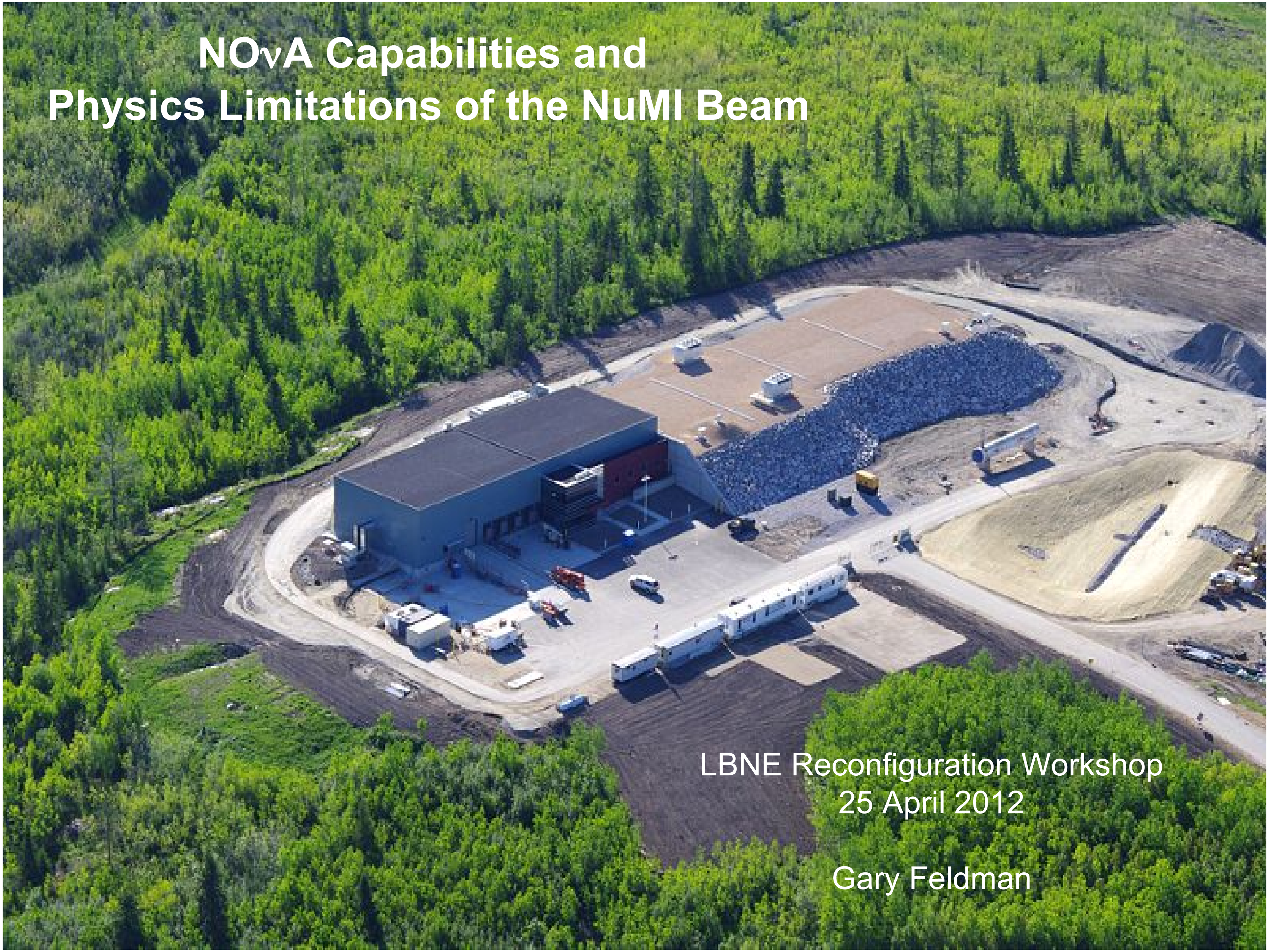
NOνA Capabilities and Physics Limitations of the NuMI Beam



LBNE Reconfiguration Workshop
25 April 2012

Gary Feldman

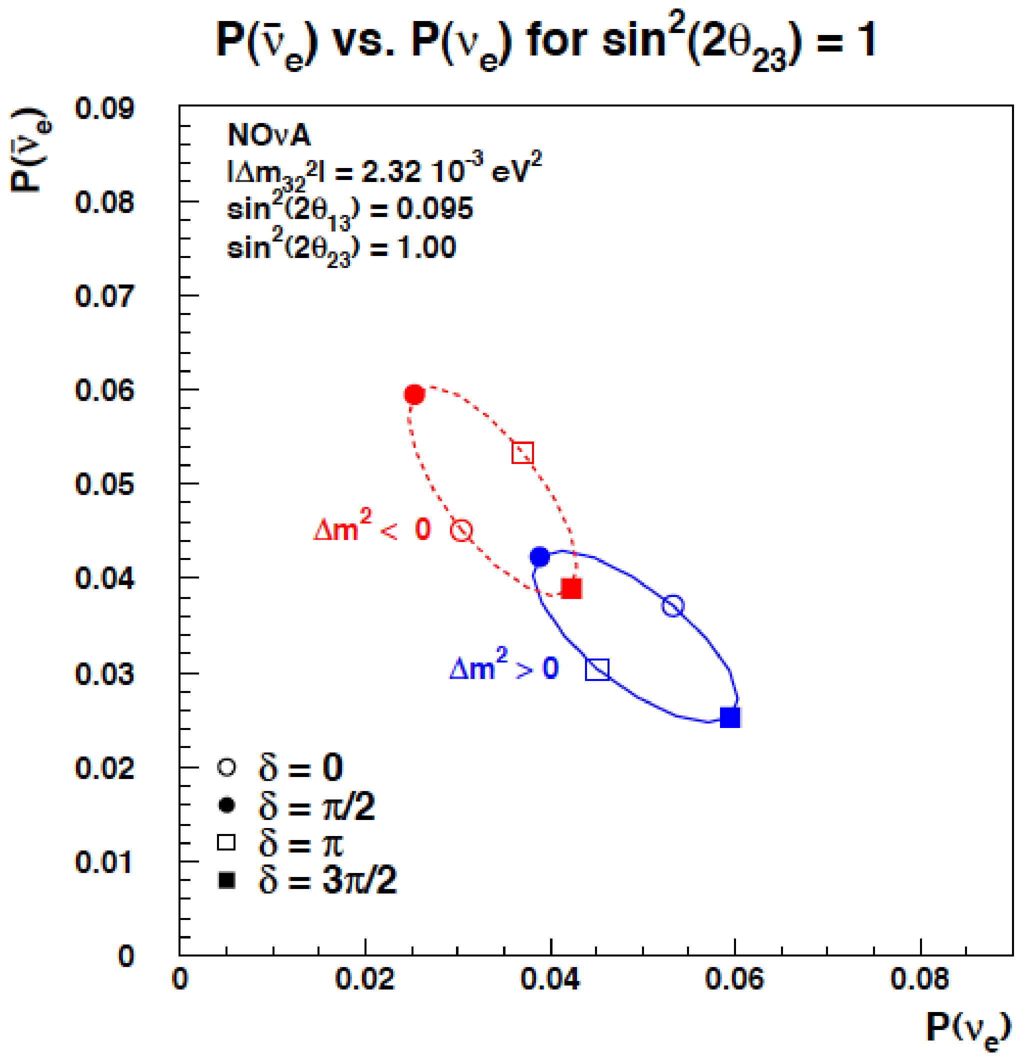
Introduction

- The purpose of this talk is to indicate what we currently think NOνA can accomplish in 6 years of running, and in the process, indicate what the physics limitations of the NuMI beam are for any future experiment on it.

Bi-Probability Plots

- The main tool I will use are bi-probability plots, which show the loci of possible measurements, given a set of parameters, a neutrino energy, and a baseline.
- The fixed parameters will be the well-measured values of the Δm^2's, $\sin^2(2\theta_{12})$, and now $\sin^2(2\theta_{13})$, which I will take to be 0.095. $\sin^2(2\theta_{23})$ will be varied between 0.95 and 1.00.
- The energy will be specified or be 2.0 GeV for NOνA.
- The plots will show the probabilities for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ as a function of the mass ordering (i.e., the sign of Δm_{32}^2) and the CP-violating phase δ.

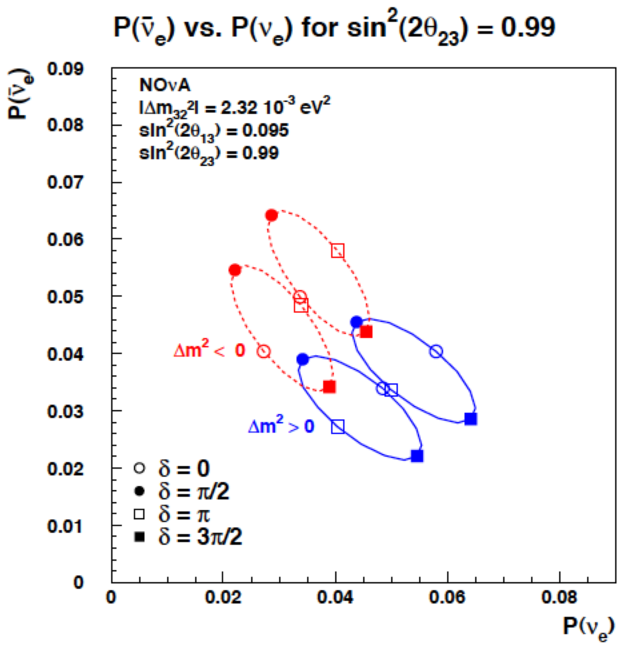
$\sin^2(2\theta_{23}) = 1.00$

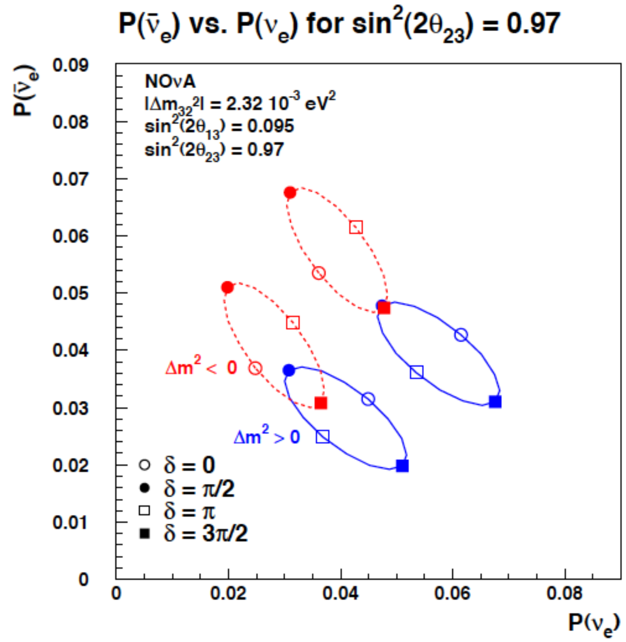


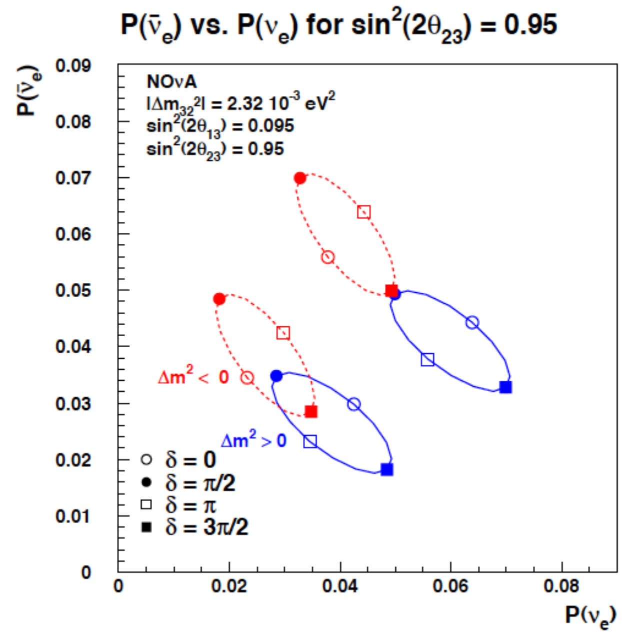
$\sin^2(\theta_{23})$ Term

- $\bar{\nu}_e$ disappearance in a reactor experiment is proportional to $\sin^2(2\theta_{13})$.
- However, $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance in an accelerator experiment is proportional to $\sin^2(\theta_{23})\,\sin^2(2\theta_{13})$, to first order.
- If $\sin^2(2\theta_{23}) \neq 1.0$, there is an ambiguity as to whether θ_{23} is larger or smaller than 45^o.
  - $\theta_{23} < 45^o$ implies that ν_3 couples more strongly to ν_τ than to ν_μ. $\theta_{23} > 45^o$ implies the opposite.
- The $\sin^2(\theta_{23})$ term is unimportant when comparing accelerator experiments; however, it is crucial in comparing accelerator to reactor experiments.

$\sin^2(2\theta_{23}) = 0.99, 0.97, \text{ and } 0.95$





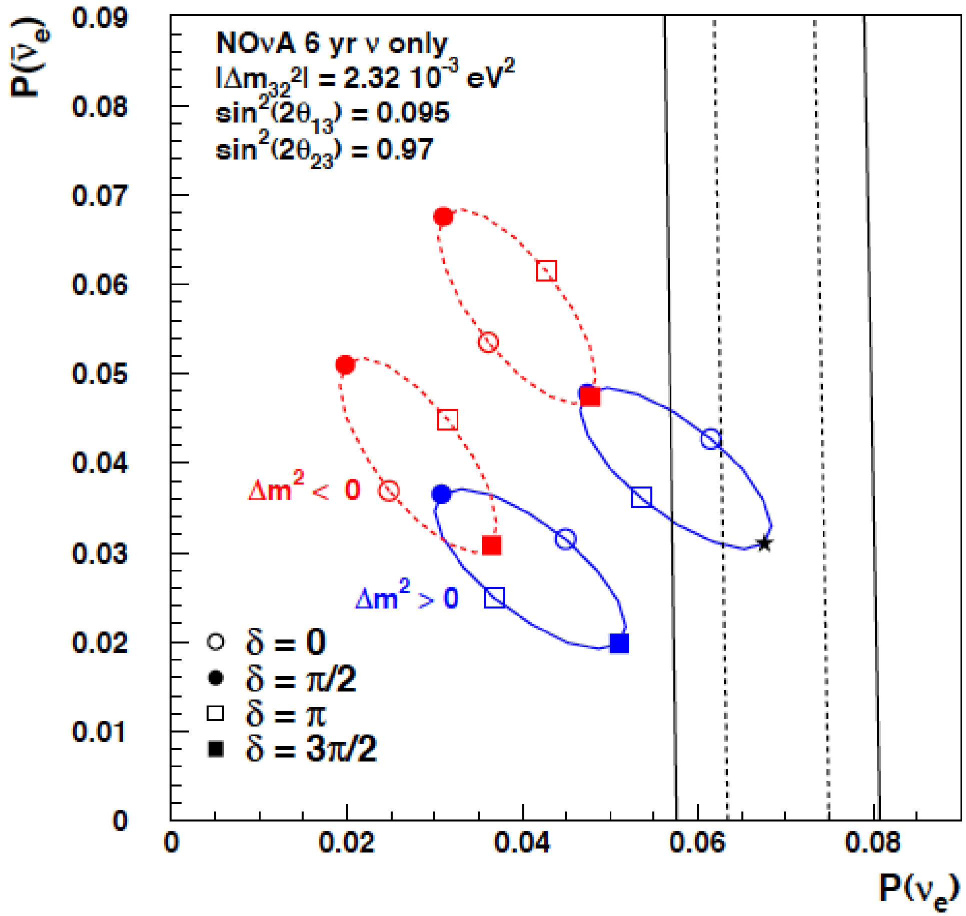


Strategies to Resolve the Mass Ordering

- There are two completely different strategies for *any* experiment on the NuMI beamline to resolve the mass ordering:
  - Plan A, for the most part, involves doing it all internally by measuring both neutrinos and antineutrinos.
    - A possible variant is using only neutrinos or only antineutrinos and comparing to reactor experiments, but we will see that this is not optimal.
    - We will see that no experiment can guarantee that Plan A will work.
  - Plan B will involve comparing (usually) neutrino running with an experiment on another baseline.

Can NOνA Run with ν Only?

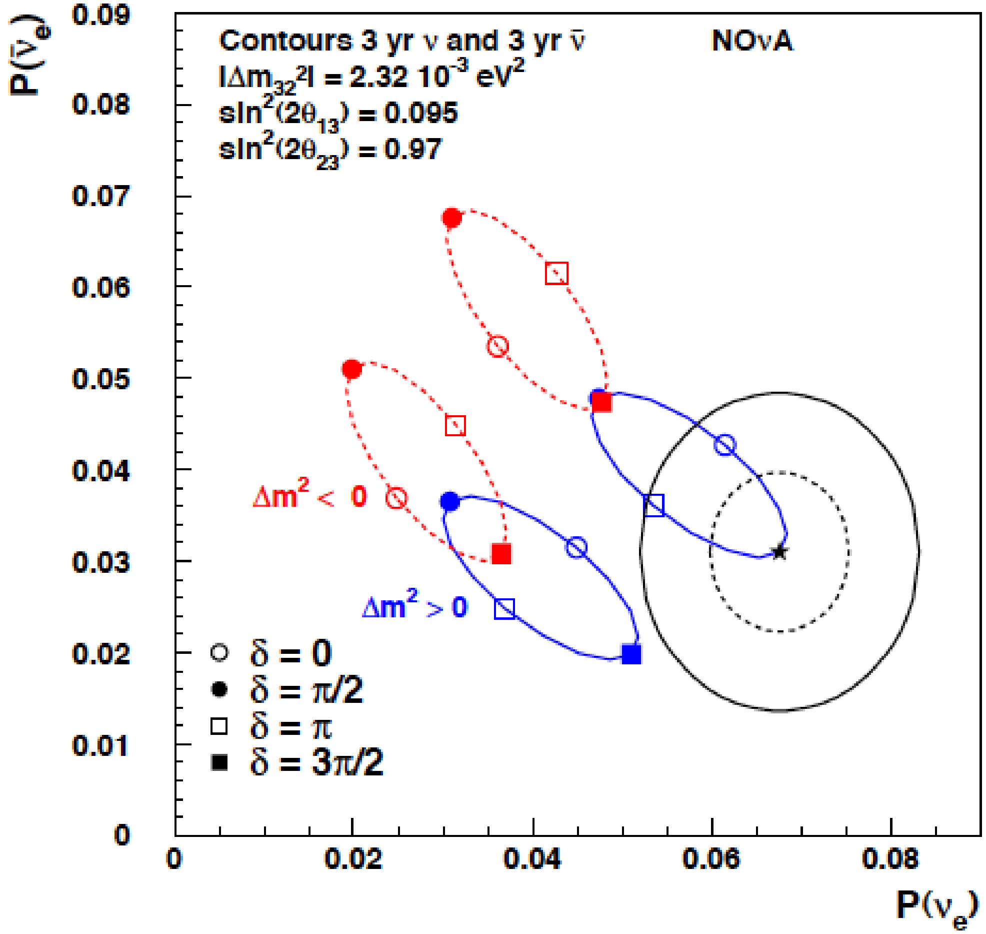
1 and 2 σ Bands for Starred Point



For points at the extremities, the answer is yes, however…

3 Years Each ν and $\bar{\nu}$

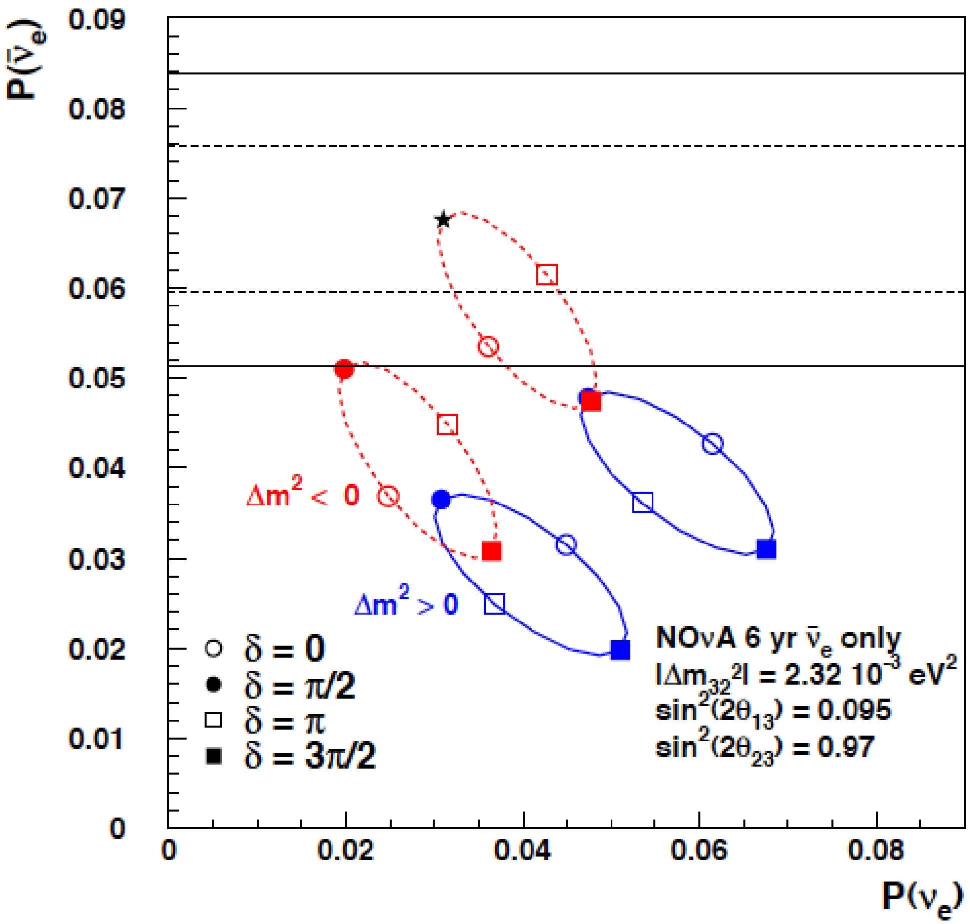
1 and 2 σ Contours for Starred Point



NOνA does about as well with 3 years of each. In addition, this plan rules out no CP violation at a greater significance and it provides a constraint on the model and on the measurements.

$\bar{\nu}$ Only Running

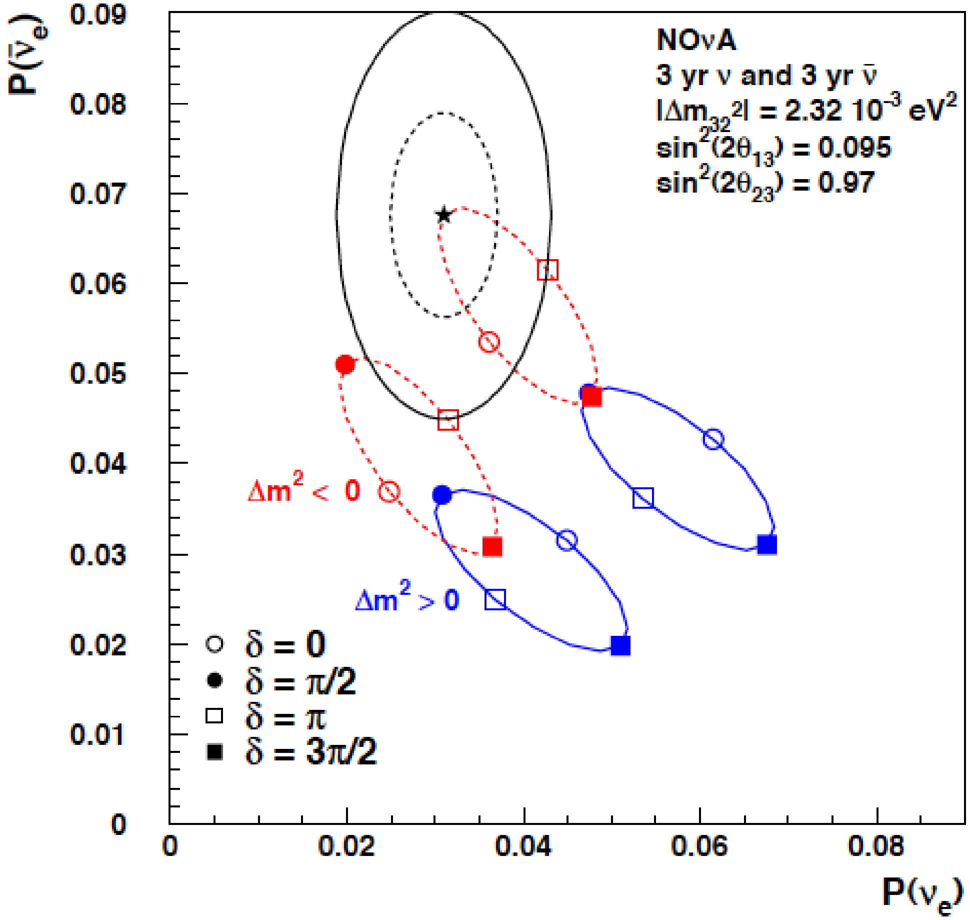
1 and 2 σ Bands for Starred Point



Statistics are worse, but it is possible to run antineutrinos only for extreme points in the inverted mass ordering.

3 Years Each ν and $\bar{\nu}$

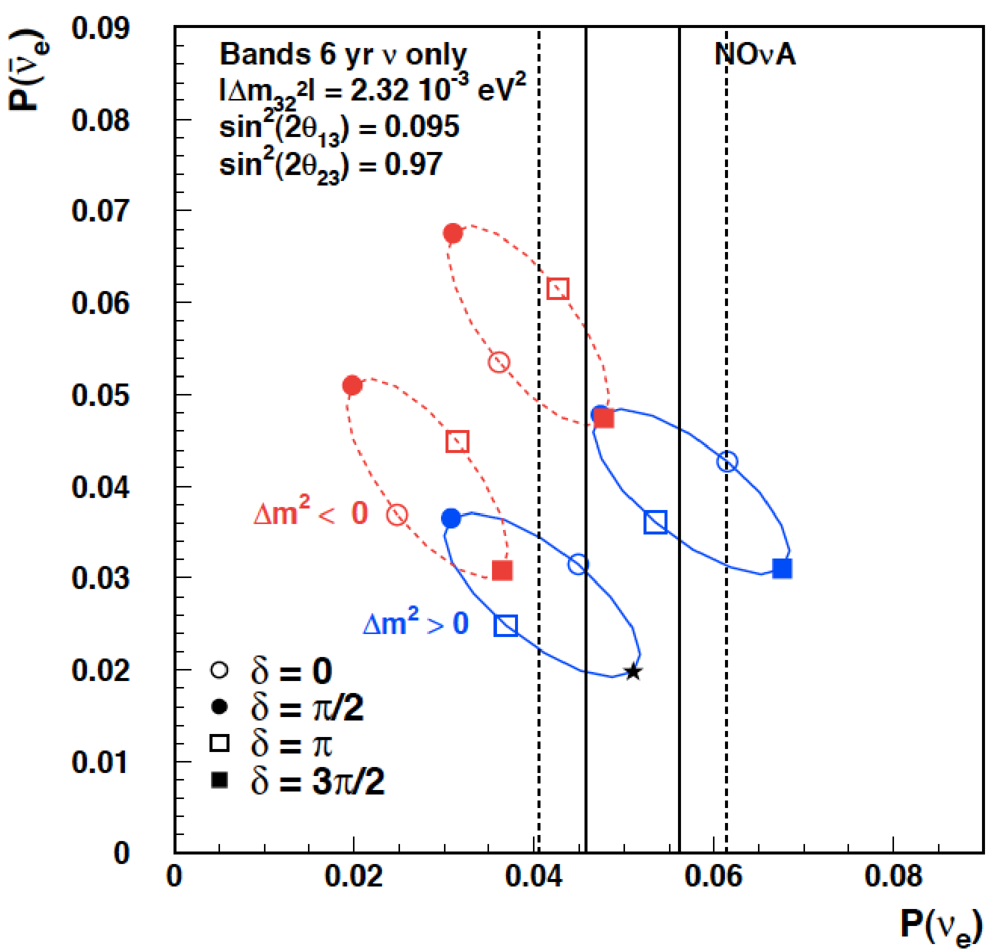
1 and 2 σ Contours for Starred Point



3 years of each works as well, and the previous comments apply as well.

A Look at the $\theta_{23} < 45^o$ Case

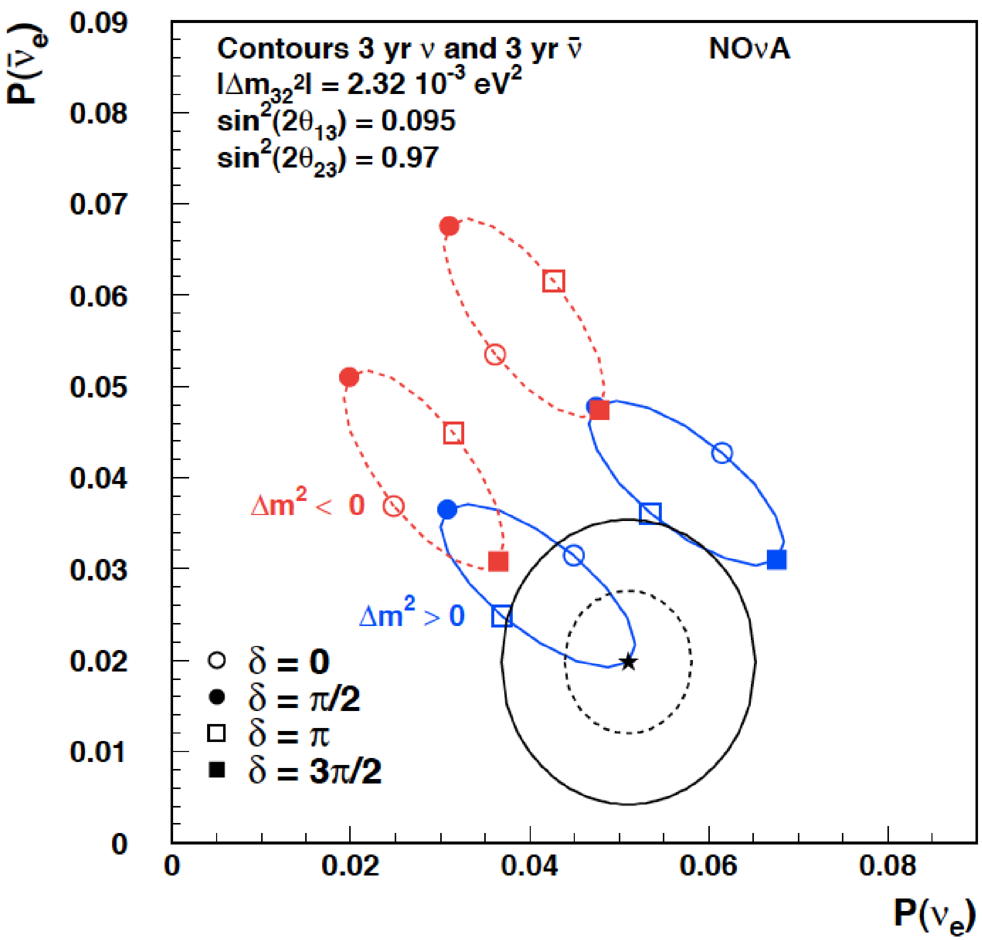
1 and 2 σ Bands for Starred Point



It is clear that ν only running would not work here (or for most other points).

A Look at the $\theta_{23} < 45^o$ Case

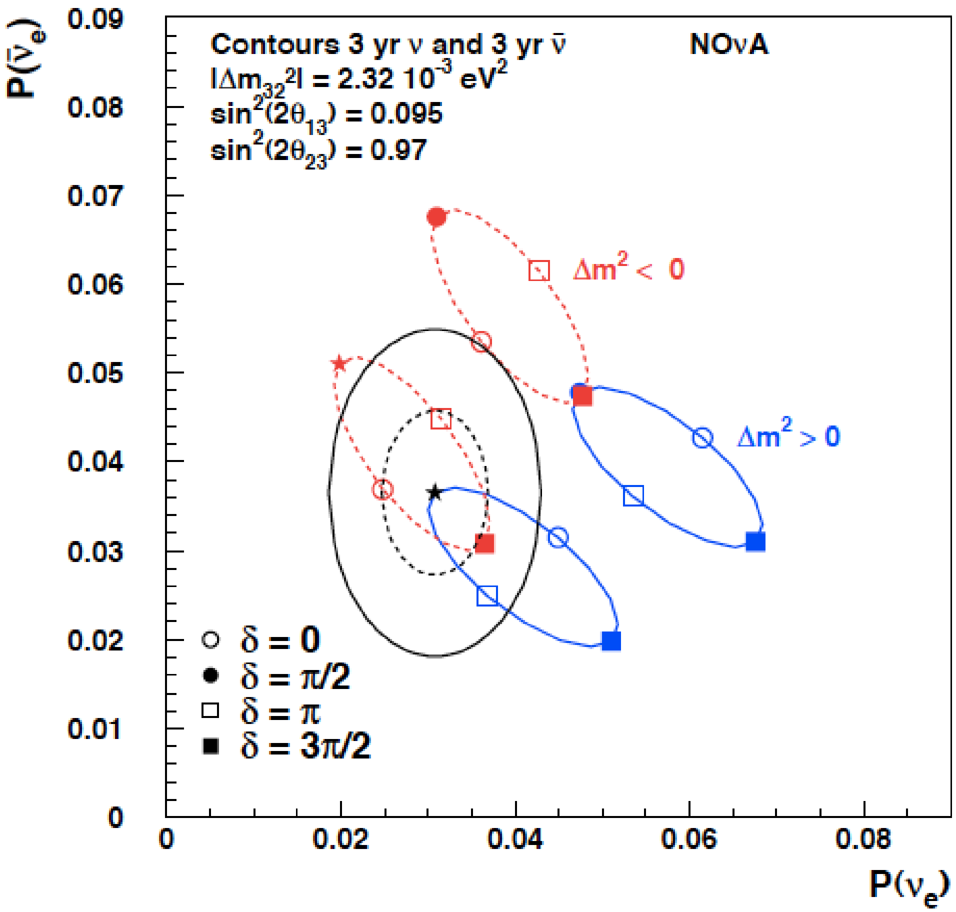
1 and 2 σ Contours for Starred Point



The statistics are a little worse than for the other octant, but the conclusions are similar.

Point at which the Mass Ordering Cannot Be Resolved by NOνA Alone.

1 and 2 σ Contours for Starred Point

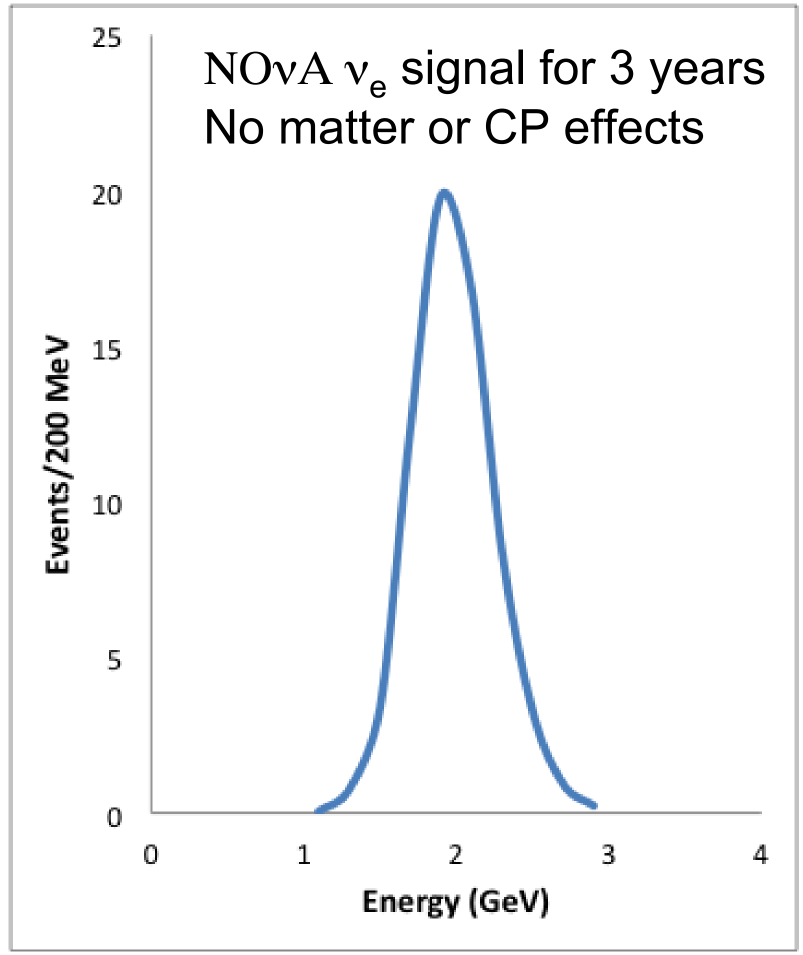


So far I have only considered the easy points. Here is one where a simple rate measurement does not work.

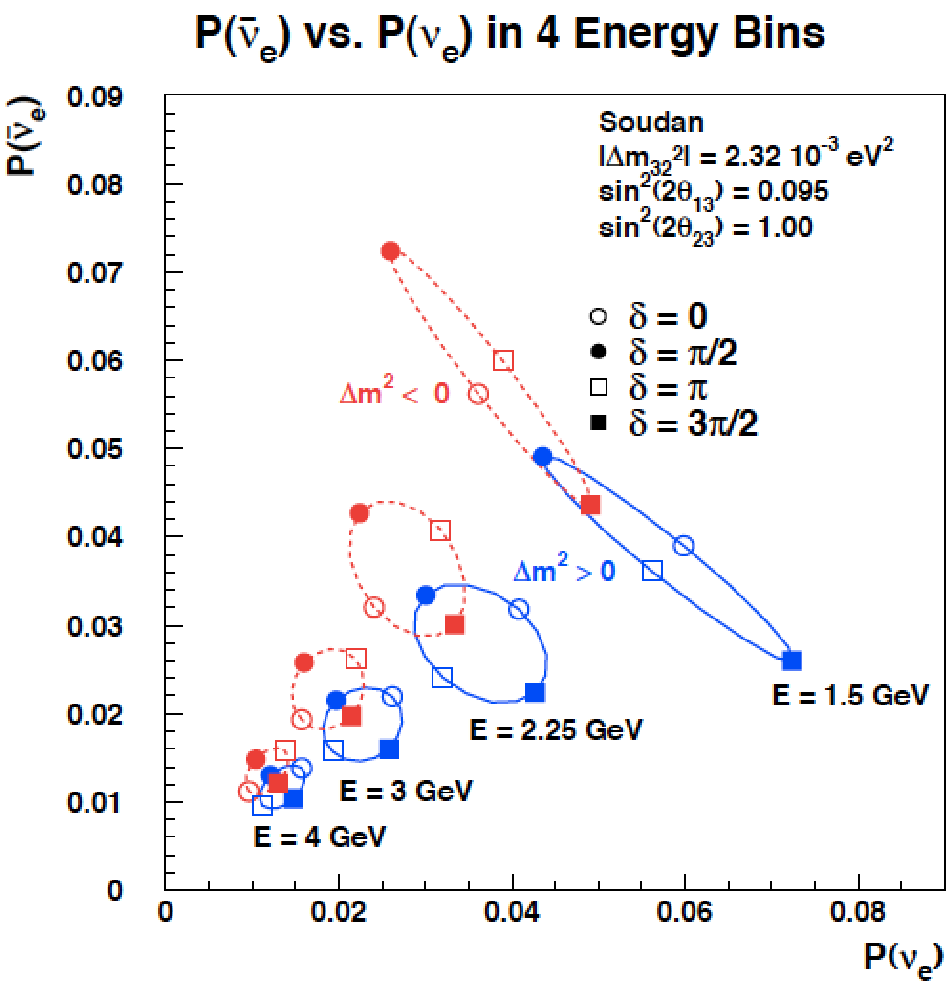
What about using the energy dependence?

Using the Energy Dependence

- NOνA has a very narrow-band beam, so looking at a wide-band beam at Soudan will be more instructive.



Soudan Energy Bins



Note that the bi-probability Plots are symmetric about the diagonal.

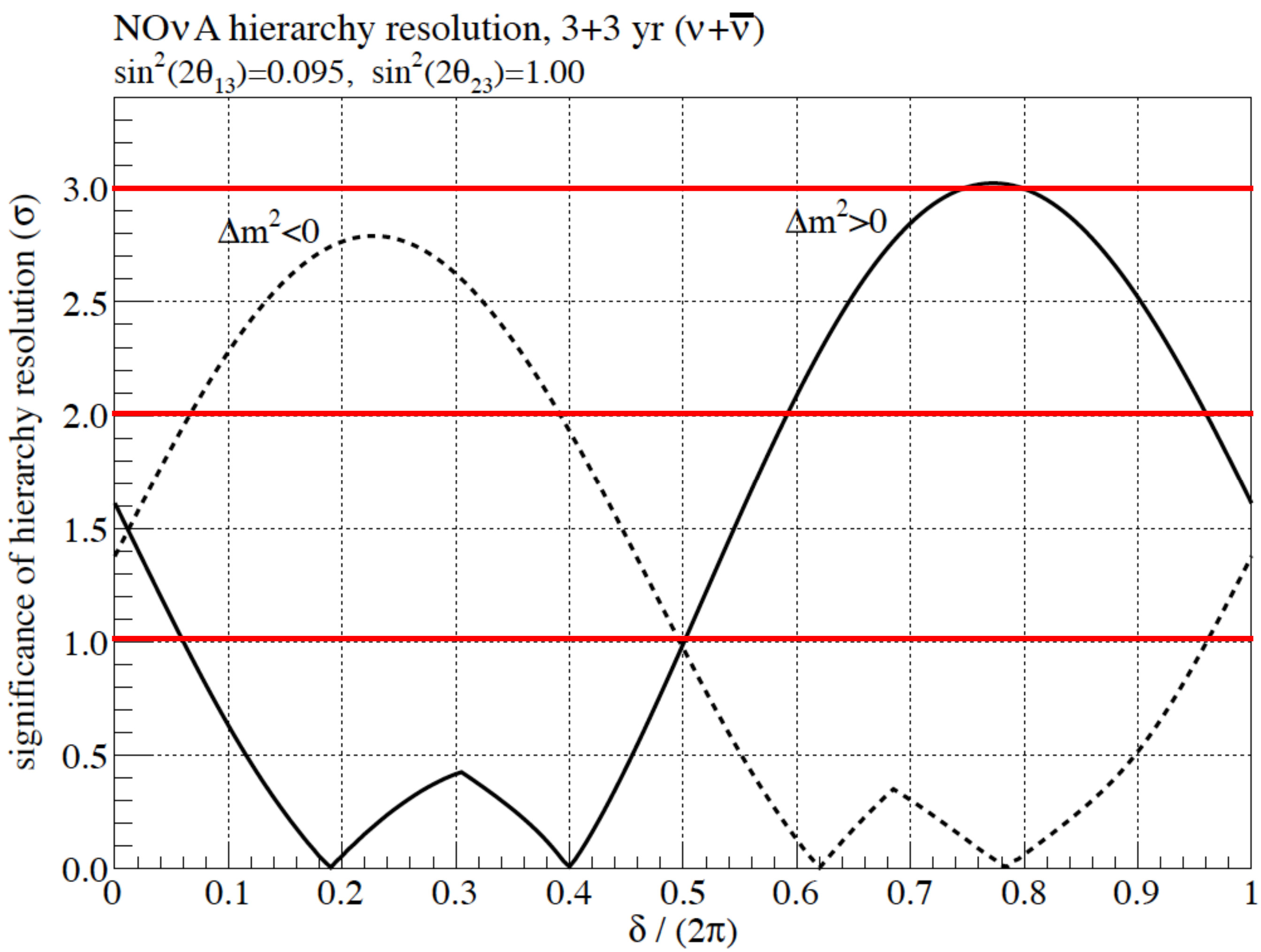
This is due to the invariance of neutrino oscillations to the simultaneous exchange of three variables: $\nu \leftrightarrow \bar{\nu}$, $\Delta m^2 \leftrightarrow -\Delta m^2$, and $\delta \leftrightarrow \delta + \pi$

There is some energy dependence, but not enough where you need it.

The Limitation of Plan A

- We have seen that no experiment on the NuMI beamline (Soudan or Ash River) can guarantee being able to resolve the mass ordering by itself.
- Before moving to a consideration of Plan B, I want to show how well NOνA can do with Plan A and 6 years of running.

Significance of the Mass Ordering Resolution for NOνA (Plan A)



Rate only
10% systematic
on the background.

Odds of NOνA Alone Resolving the Mass Ordering at Different Significance Levels

Rate only

	$\Delta m^2 > 0$	$\Delta m^2 < 0$
1σ	56%	55%
2σ	37%	32%
3σ	5%	0%

Note: These are based on a simple analysis. NOνA hopes to do better as the analyses become more sophisticated.

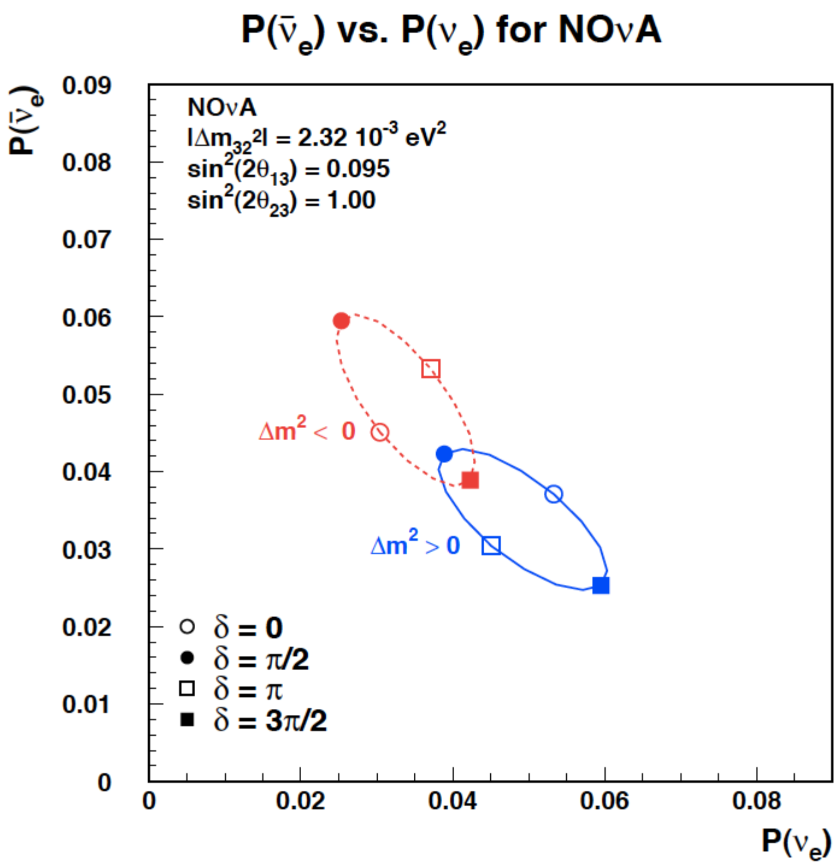
Also, even in NOνA, there is a few percent improvement by incorporating the energy dependence.

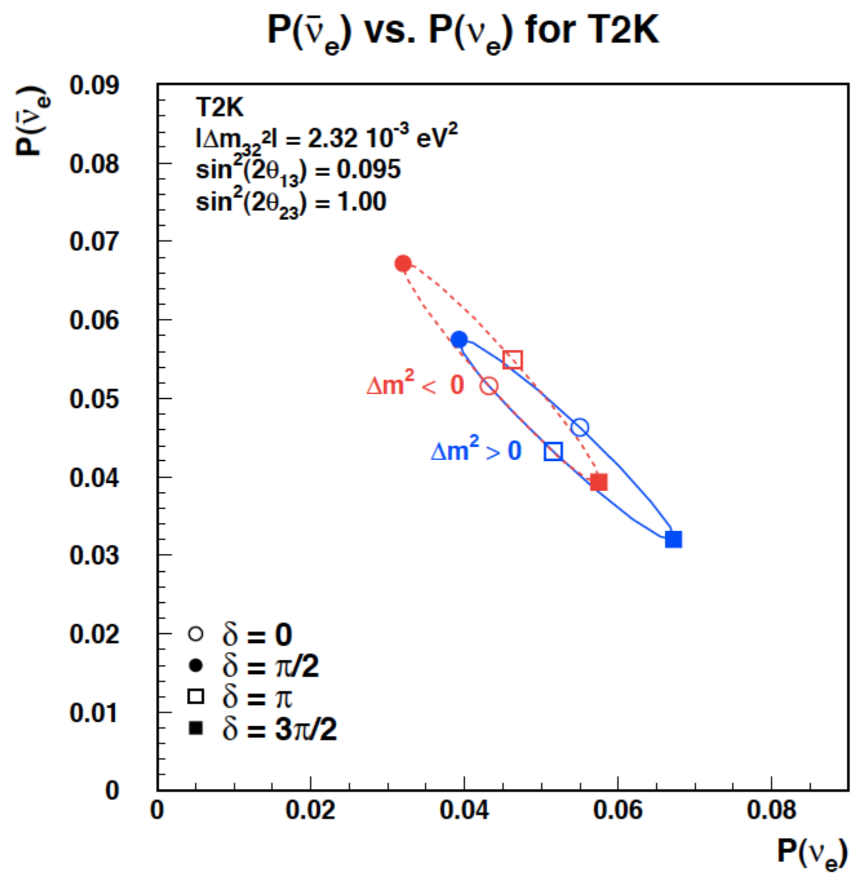
Plan B

- At each point of the kinematic oscillation phase $\frac{\Delta m^2 L}{4E}$,

  NOνA (or another experiment on the NuMI beamline) and T2K will measure the identical oscillation probabilities, except for the matter effect, which determines the mass ordering.
- Thus, the strategy of Plan B is straightforward. Each experiment gets as much data on neutrino running as it can. If the oscillation probability is higher in NOνA, it is the normal mass ordering. Otherwise, it is the inverted.
- It is that simple (in principle, but not in practice).

NOνA-T2K Comparison





Warning: These plots are not at the same kinematic phase.

Comparison to T2K

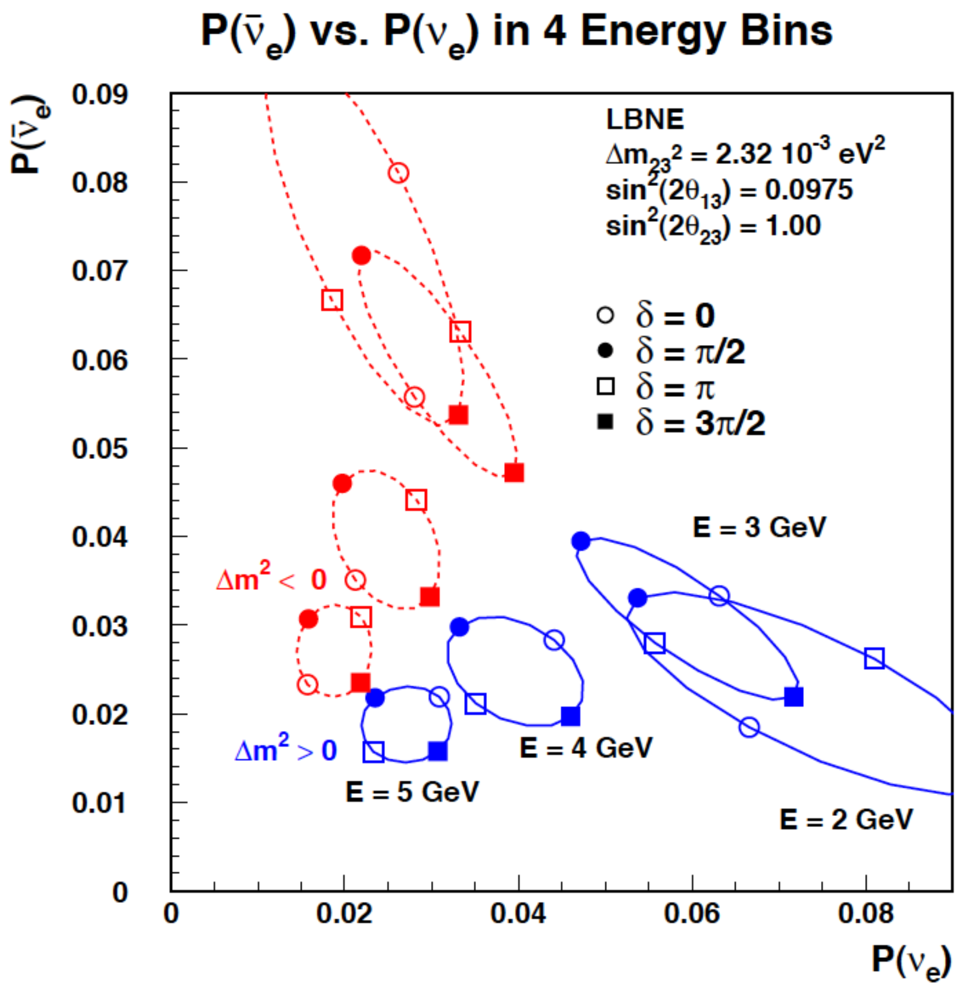
- Correcting for the identical kinematic phase is not easy since it depends on the physics parameters that you are trying to measure. (Theorists warned us about this problem when the experiments were being planned.)
- Thus, the simple strategy of just running neutrinos will not work.
- I have not tried to work out an optimum strategy. However, if we take the test point as

$$\Delta m^2 > 0, \delta = \pi / 2, \text{and } \sin^2(2\theta_{23}) = 1.00,$$

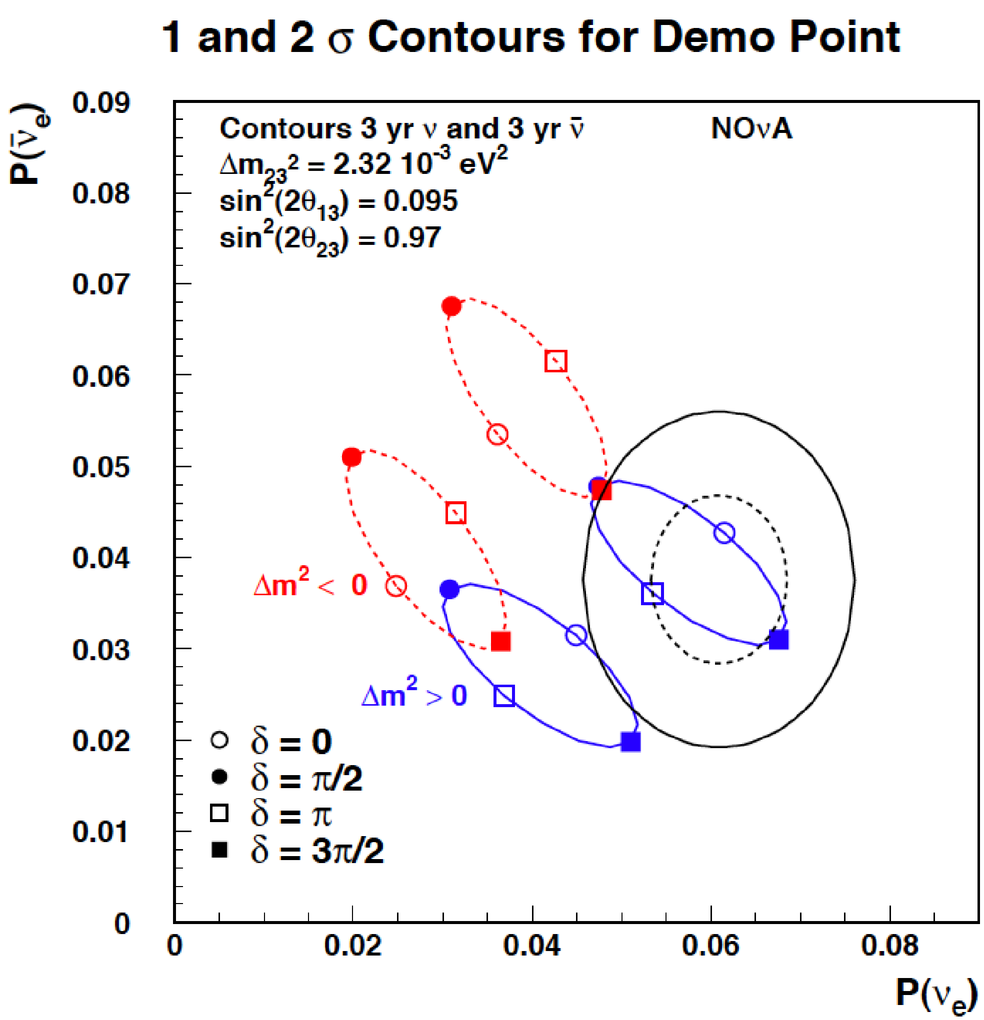
and T2K only runs neutrinos until June 2030, then they should have a 4.6% (1 σ) measurement of the oscillation probability, based on the projected data they sent us.

Backup Slides

LBNE Energy Bins



Note on 1 DOF Contours



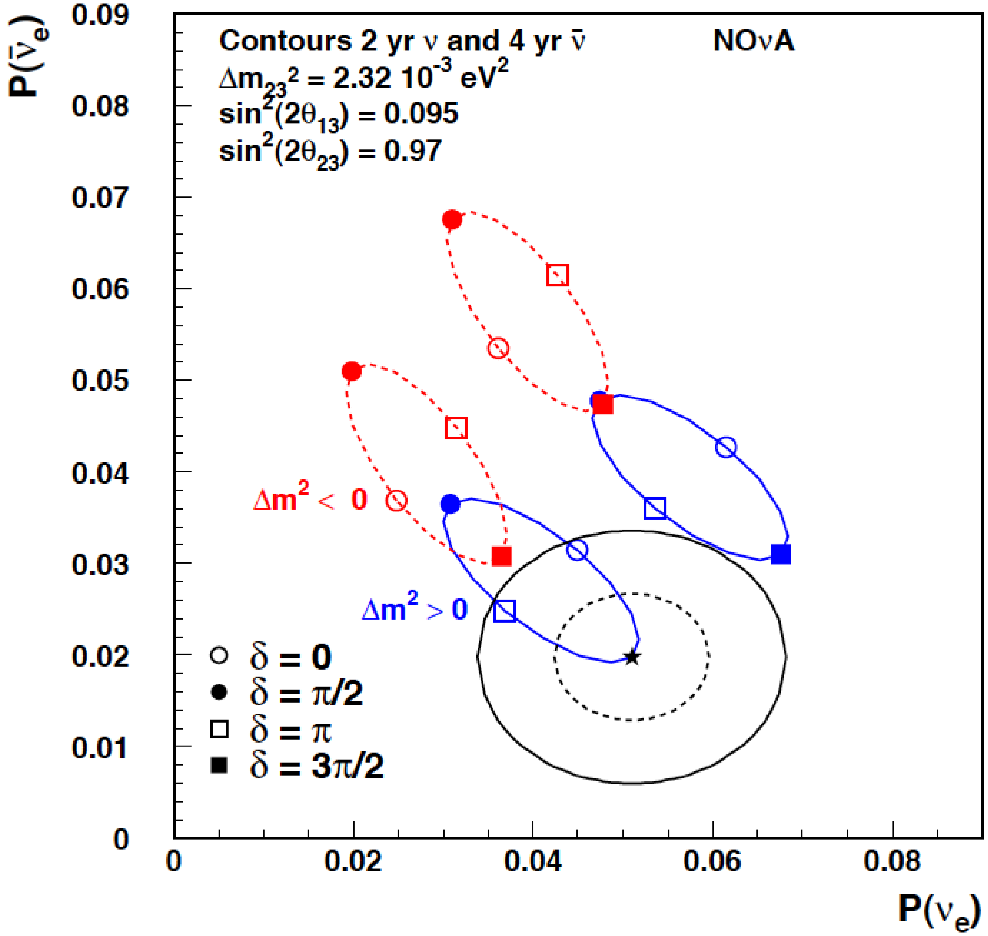
N.B. The contours are one degree-of-freedom contours.

Suppose we measure the shown contour. Then we have established that the mass ordering is normal at 95% C.L. and we have established that $\theta_{23} > 45^o$ at the 95% C.L. (assuming that we know $\sin^2(2\theta_{23})$ perfectly, which we will not).

What we have **not** established is that both are true at the 95% C.L.

2 Years of ν and 4 Years of $\bar{\nu}$

1 and 2 σ Contours for Starred Point

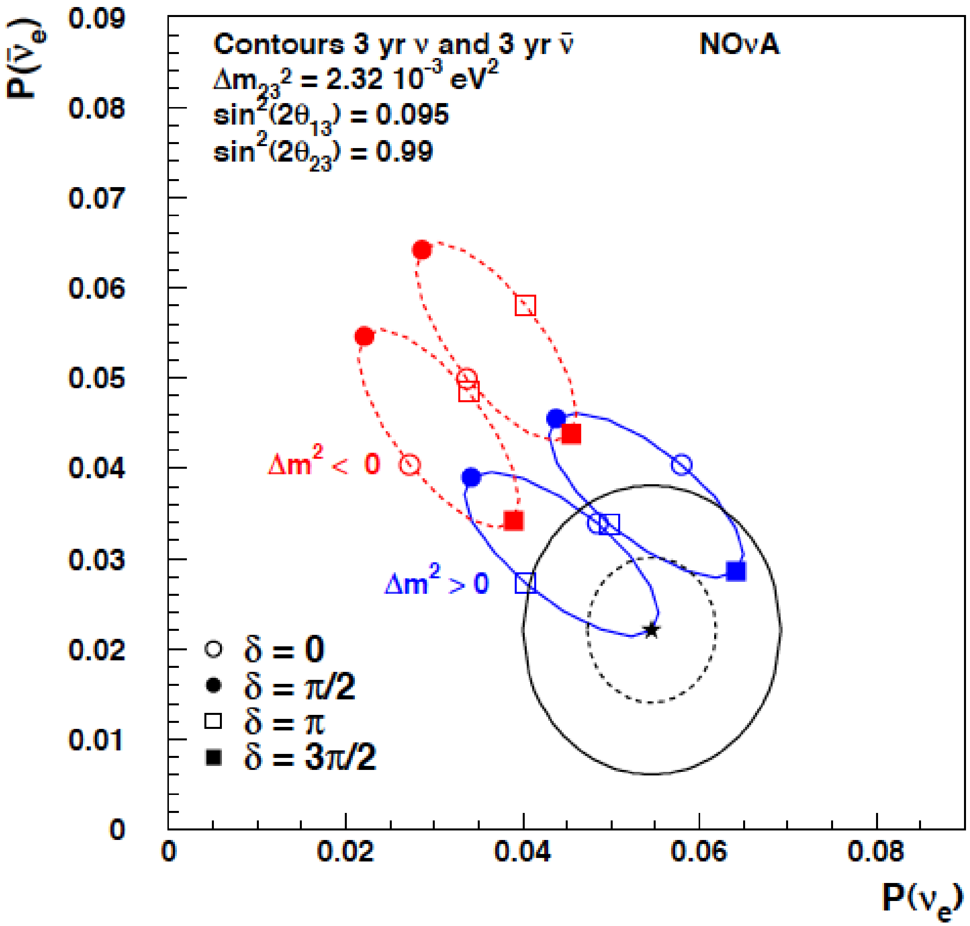


It is a hair better on the θ_{23} ambiguity and a hair worse on the mass ordering.

Conclusion: We are not too sensitive to the running strategy and can fine tune as we go.

Does the Sensitivity to the Mass Ordering Change with $\sin^2(2\theta_{23})$?

1 and 2 σ Contours for Starred Point

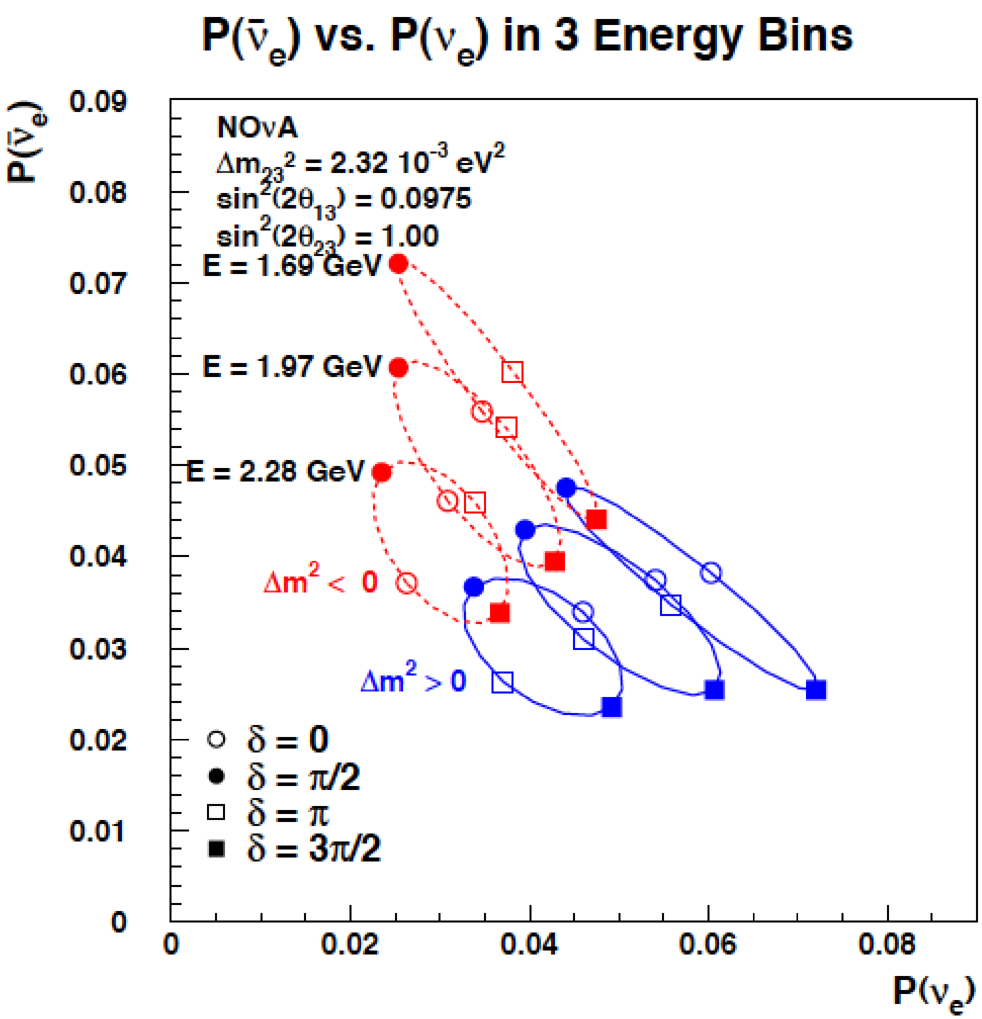


No, the sensitivity to the mass ordering is independent of $\sin^2(2\theta_{23})$ to first order.

This is probably as close as we will get to determining whether the θ_{23} mixing is maximal.

The interesting thing is that we have 1σ sensitivity to it here. Is it possible that a high statistics ν_e appearance experiment could be the most sensitive measure of this?

NOνA 3 Energy Bins



Note that the bi-probability Plots are symmetric about the diagonal.

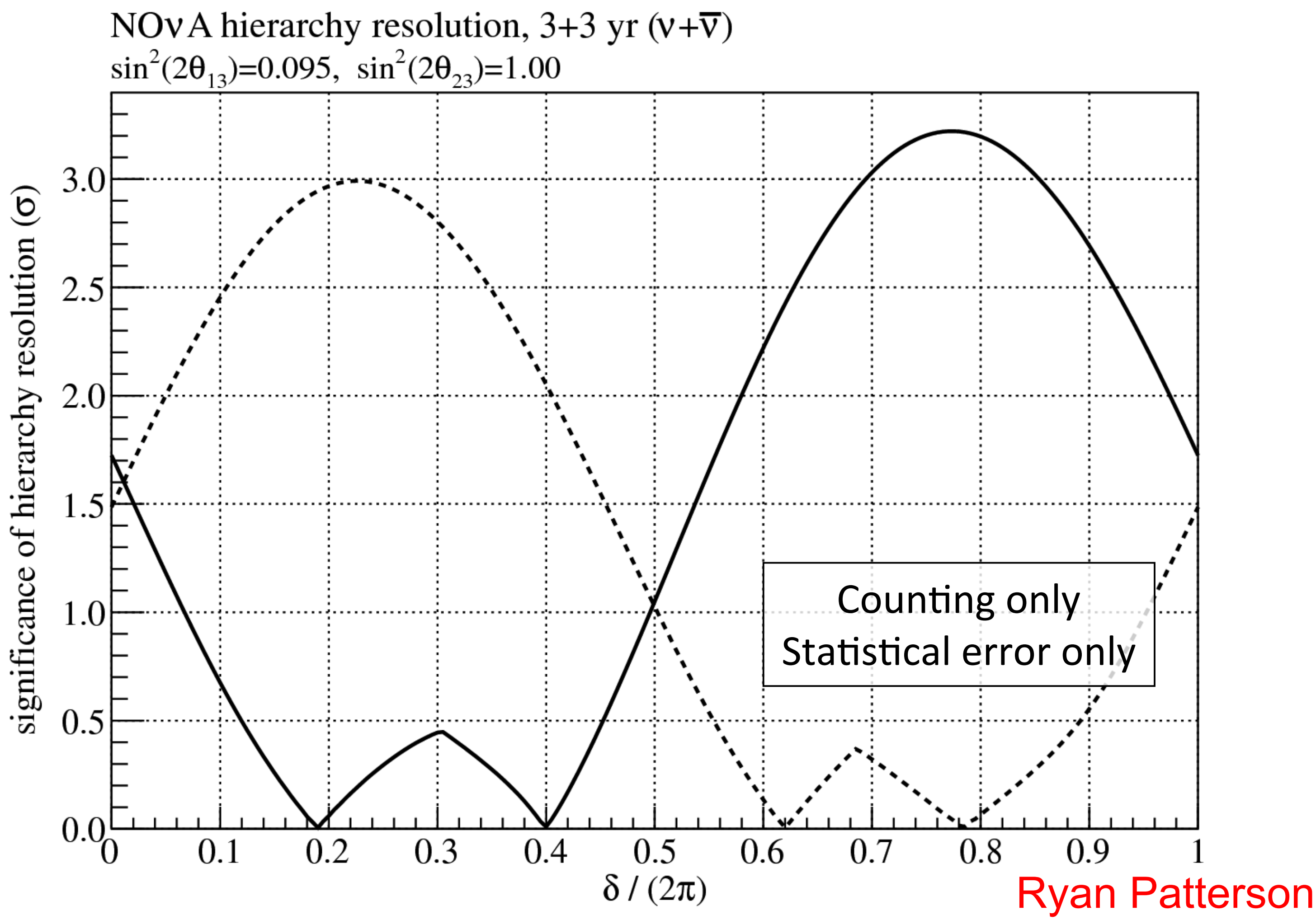
This is due to the invariance of neutrino oscillations to the simultaneous exchange of three variables:

$\nu \leftrightarrow \bar{\nu}$

normal $\leftrightarrow$ inverted mass ordering

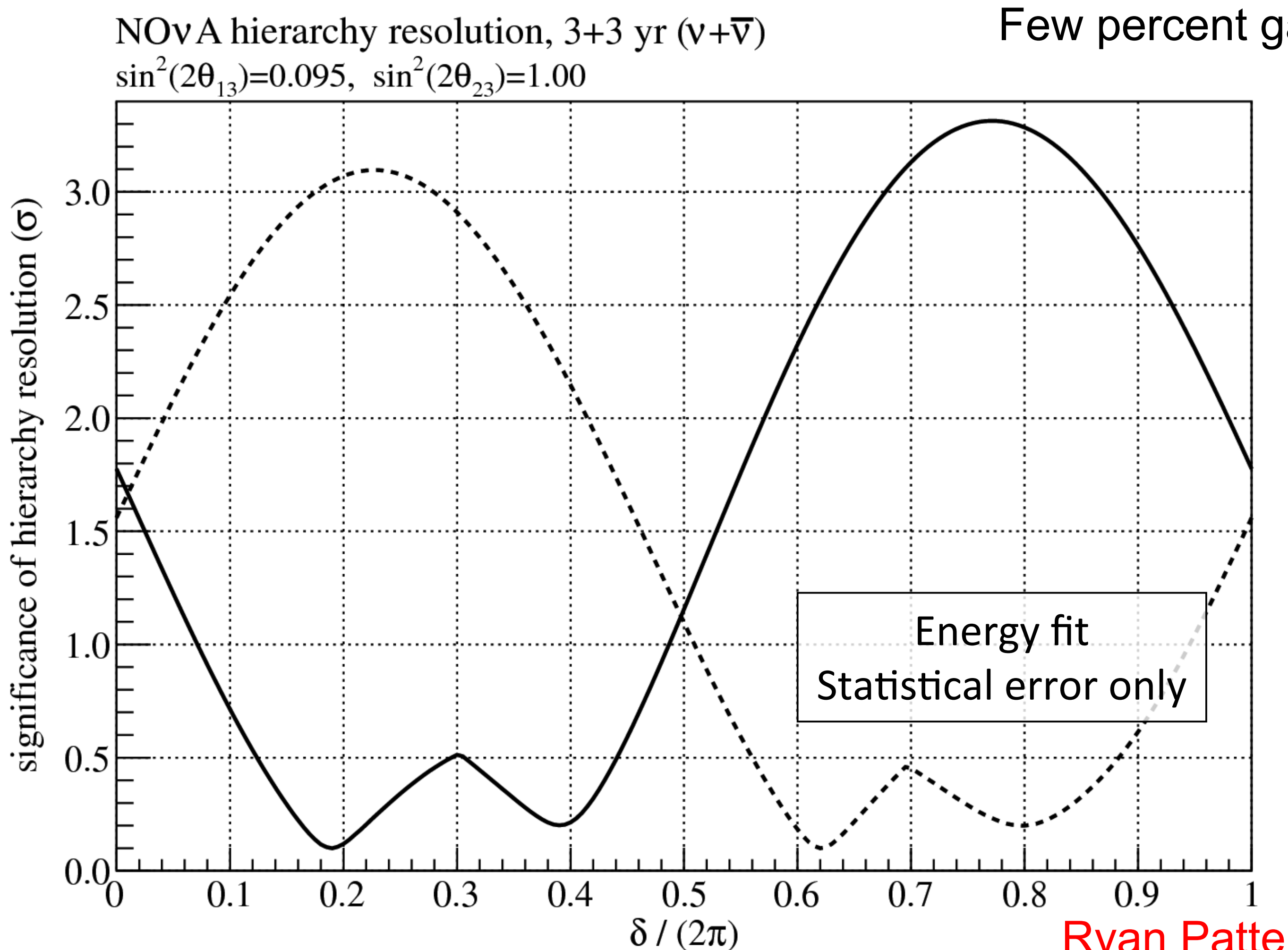
$\delta \leftrightarrow \delta + \pi$

Significance of the Mass Ordering Resolution without Energy Fit



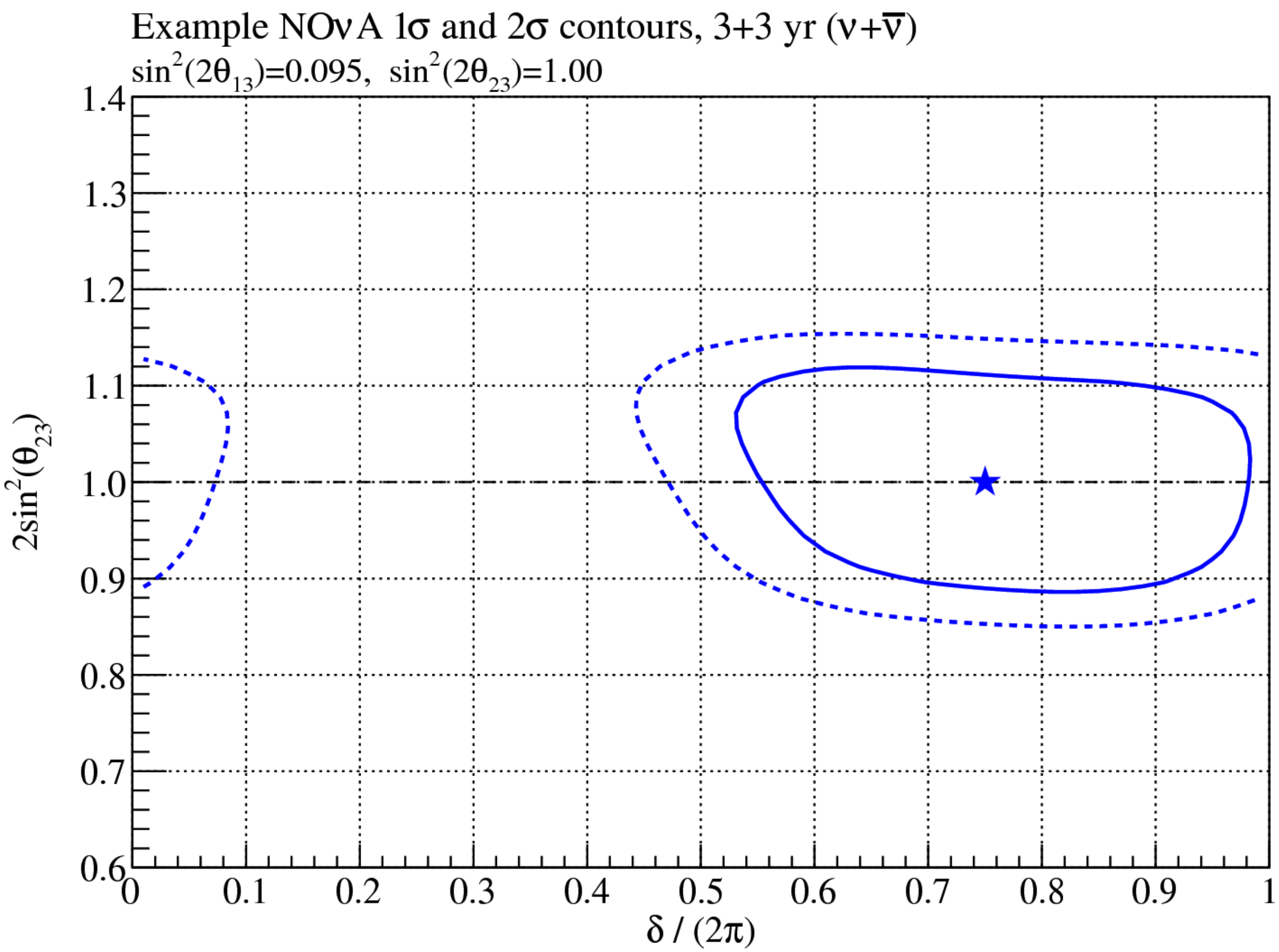
Significance of the Mass Ordering Resolution with Energy Fit

Few percent gain

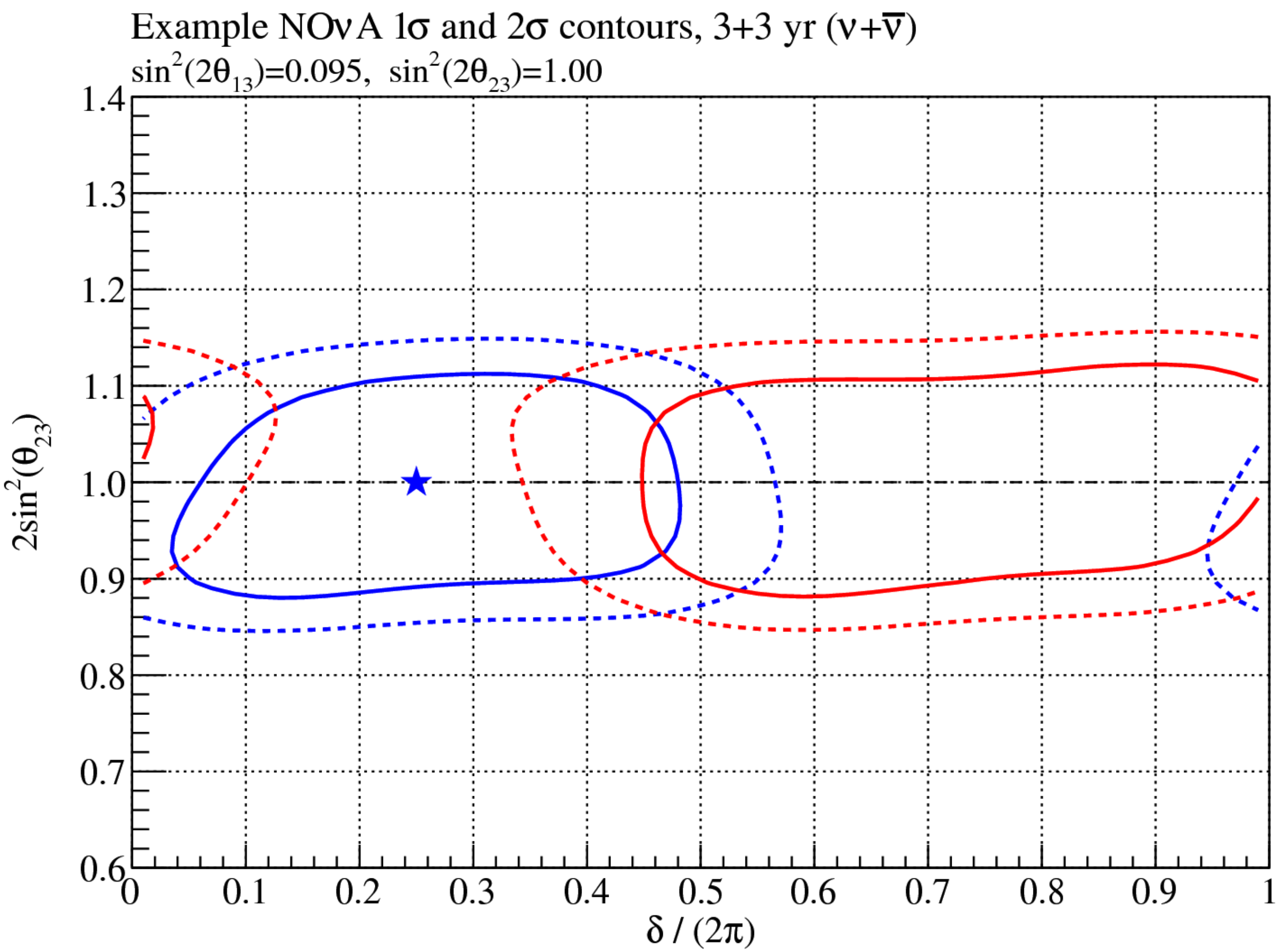


Ryan Patterson

θ_{23} Octant, δ, and Mass Ordering All on One Plot



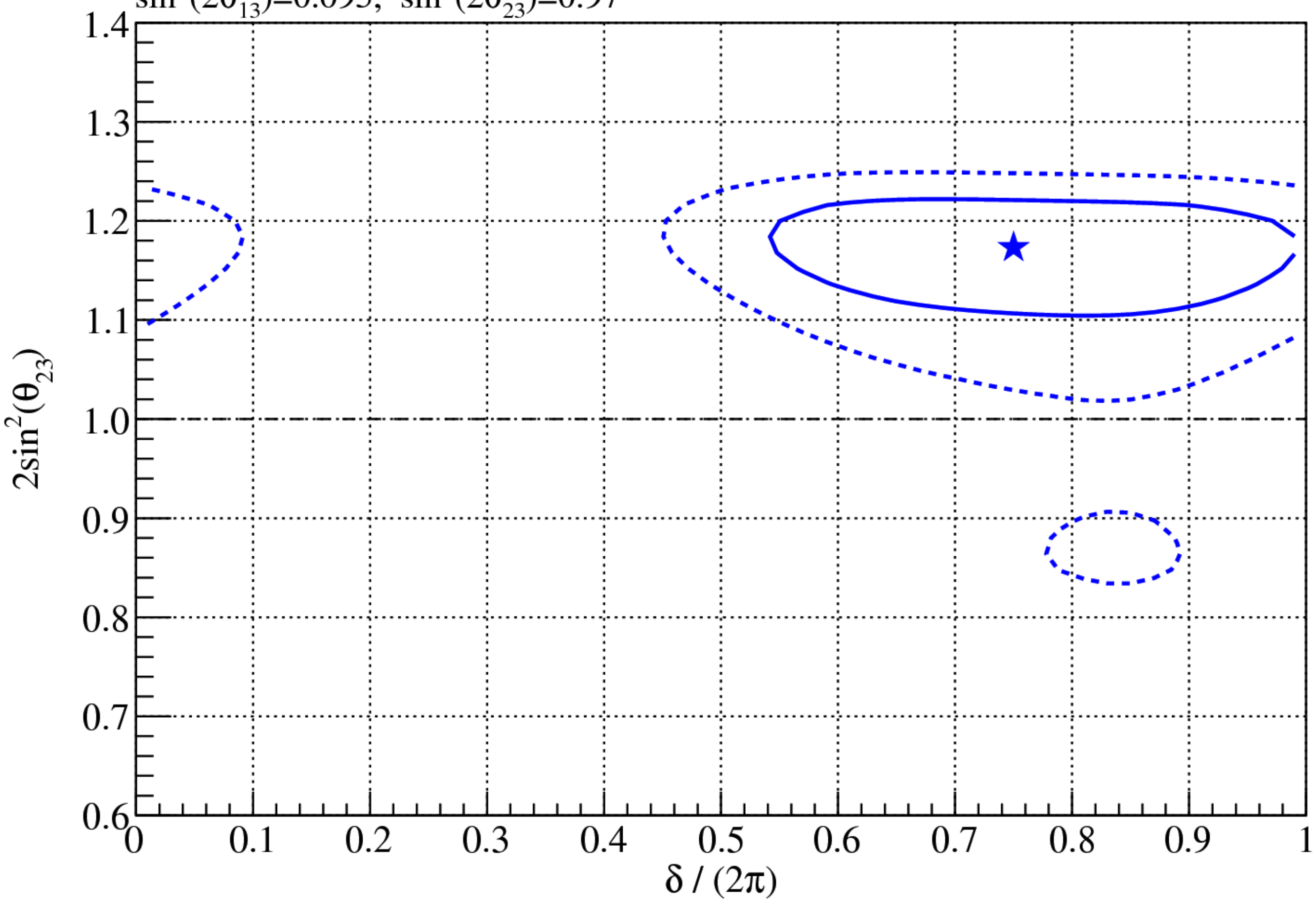
θ_{23} Octant, δ, and Mass Ordering All on One Plot



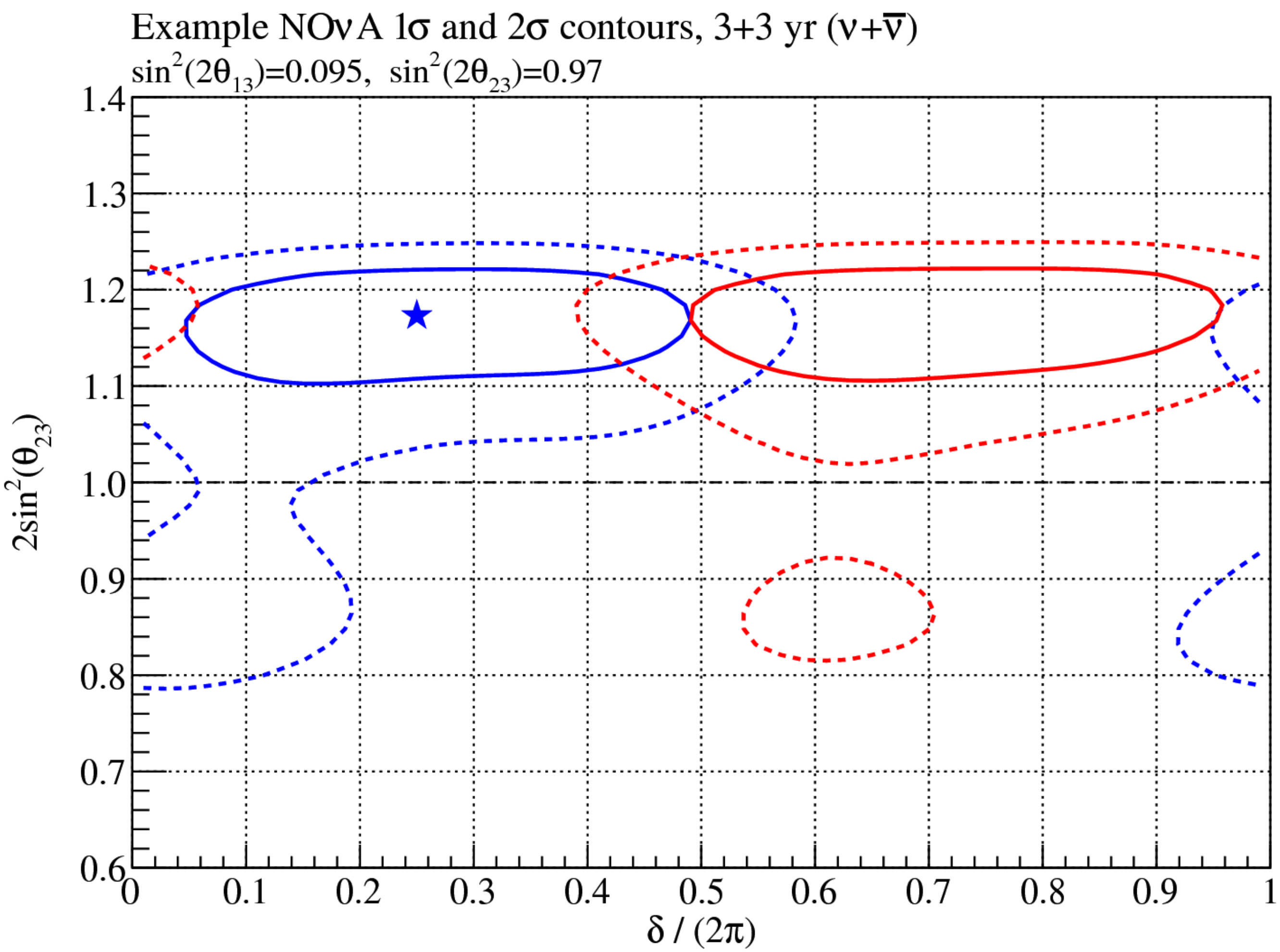
θ_{23} Octant, δ, and Mass Ordering All on One Plot

Example NOνA 1σ and 2σ contours, 3+3 yr ($\nu+\bar{\nu}$)

$\sin^2(2\theta_{13})=0.095$, $\sin^2(2\theta_{23})=0.97$



θ_{23} Octant, δ, and Mass Ordering All on One Plot



θ_{23} Octant, δ, and Mass Ordering All on One Plot: 1+1 Years Running