NOνA with the Proton Driver

Fermilab Proton Driver Workshop
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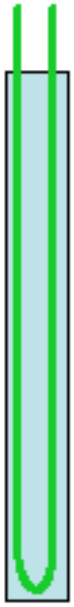
The NOνA Experiment

- As Boris explained yesterday, the key to determining the unknown parameters of the νSM, $\sin^2(2\theta_{13})$, $\text{sign}(\Delta m_{32}^2)$, and δ, is the measurement of $\nu_\mu \rightarrow \nu_e$ oscillations.
- NOνA is a proposed 2nd experiment for the NuMI beamline
  - 14 mrad off-axis to give a narrow-band beam around the 1st oscillation maximum
  - 50 kT (or alternatively 25 kT)
  - optimized for electron detection

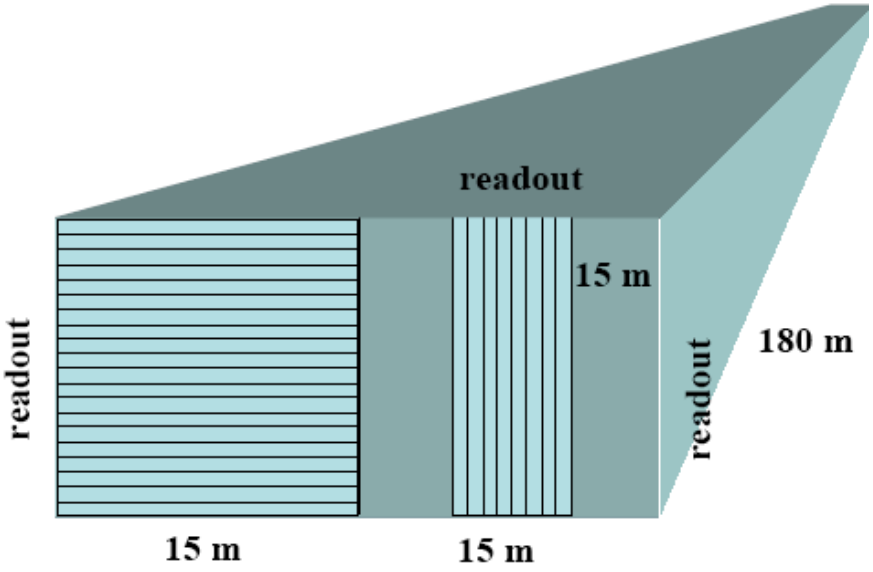
Baseline Detector

50 kT

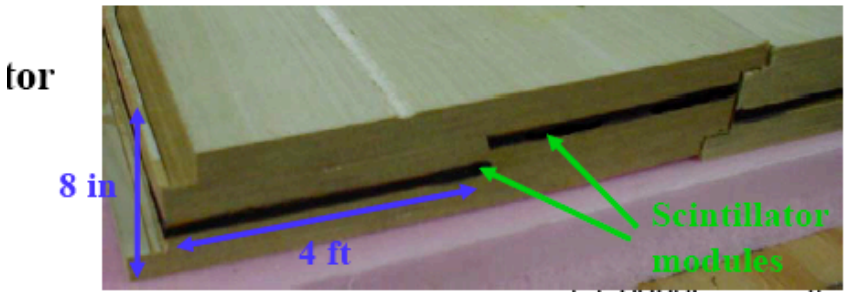
Liquid Scintillator:
1.2 m x 3 cm x 14.4 m
30-cell PCV extrusions,
24 extrusions/plane,
750 planes
= 18,000 extrusions
= 540,000 channels
U-shaped WLS fiber
Into APD readout →



Absorber:
20 cm particleboard/
plane (~1/3 X_o)



800 planes X, absorber, Y, absorber, … = detector

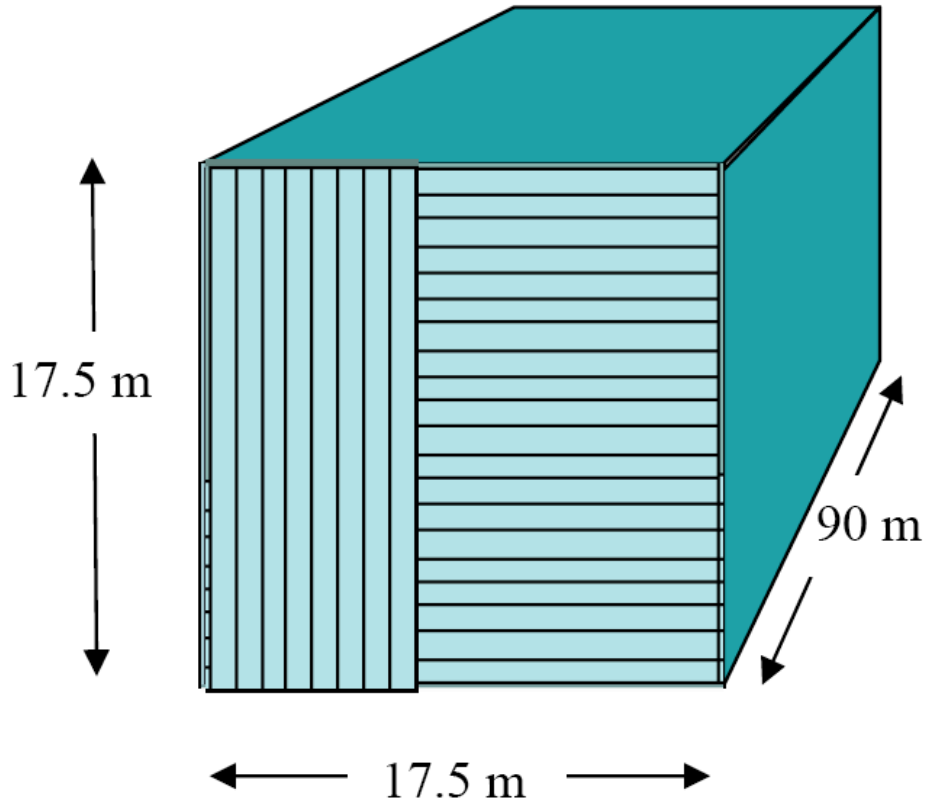


Alternative Under Study: Totally Active Scintillator Detector (TASD)

25 kT

Liquid Scintillator:
1.28 m x 4.9 cm x 17.5 m
32-cell PCV extrusions,
14 extrusions/plane,
1845 planes
= 25,830 extrusions
= 826,560 channels
U-shaped WLS fiber into APD readout

Absorber: None

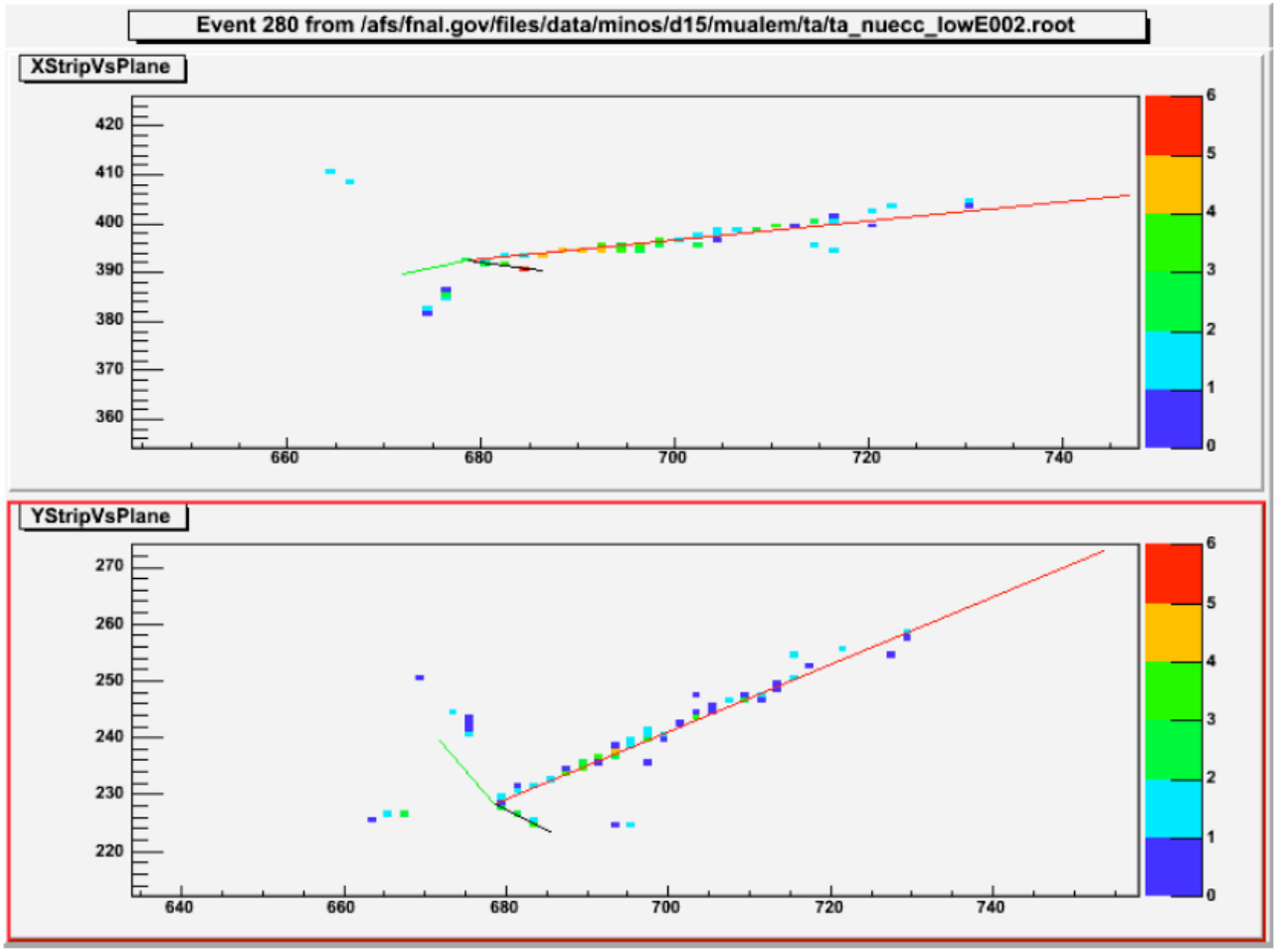


Comparisons

	Baseline	TASD
Mass	50 kT	25 kT
Optimized ν_e efficiency	18%	32%
Optimized s/b	4.8	7.7
FoM	24.5	24
Cost	$147M	$159M

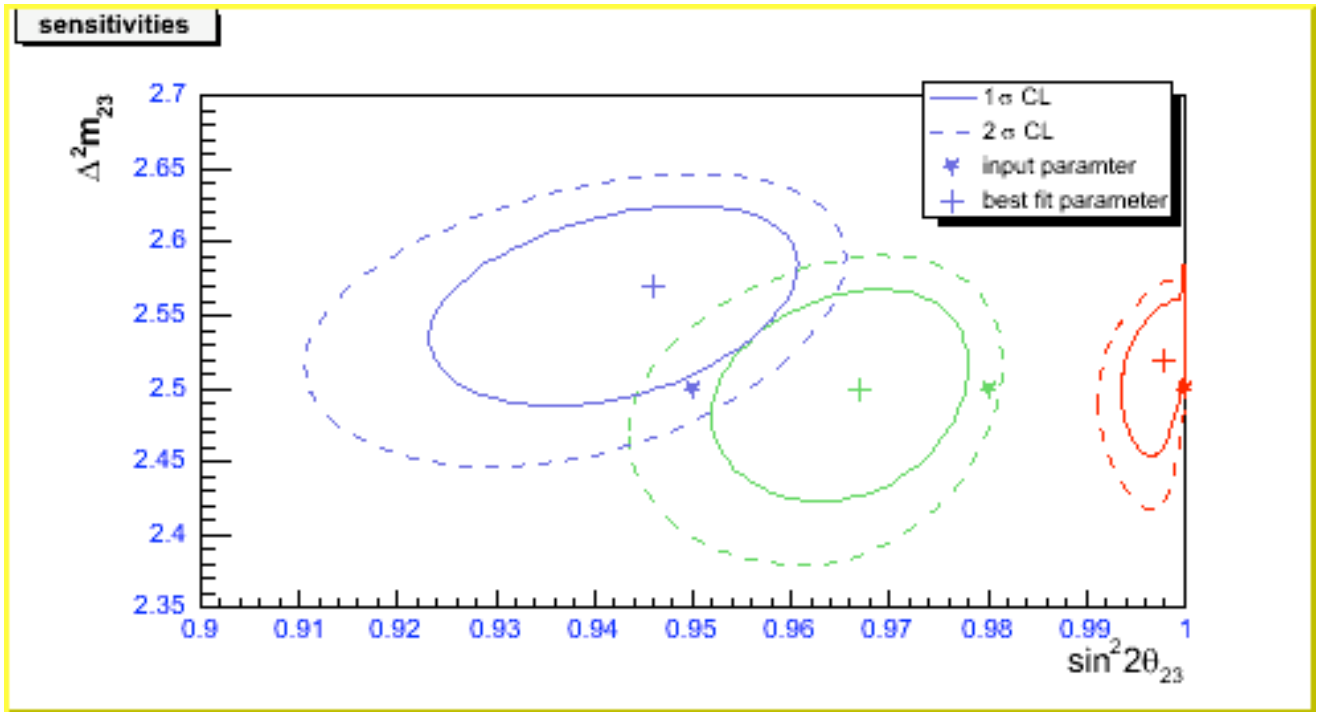
No obvious drawbacks to TASD so far.

Typical TASD Event: $\nu_e A \rightarrow p\, e^- \pi^0$, $E_\nu = 1.65$ GeV



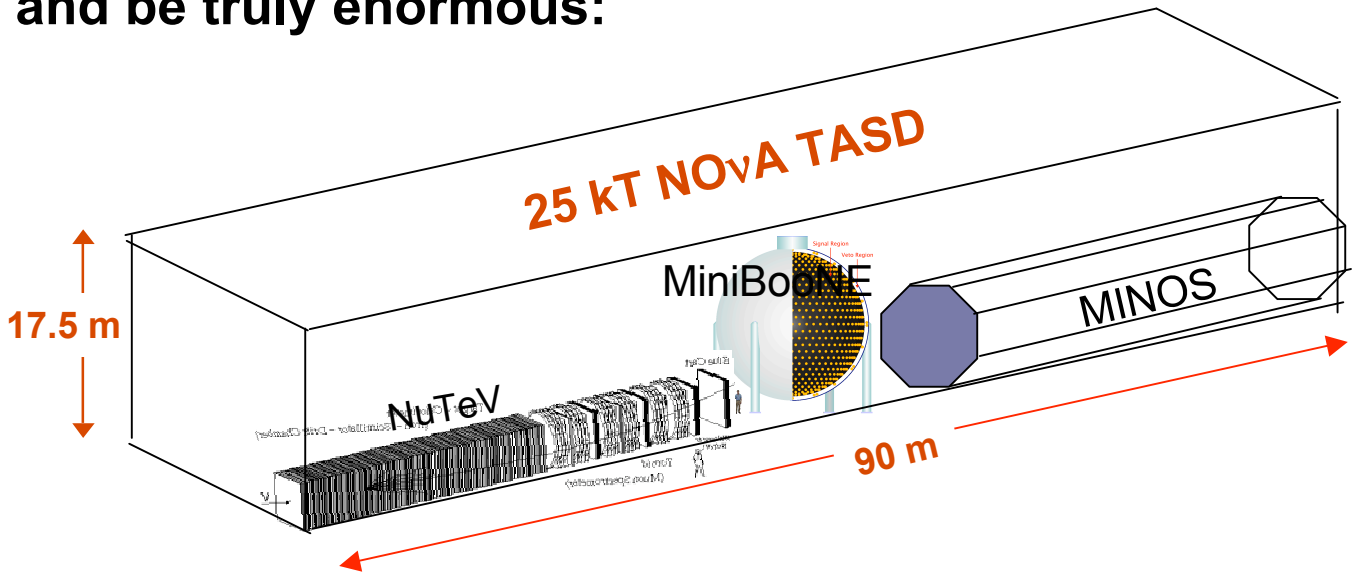
Bonus Physics with TASD

- **Better resolution gives many bonuses**
  - **Excellent measurement of $\sin^2(2\theta_{23})$**



Statistically Limited

- **NOνA will be statistically limited. Thus, the power of the experiment is proportional to mass times the neutrino flux.**
- **Assume 4 x 10^{20} pot/yr without the PD and 20 x 10^{20} pot/yr with the PD, a factor of 5.**
- **Same effect as building 5 NOνA's, but would cost 600 M$ more and be truly enormous:**



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

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

  Atmospheric-solar interference terms — contains the CP violation

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

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

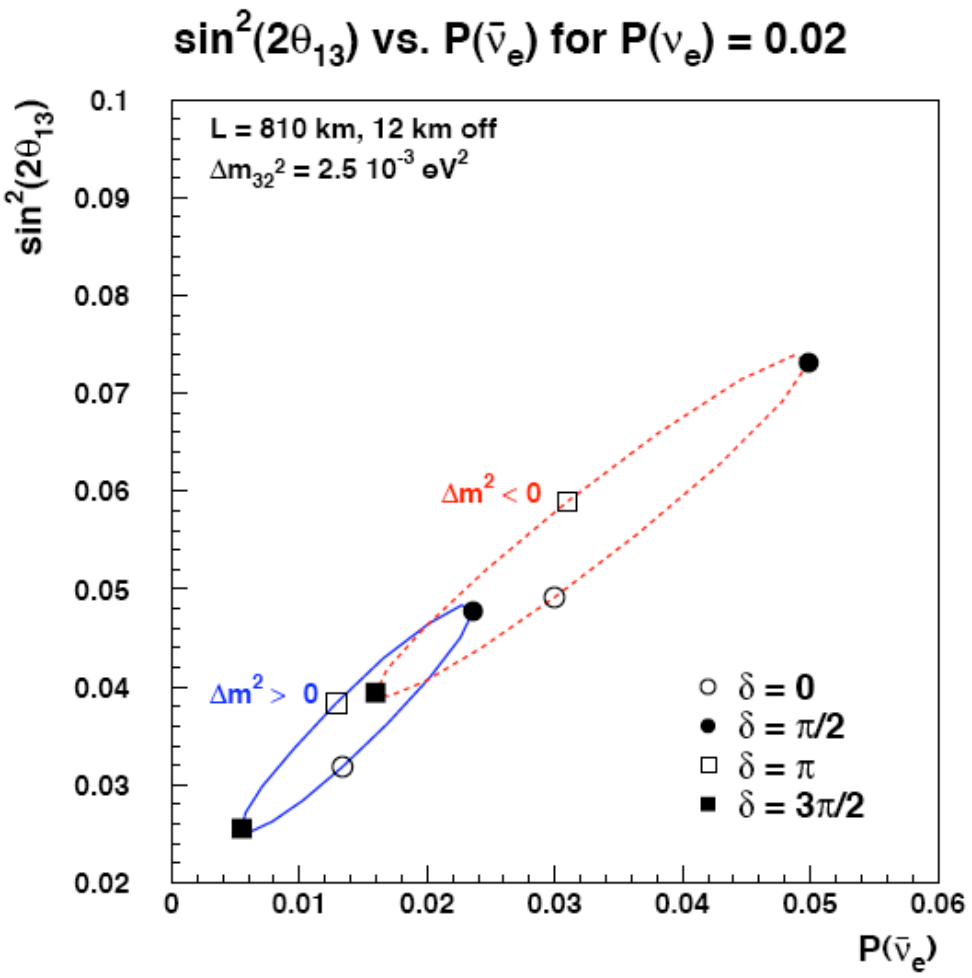
$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- 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.

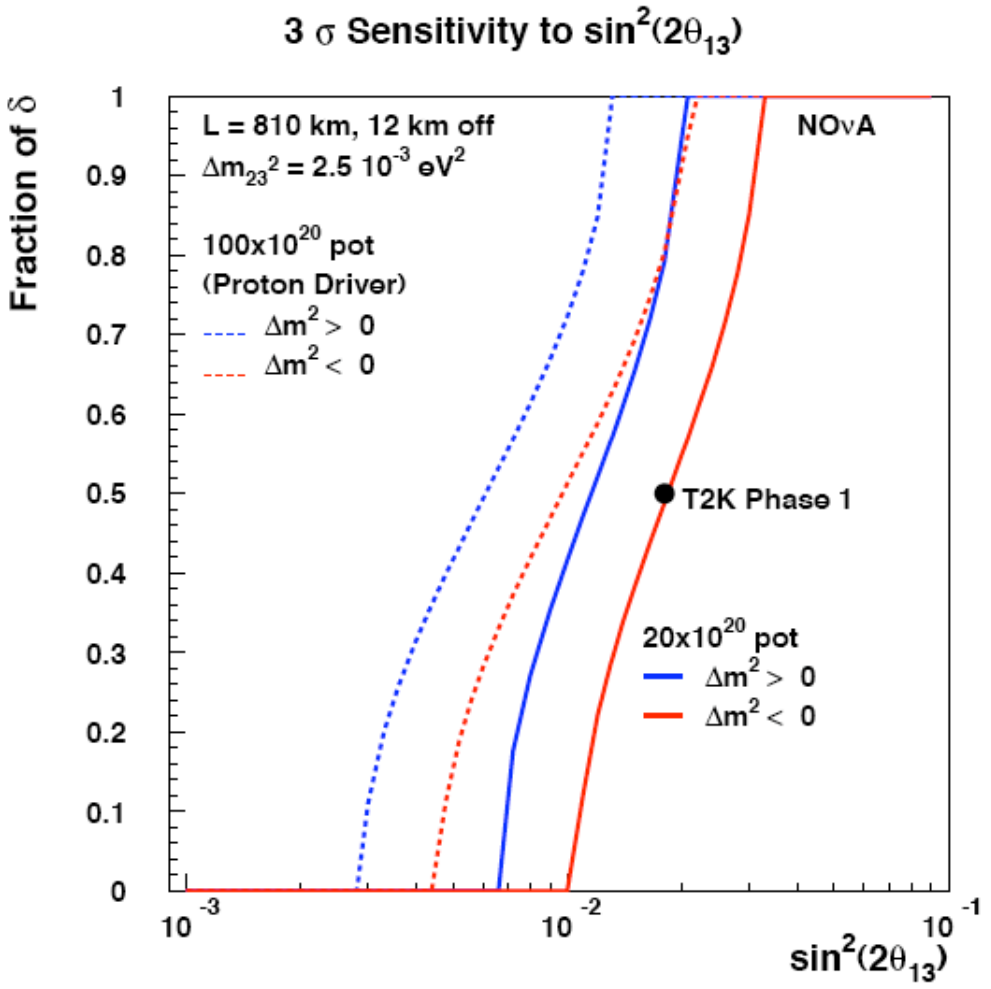
$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2} G_F \rho_e} \approx 11\,\text{GeV for the earth's crust.}$$

About a ±23% effect for NuMI, but only a ±11% effect for JPARC .

Probability Plot



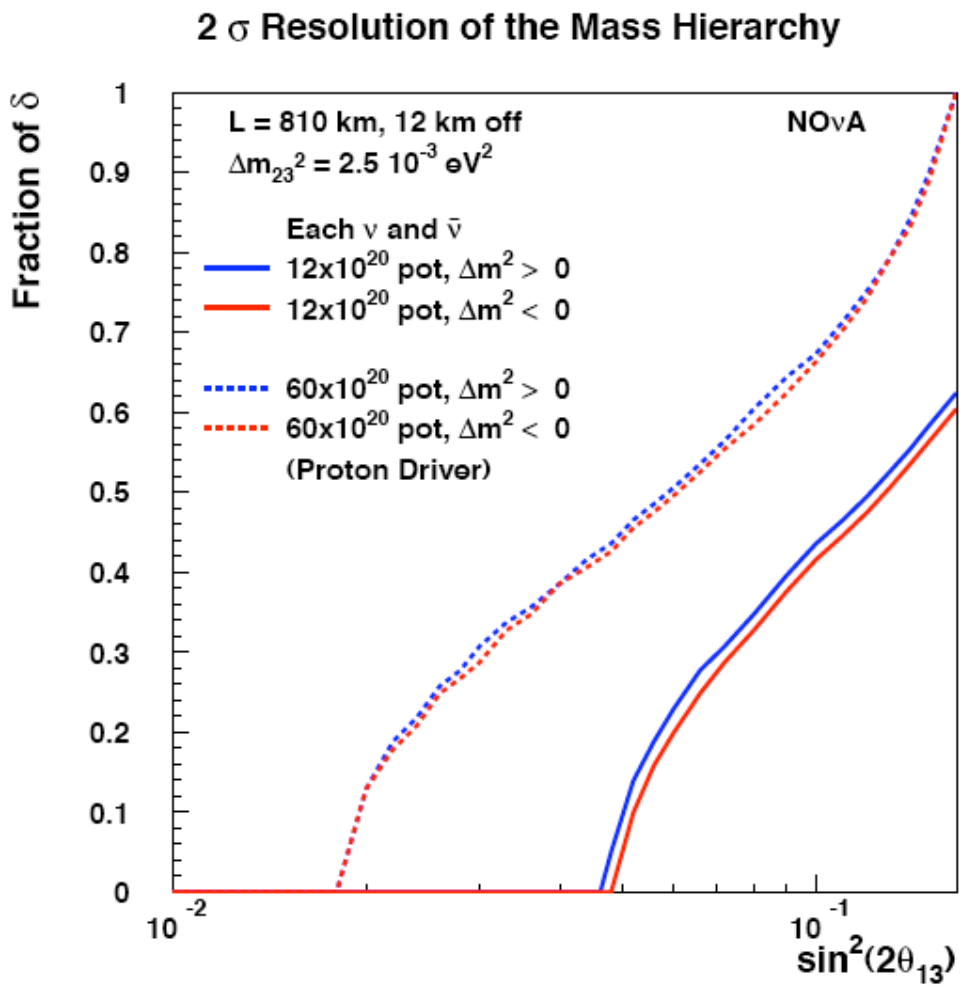
3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$



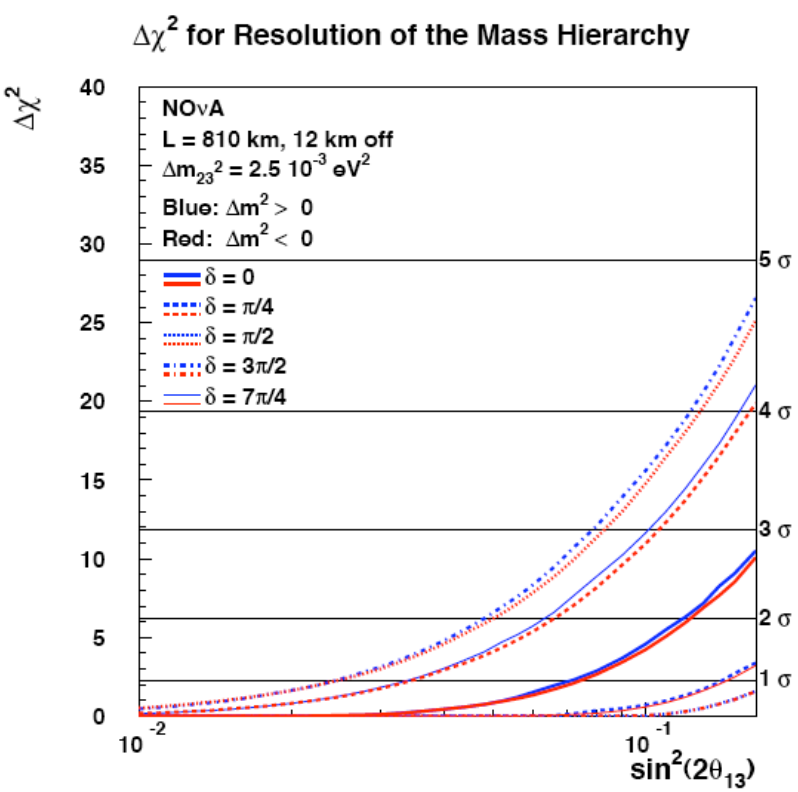
Resolving the Mass Ordering

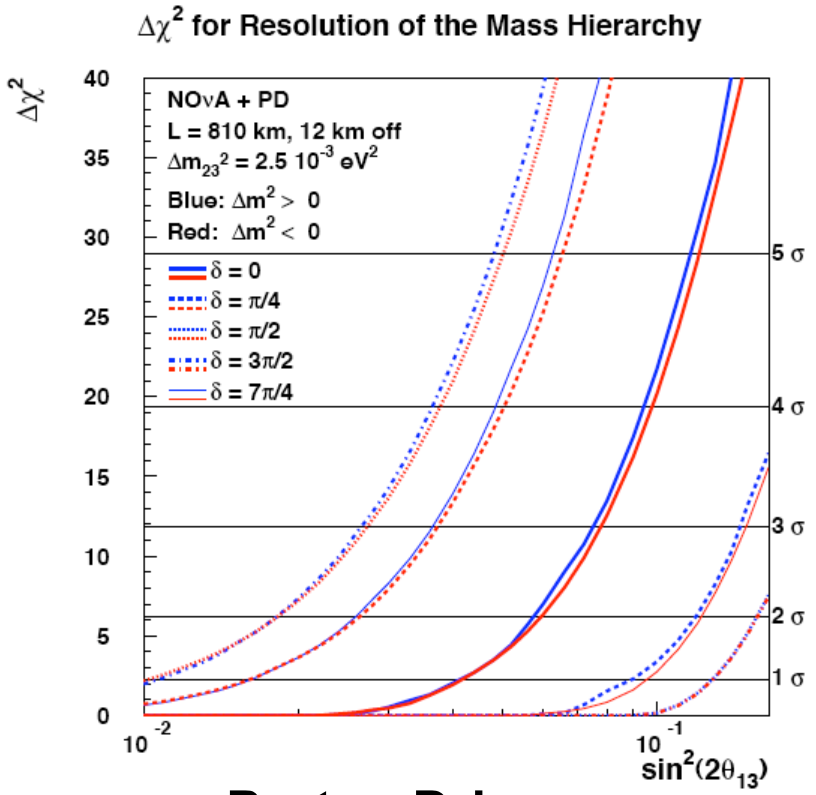
- **The unique contribution of NOνA is resolving the mass ordering using the 810 km baseline.**
- **We can envision a step-by-step program capable of determining the mass ordering for most of the region available to conventional neutrino beams.**

95% CL Resolution of the Mass Hierarchy



Resolution of the Mass Hierarchy

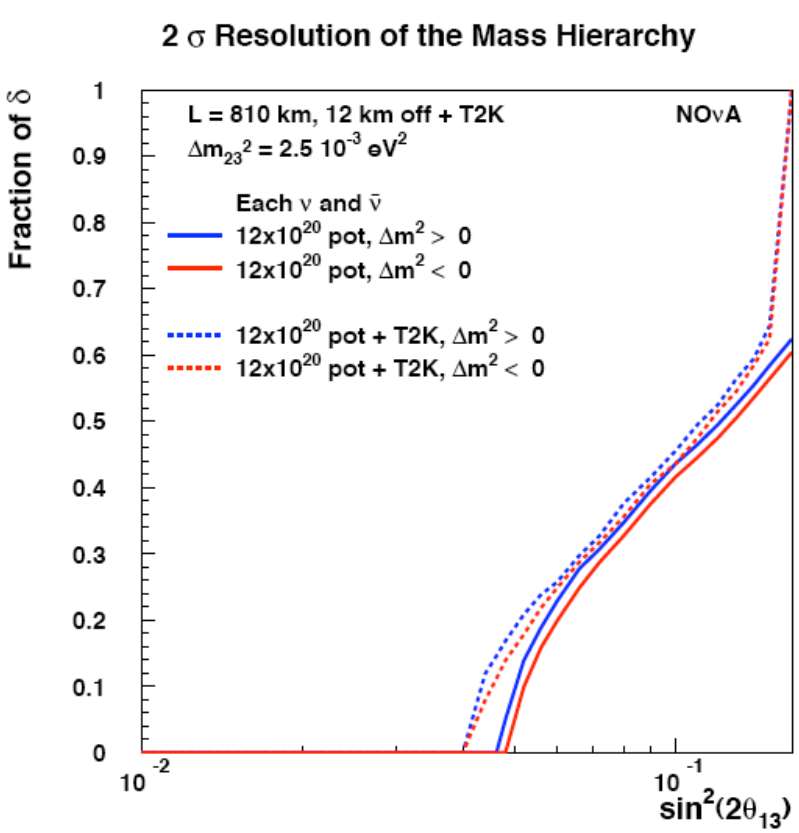


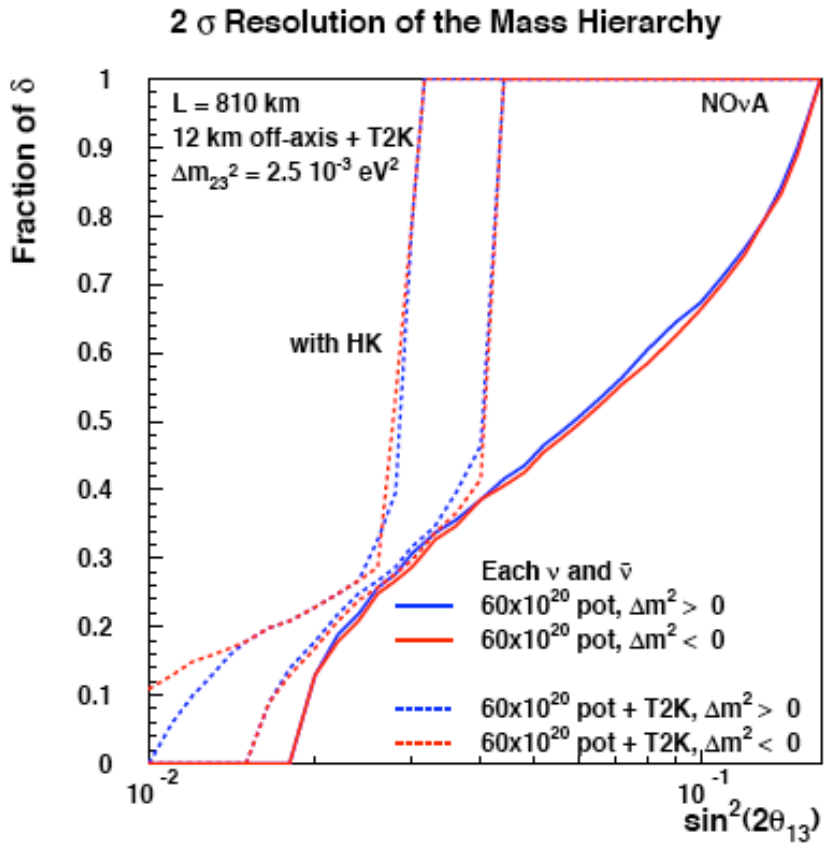


Proton Driver

Note that a Proton Driver changes a 1σ effect into a 3σ effect: $\Delta\chi^2=2.3 \rightarrow \Delta\chi^2=11.8$.

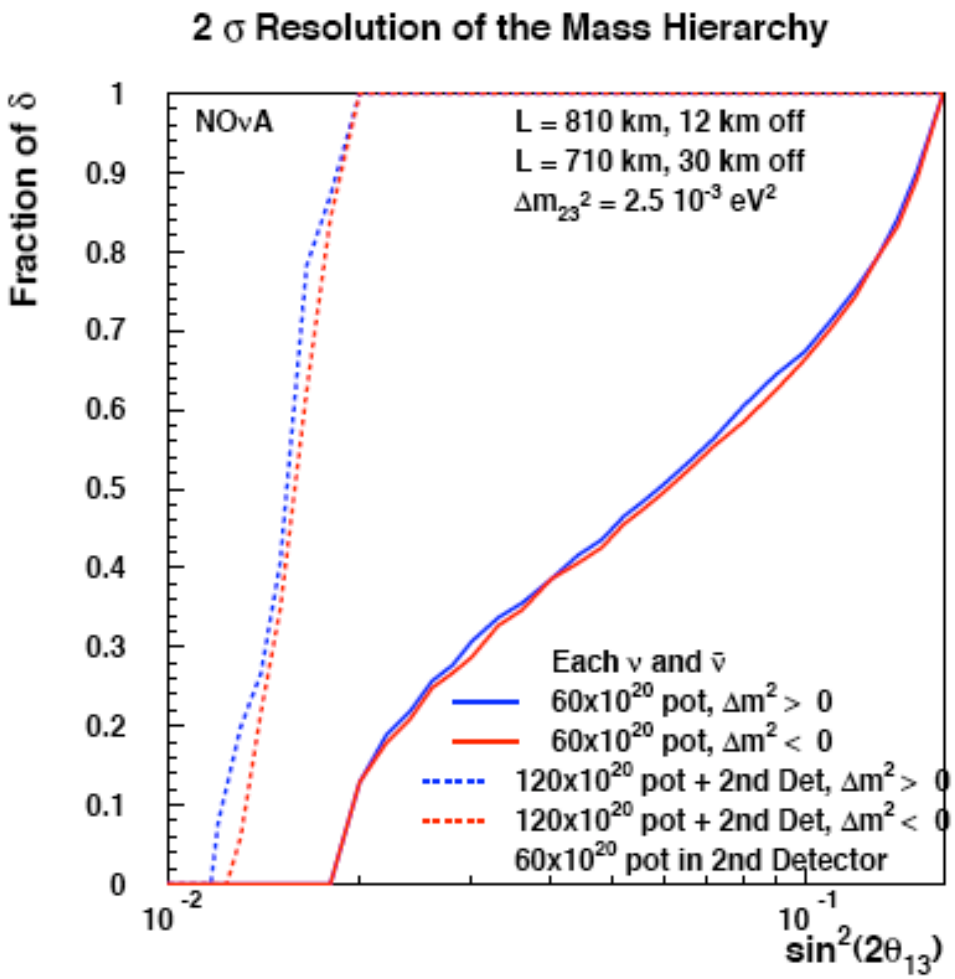
Combination with T2K



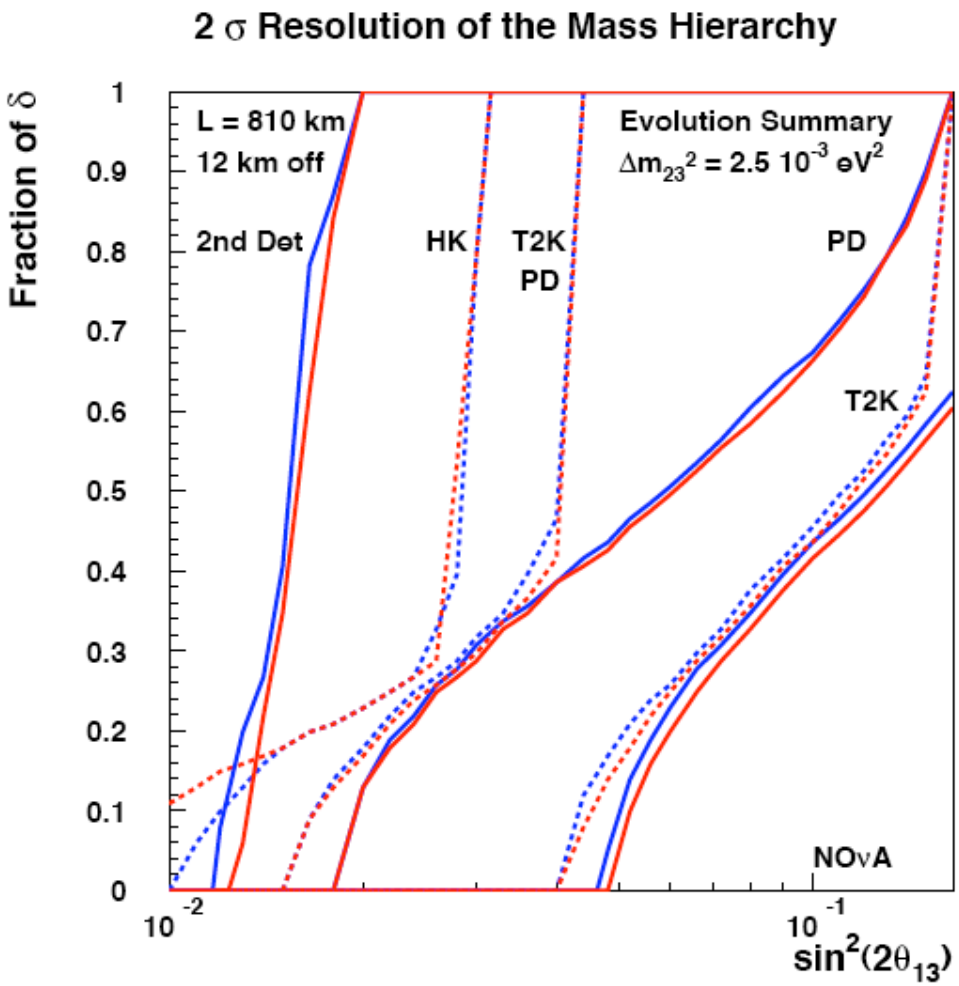


Proton Drivers

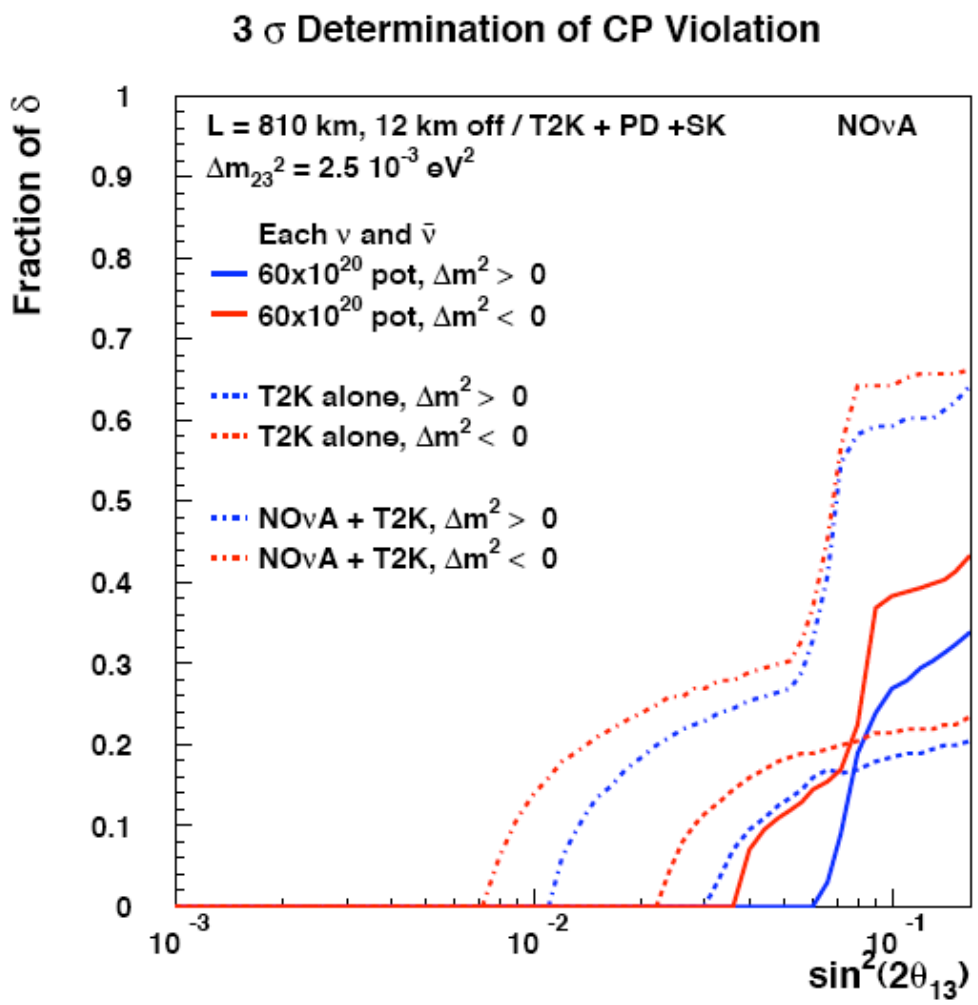
Combination with a 2nd OA Detector at the 2nd Maximum



Mass Hierarchy Resolution Summary



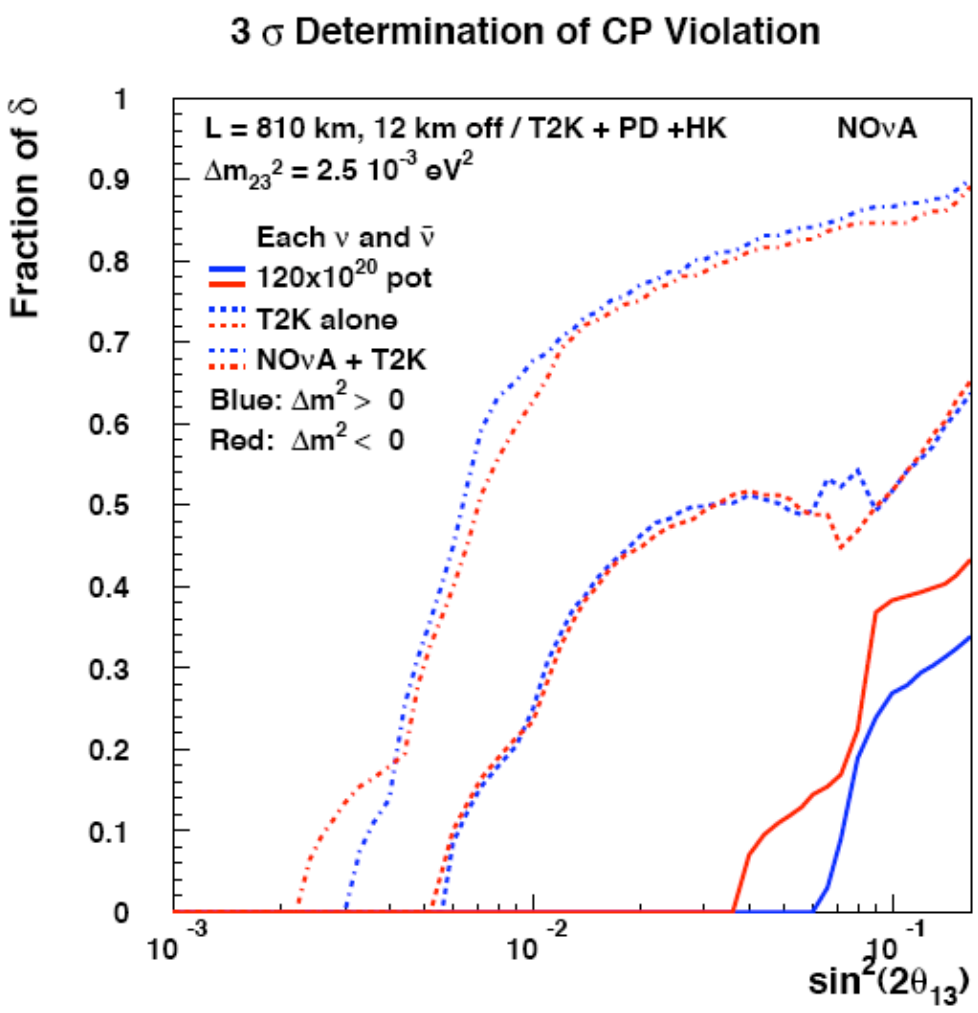
3σ Demonstration of CP Violation



With proton drivers

(No 3σ CP effect in either T2K or NOνA without them.)

3 σ Demonstration of CP Violation



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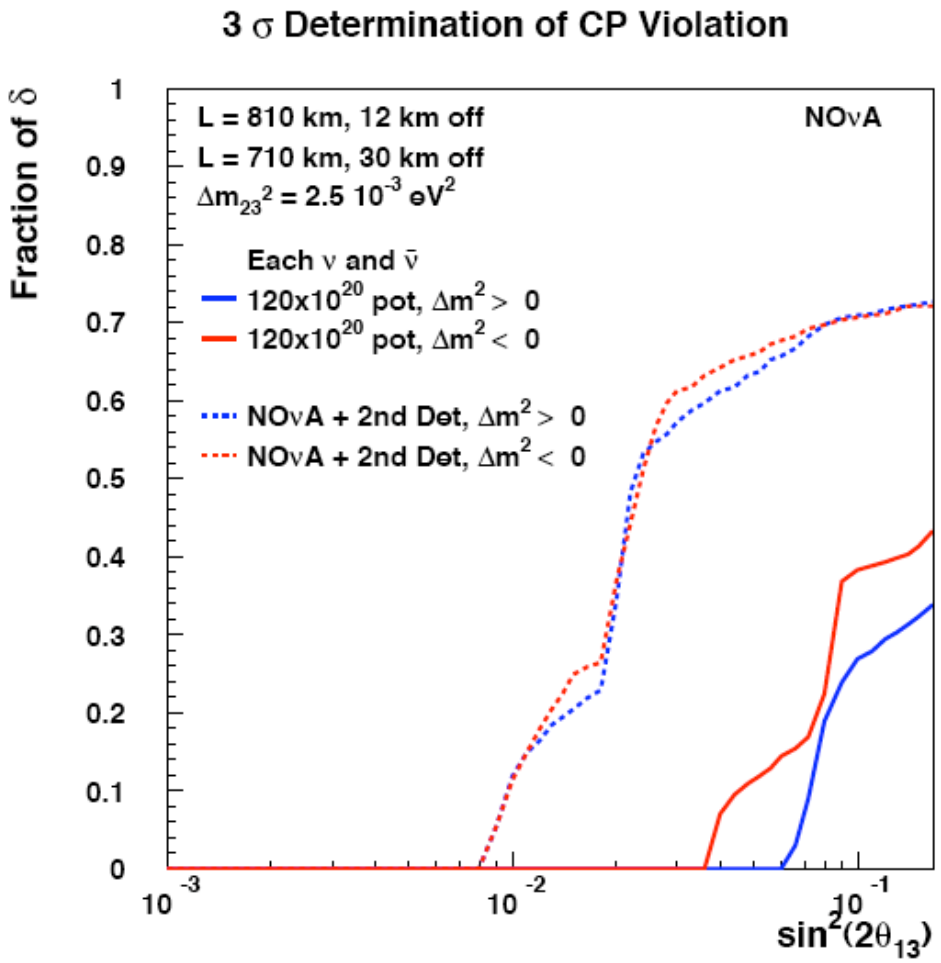
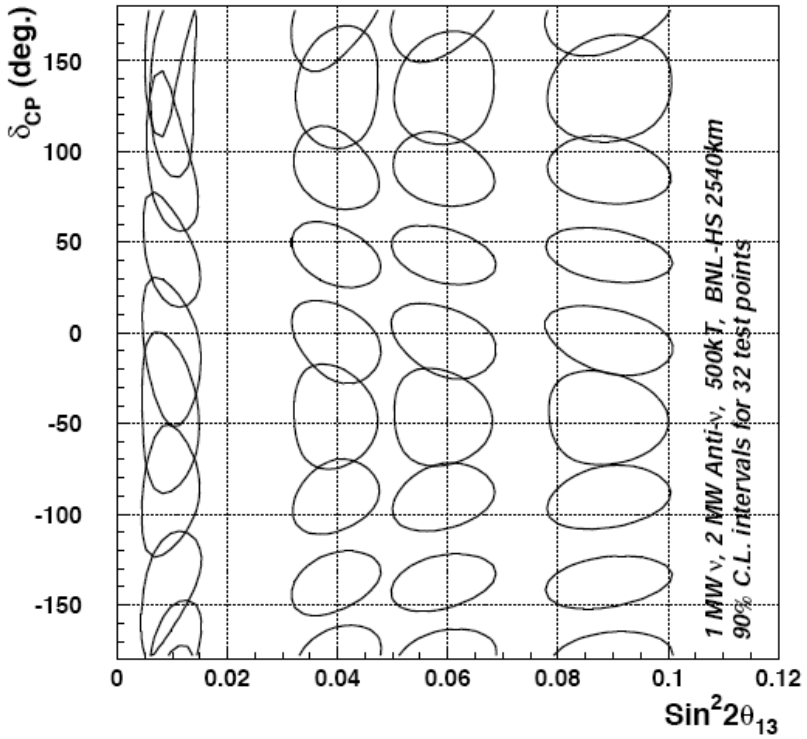
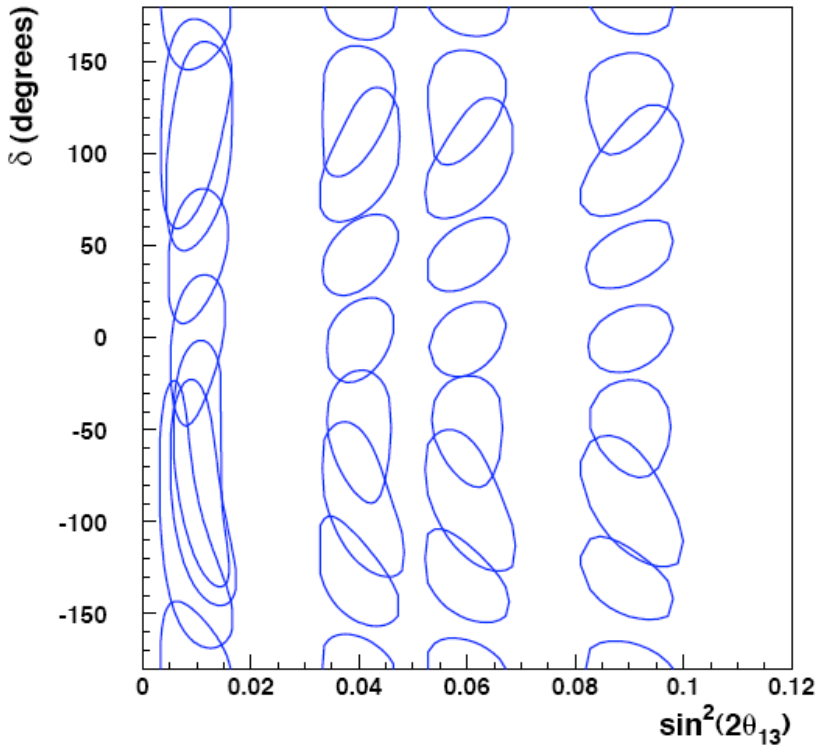


2nd Off-axis detector at the 2nd maximum

90% CL δ vs. $\sin^2(2\theta_{13})$ 5 yrs each ν and anti-ν





BNL Proposal **NOνA + PD + 2nd Det**

Conclusion

- The Proton Driver provides a step-by-step approach to measuring all of the neutrino oscillation parameters.
- At each step, we gain the information necessary to efficiently plan the next step.
- NOνA is central to all of the steps with $\sin^2(2\theta_{13}) >$ 0.01 to 0.02.
- The Proton Driver is central regardless of the value of $\sin^2(2\theta_{13})$.