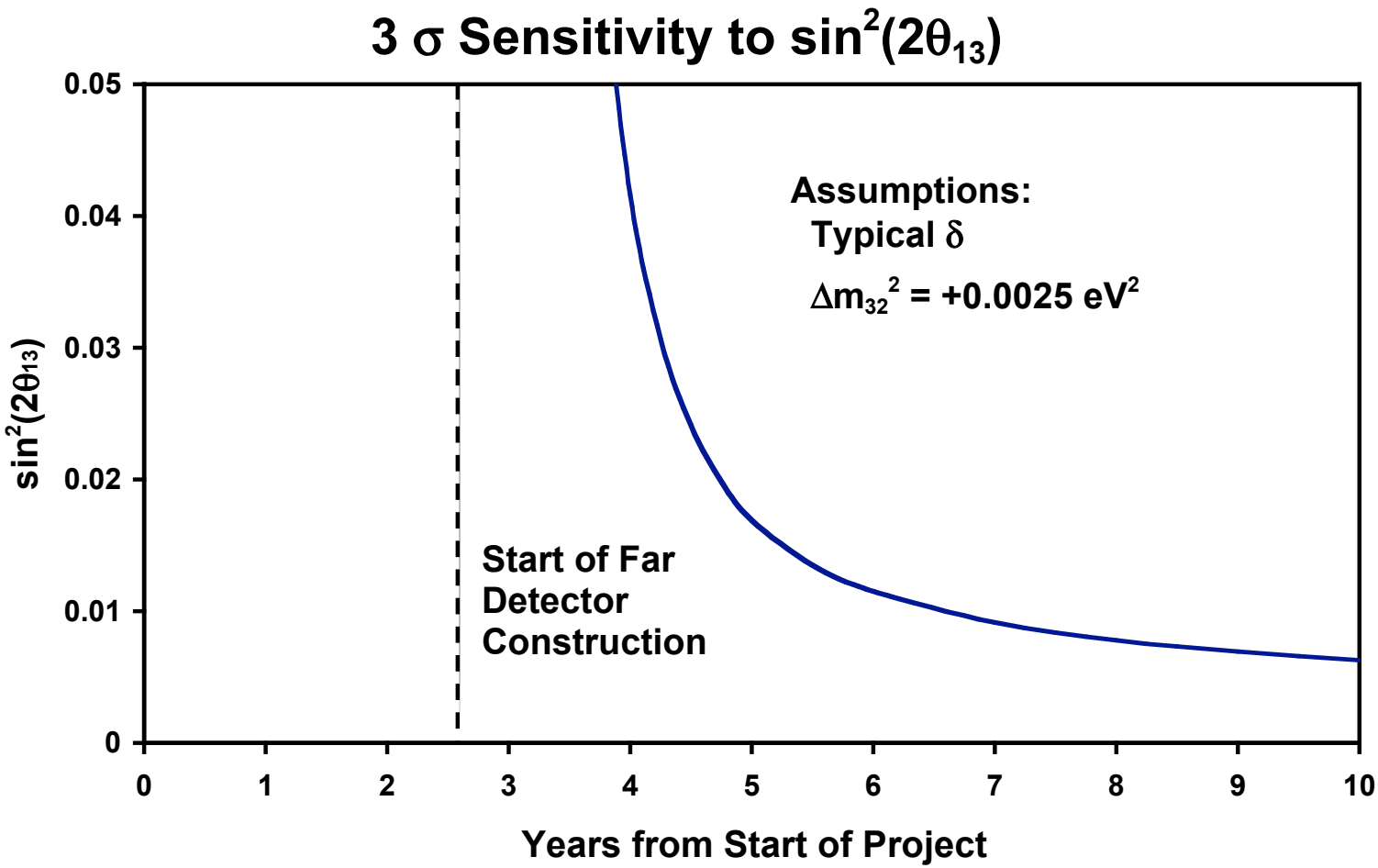
3 σ Sensitivity to $\nu_\mu \rightarrow \nu_e$



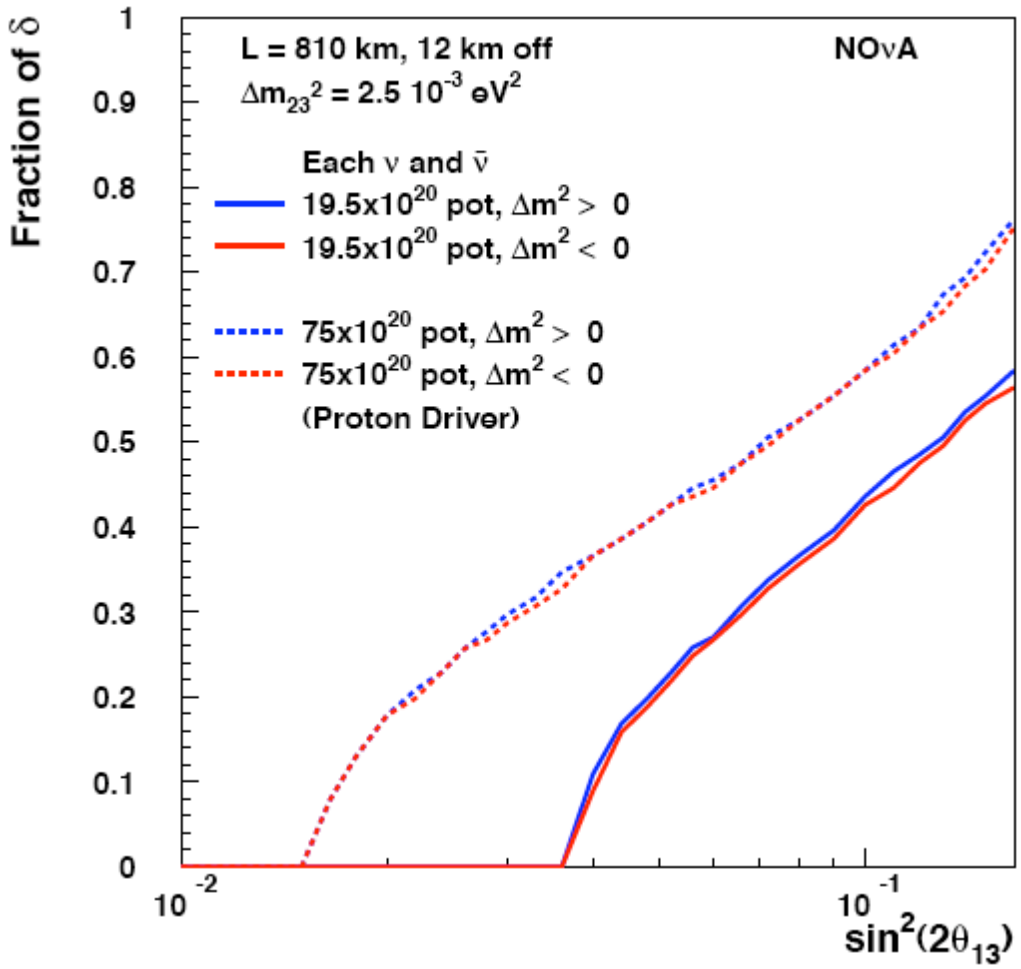


Equivalent figures

Sensitivity vs. Time



2 σ Resolution of the Mass Hierarchy

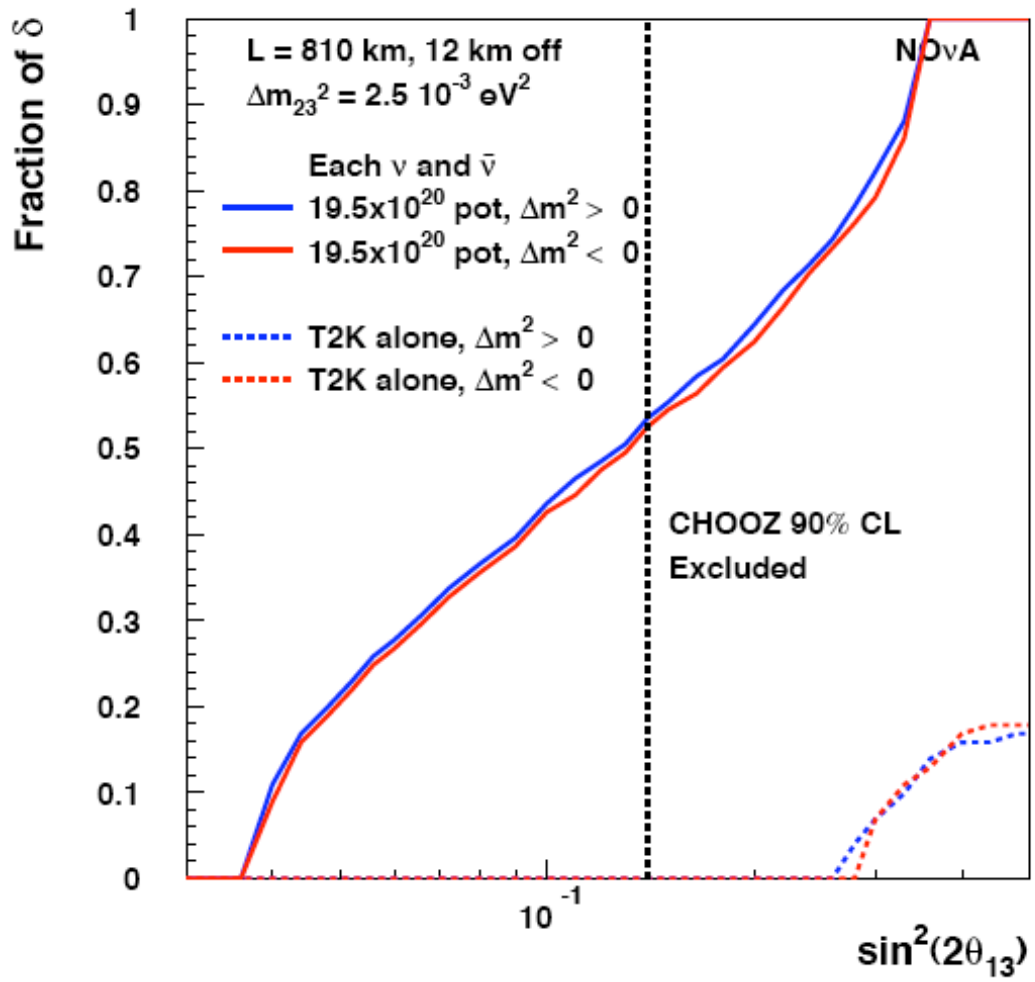


3 years each ν and ν-bar runs

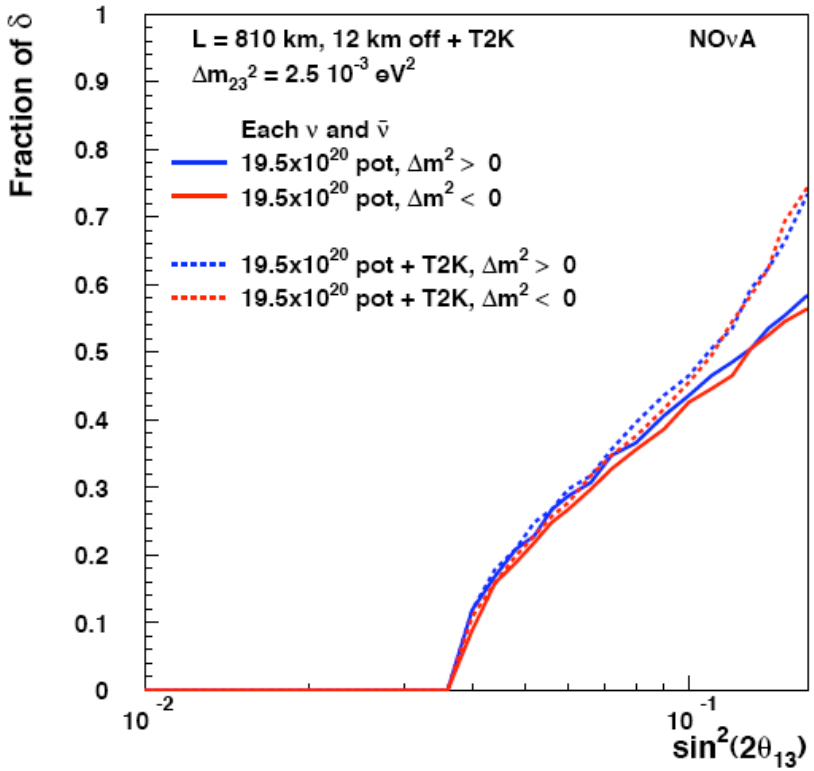
22:1 odds

Note:
$\Delta m_{21}^2 \sin(2\theta_{12})$ has increased by 16%

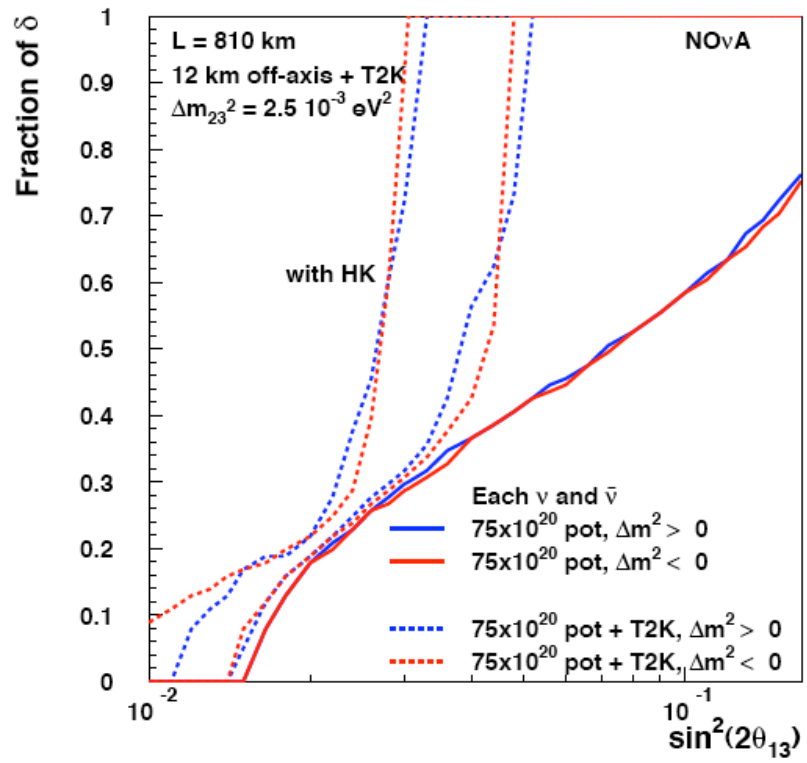
2 σ Resolution of the Mass Hierarchy



2 σ Resolution of the Mass Hierarchy

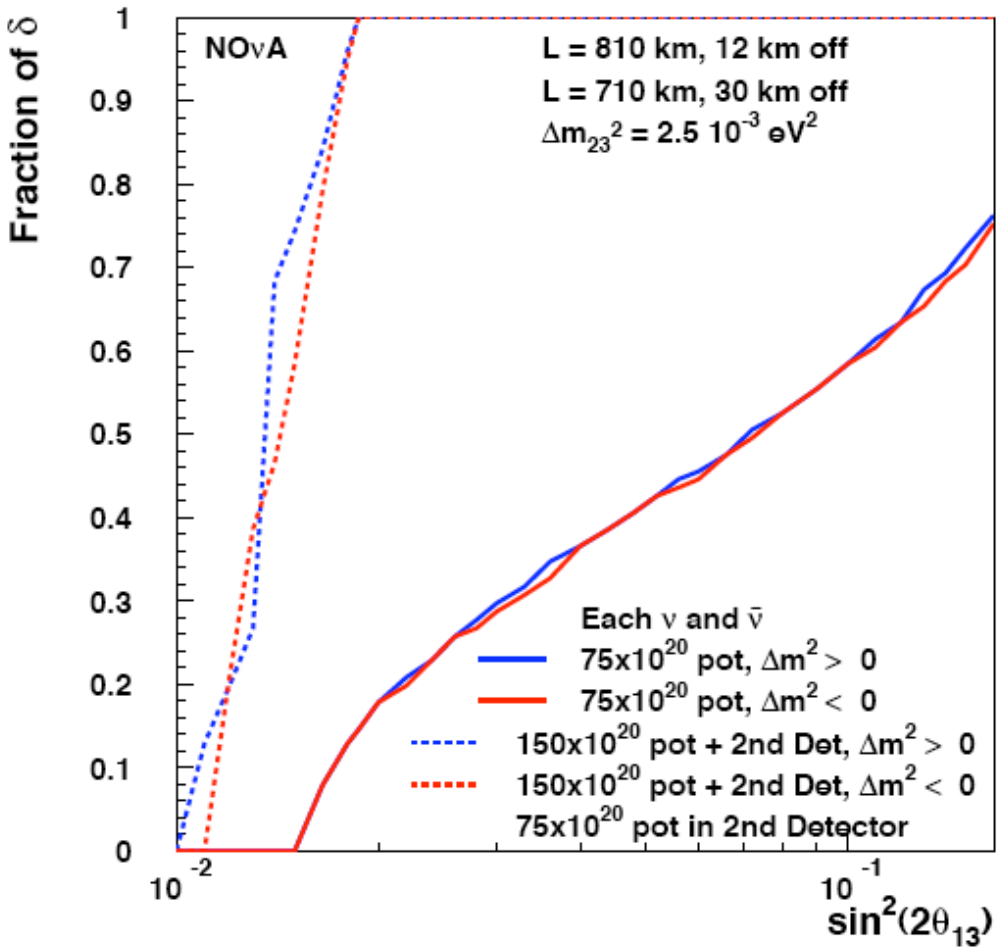


NOνA with T2K Phase 1



NOνA/PD with T2K Phase 2

2 σ Resolution of the Mass Hierarchy

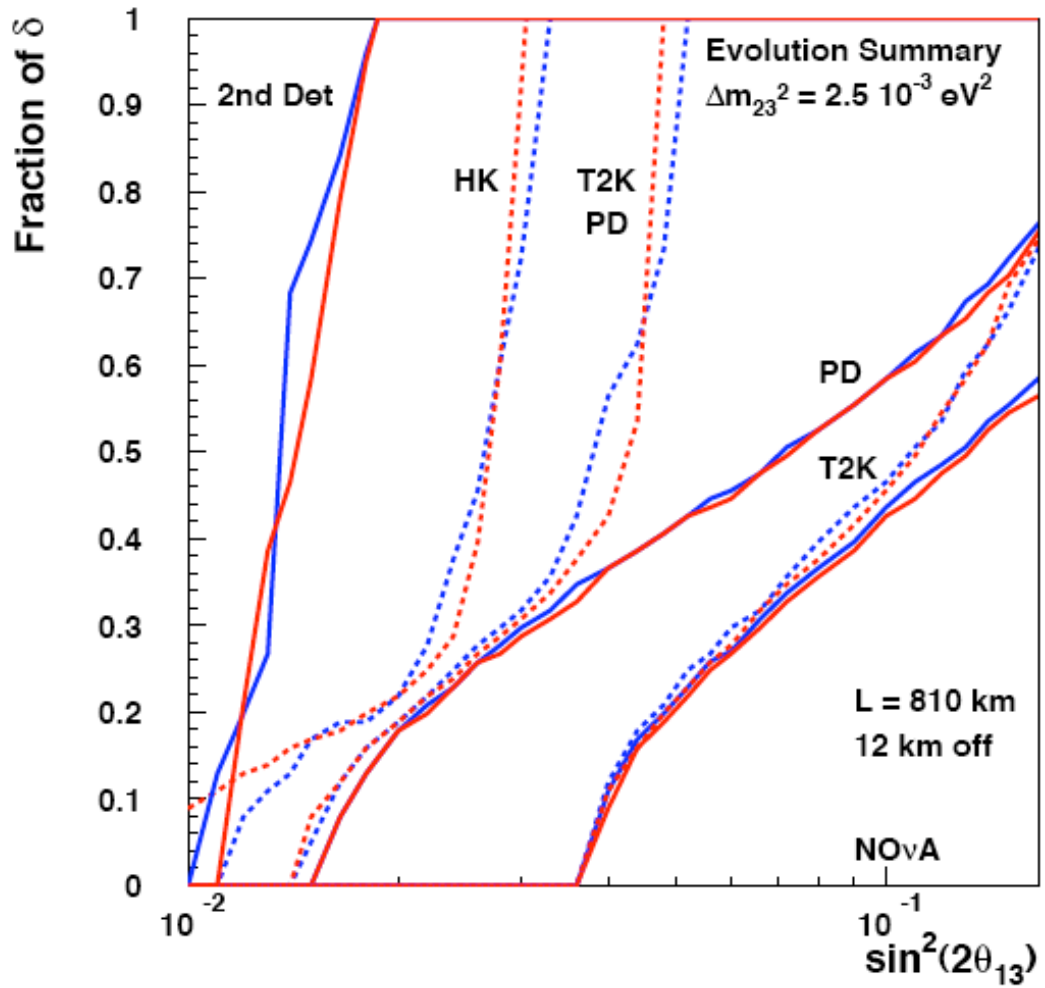


Scenario:

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 NOνA with PD and 6 years of running the second detector.

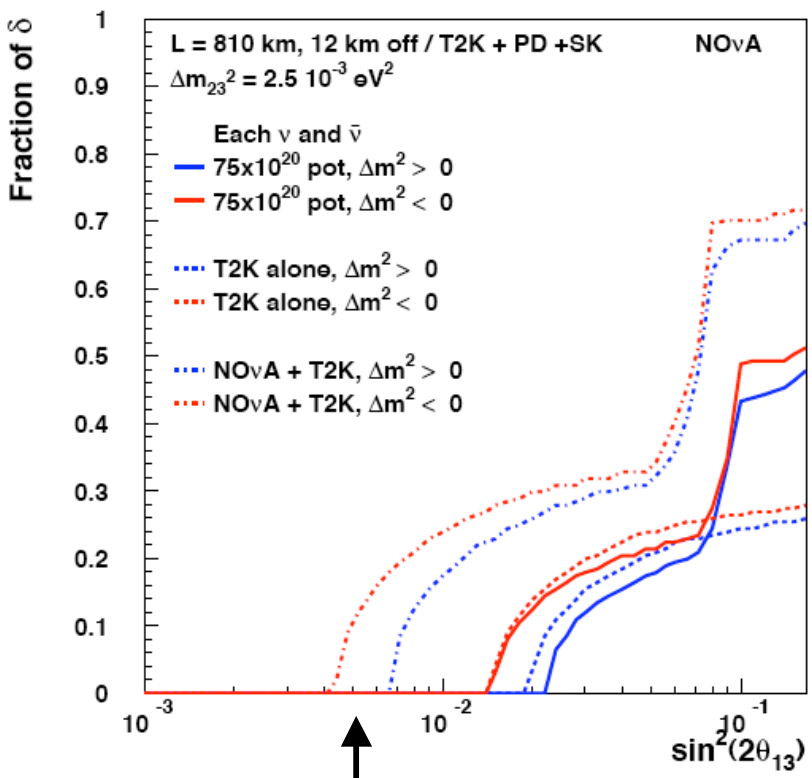
Several technologies possible for the 2nd detector. Use SK as a model for the calculation.

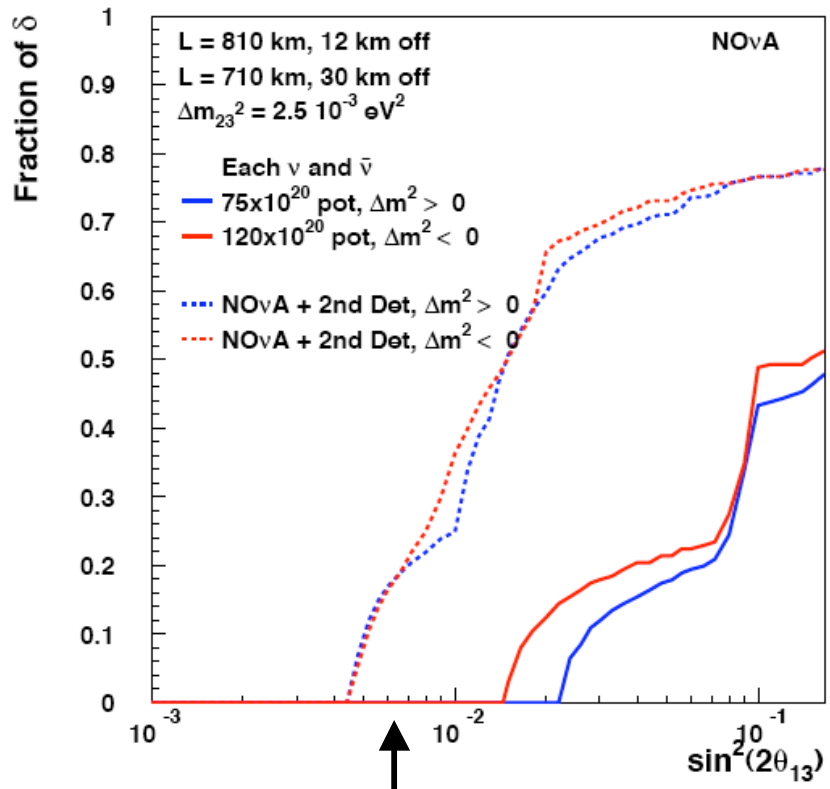
2 σ Resolution of the Mass Hierarchy



Summary plot

3 σ Determination of CP Violation

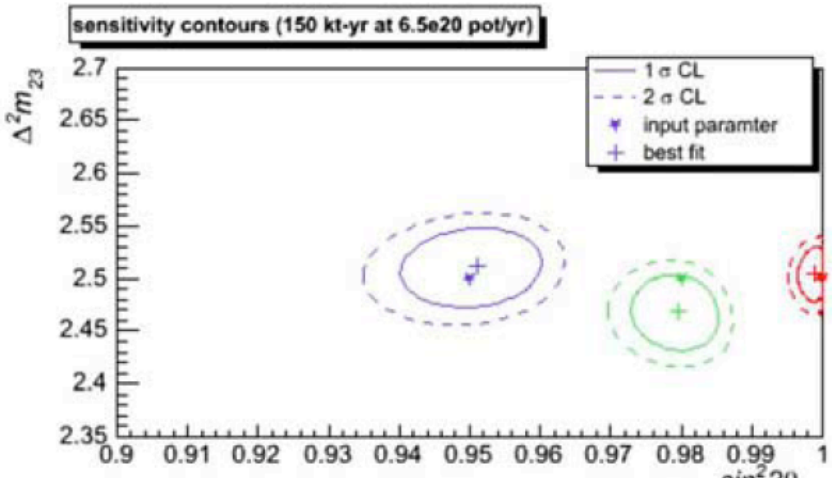




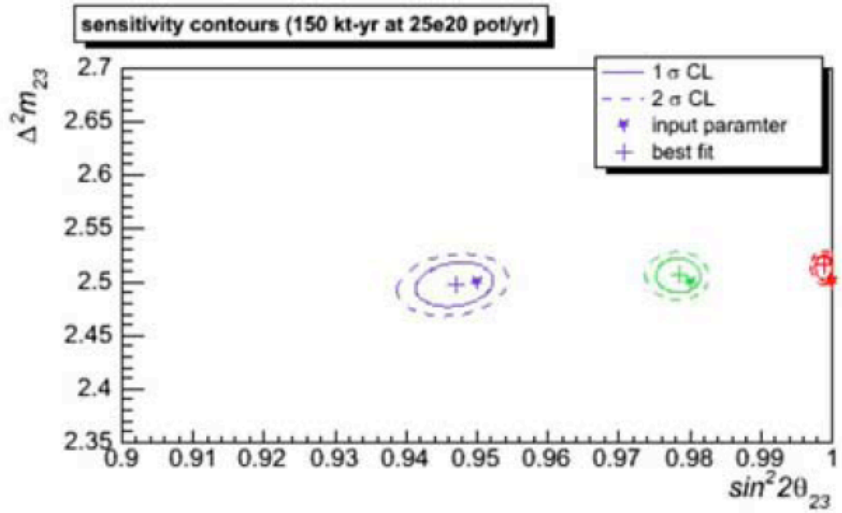
NOνA with upgraded T2K to SK

NOνA with 2nd NuMI off-axis detector

Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$

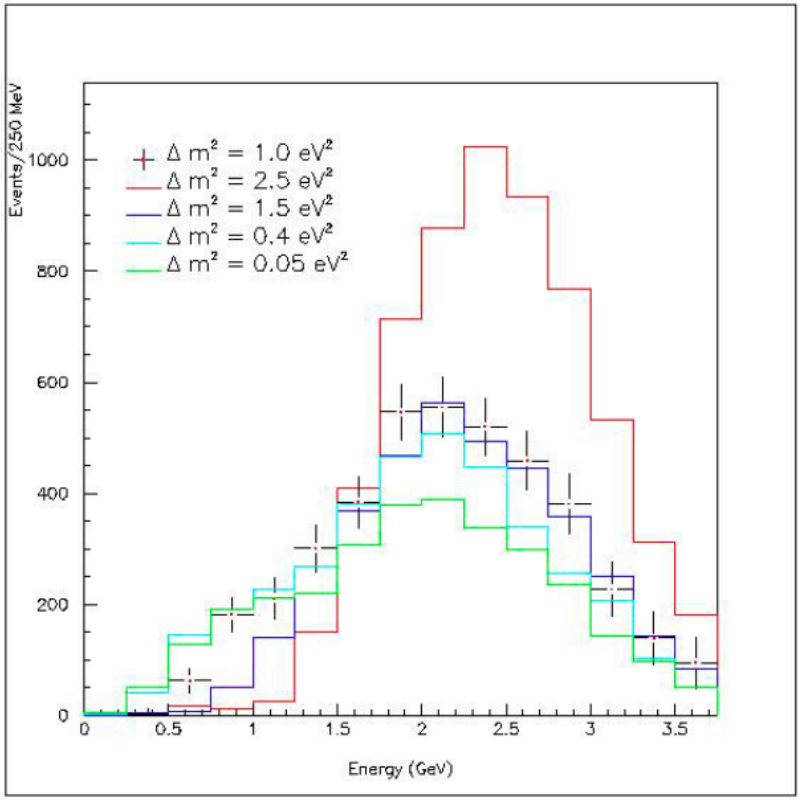


5-year ν run

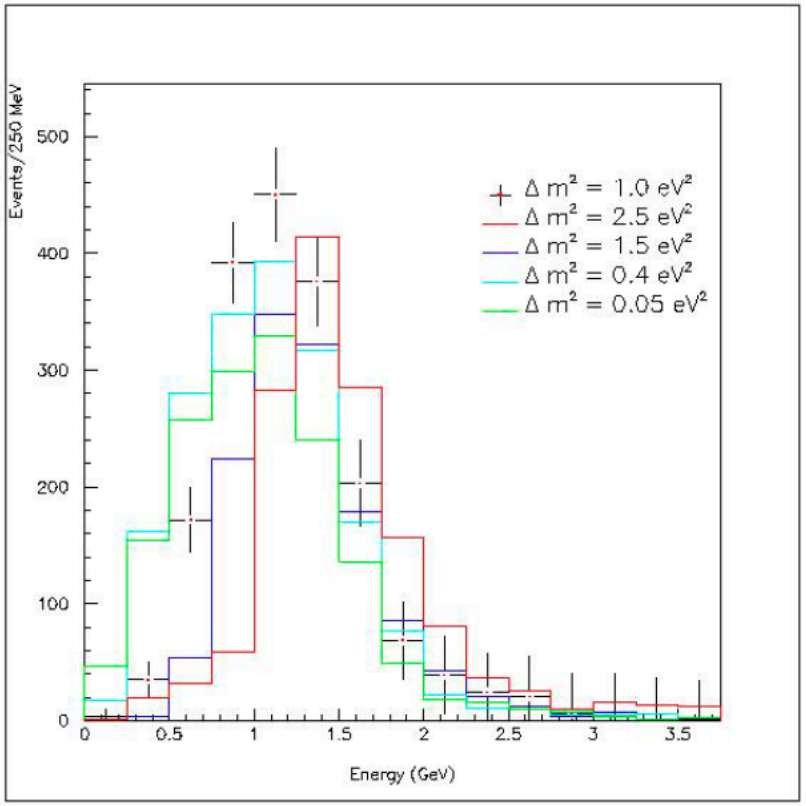


5-year ν run
with Proton Driver

Study MiniBooNE Signal



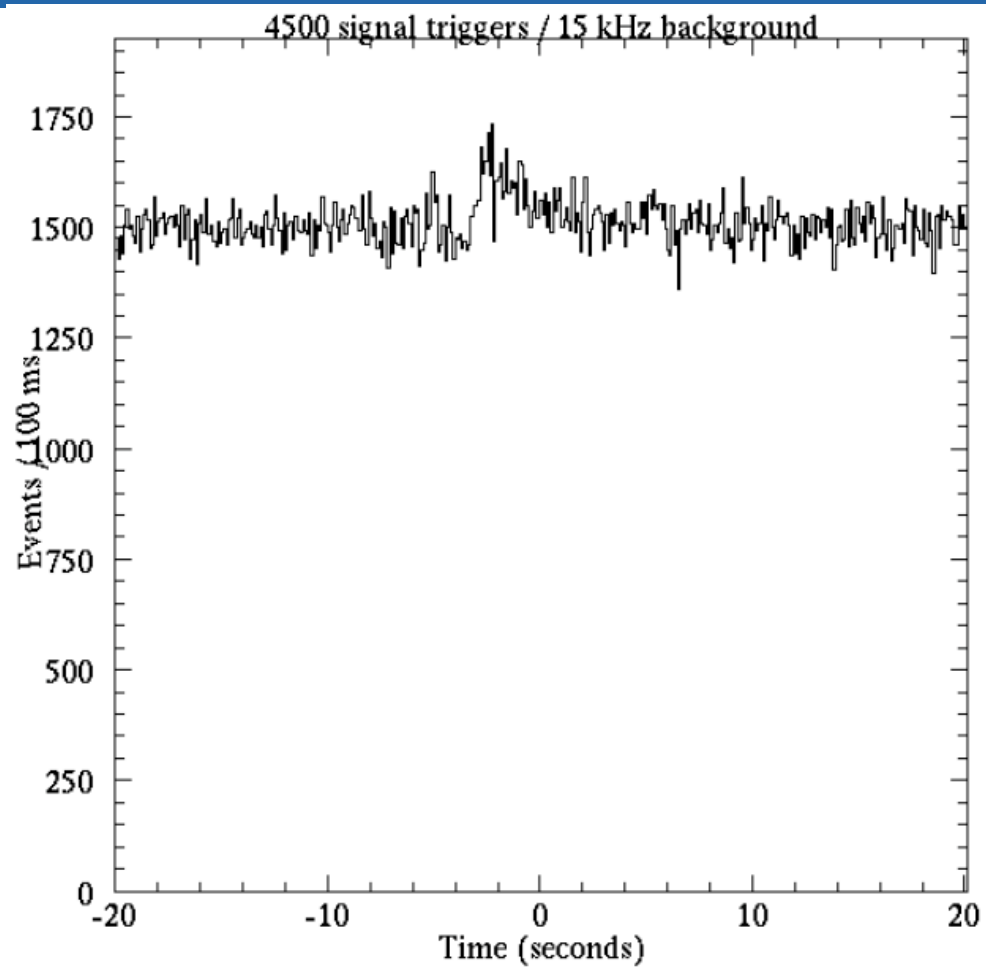
Site 1.5



Site 3

1-year ν run

Sensitivity to a Galactic Supernova



1800 events in the 1st second for a supernova 10 kps away

Conclusion

- NOνA provides a flexible approach to studying all of the parameters of neutrino oscillations
  - A long baseline approach is crucial in the context of the world program.
  - NOνA is the first stage of a flexible program where 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.
  - The full range of the NOνA/NuMI program is comparable to that of other conventional approaches.
  - NOνA can be started now.

Request

- NOνA is a stronger experiment than T2K, yet we have had no success in recruiting European collaborators. Why?
- Because they have not yet seen a Fermilab and US commitment to the experiment.
- To recruit new collaborators, and to make the strongest case to NuSAG and EPP2010, it would be quite helpful to have PAC approval at this meeting.