Neutrino Experiments in Project X

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DOE Briefing
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Fermilab ν Program

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- The Fermilab Long Baseline Neutrino Oscillation Program tries to understand the whole oscillation picture in stepwise fashion
  - MINOS - verify oscillations, measure parameters in the atmospheric sector
  - NOvA - measure $\sin^2(2\theta_{13})$ (or set much better limits) and make first attempt at mass hierarchy
  - LBNE - better sensitivity to mass hierarchy, first attempt at CP violation
  - Project X - extend the reach for mass hierarchy and **CP violation** to lower values of $\sin^2(2\theta_{13})$; builds on infrastructure of LBNE

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- For their goals, the last three programs must focus on the subdominant channel $\nu_\mu \rightarrow \nu_e$ (and charge conjugate process)

Neutrino CP Violation and the Universe

The universe contains nucleons, ***but practically no antinucleons***, making it safe for life.

The development of this matter-antimatter asymmetry requires ***CP violation*** (matter and antimatter must behave differently).

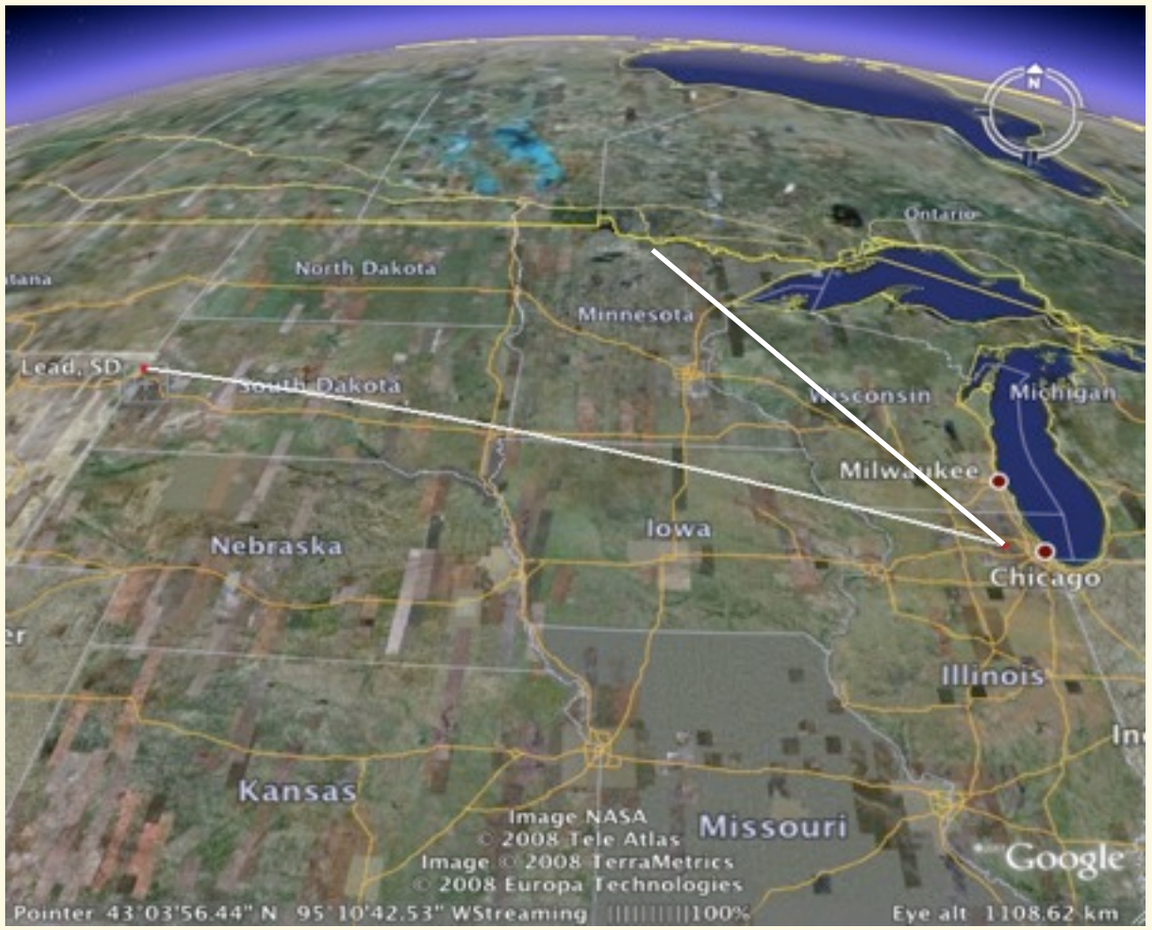
The observed ***quark*** CP violation cannot explain the cosmic nucleon-antinucleon asymmetry.

But a hypothesized ***neutrino*** CP violation can do so.

CP violation in ***light-neutrino*** oscillation would establish leptonic CP violation, and make leptogenesis more plausible.

Geography

NuMI and LBNE



Project X

LBNE: New beamline
Use of recycler

Project X: x3 Intensity
New Injector

LBNE Experiment

- Next generation neutrino experiments will require large number of events
- This is true for CP investigation even if $\sin^2 2\theta_{13}$ relatively large

- $N_{evt} = \sigma$ x flux x efficiency x mass x time
  - flux - from 700 kW proton beam
  - time - 5 yrs with neutrinos, 5 yrs with antineutrinos
  - mass - 100-200 kt Water Cerenkov (WC) or 17-34 kt LAr
  - efficiency - LAr ~6 times better for ν_e channel at ~3GeV
- We are already pushing the limits

More about Detectors

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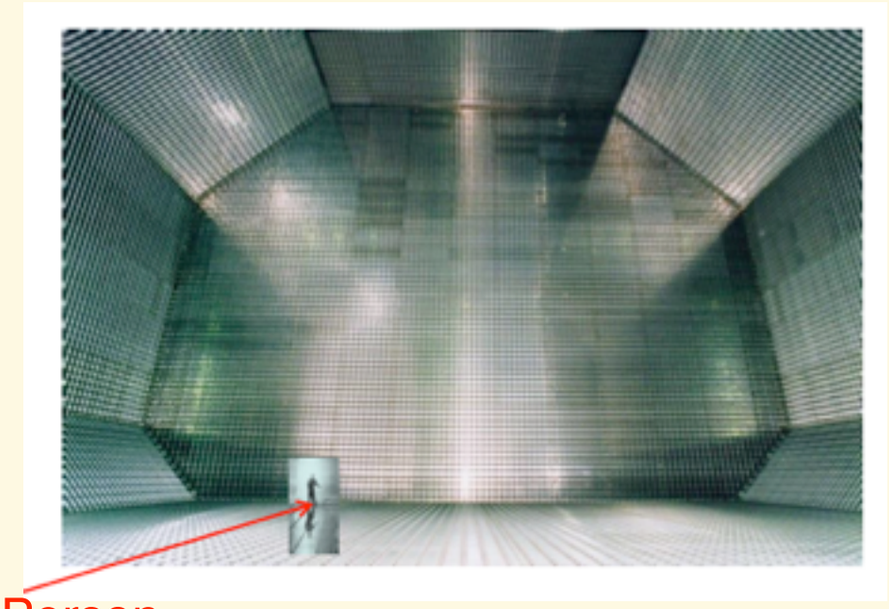
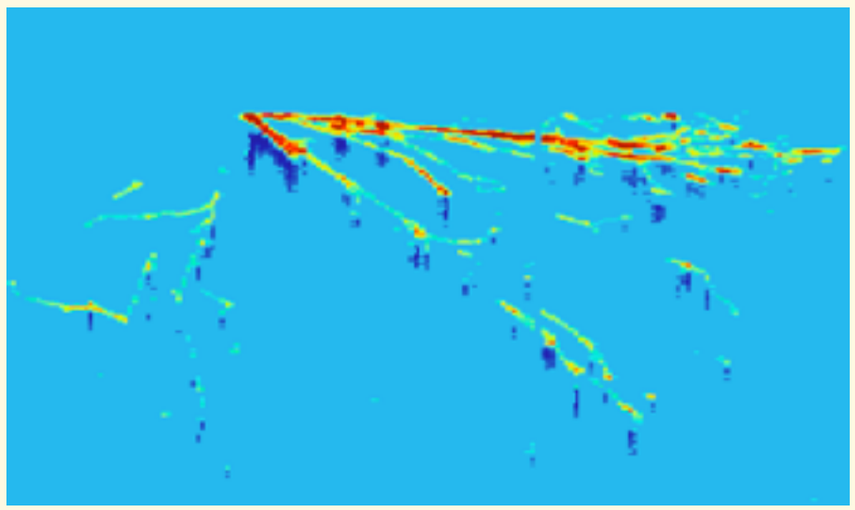
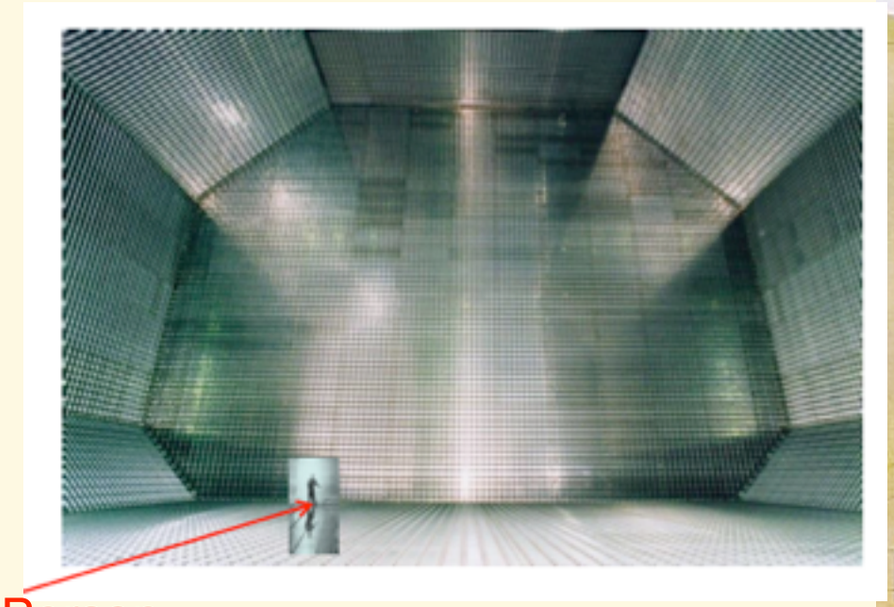


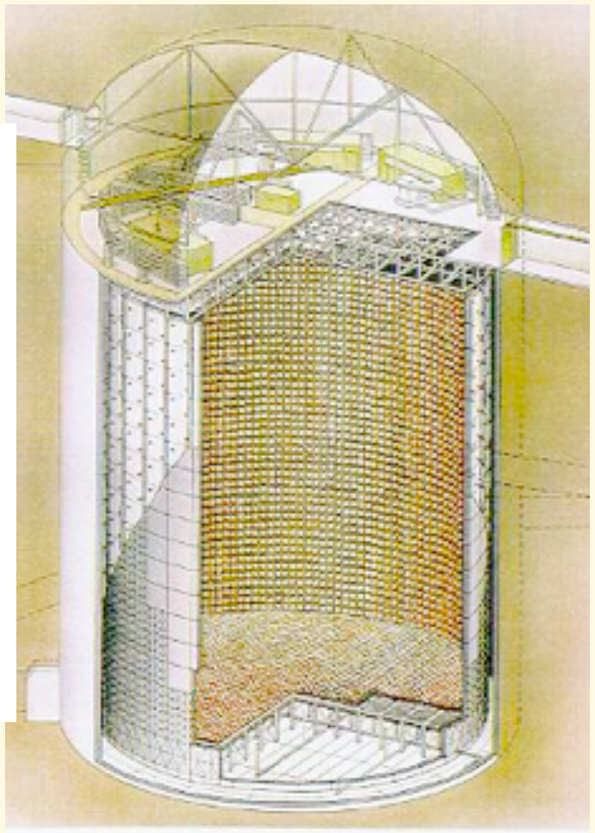
Person

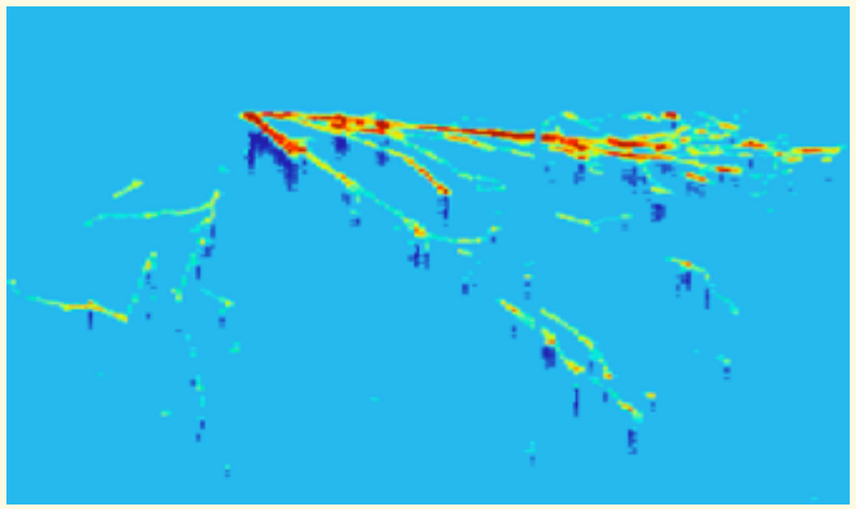


An ArgoNeut neutrino event from the NuMI beam

More about Detectors







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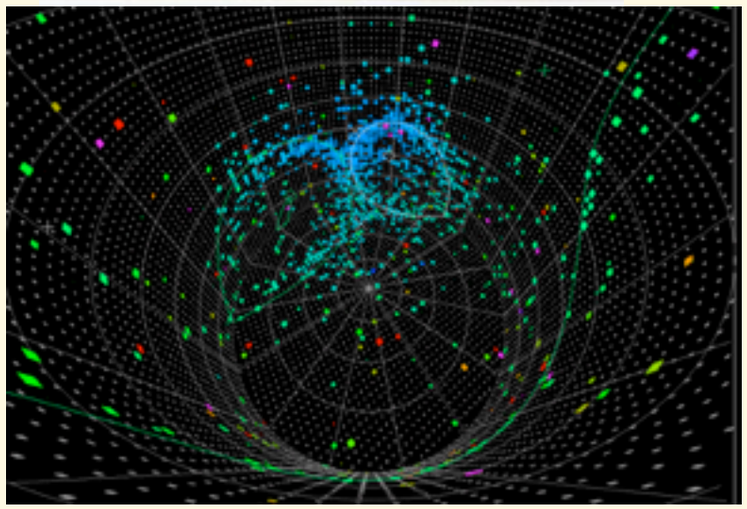

First accelerator neutrino event in SuperK (T2K beam)

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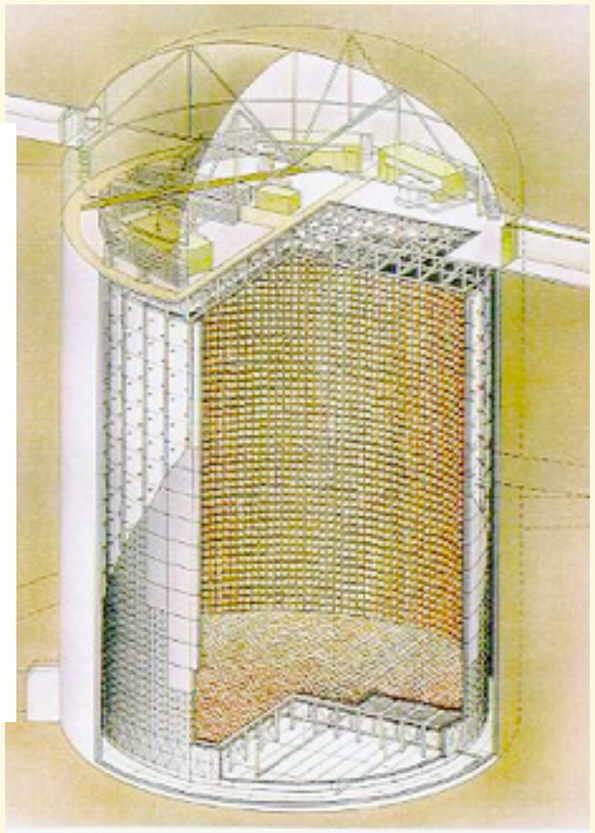
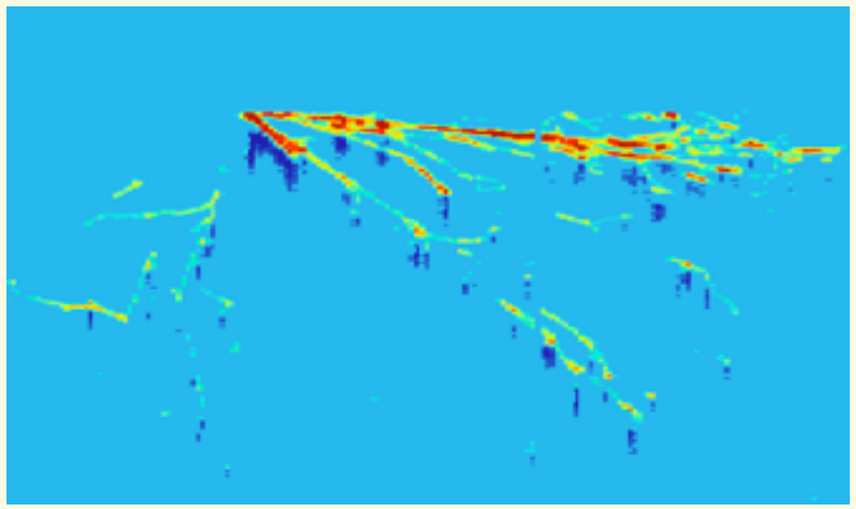


The 100 kt WC is comparable in height to Wilson Hall

But

It has to be built deep underground



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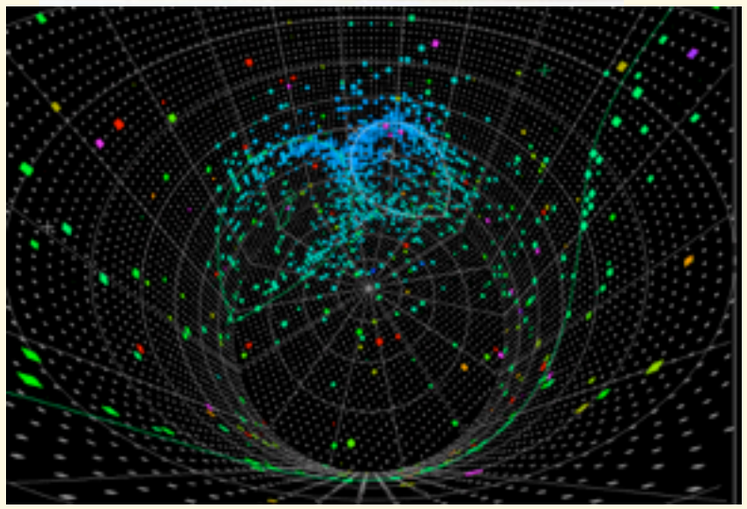

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Current Status

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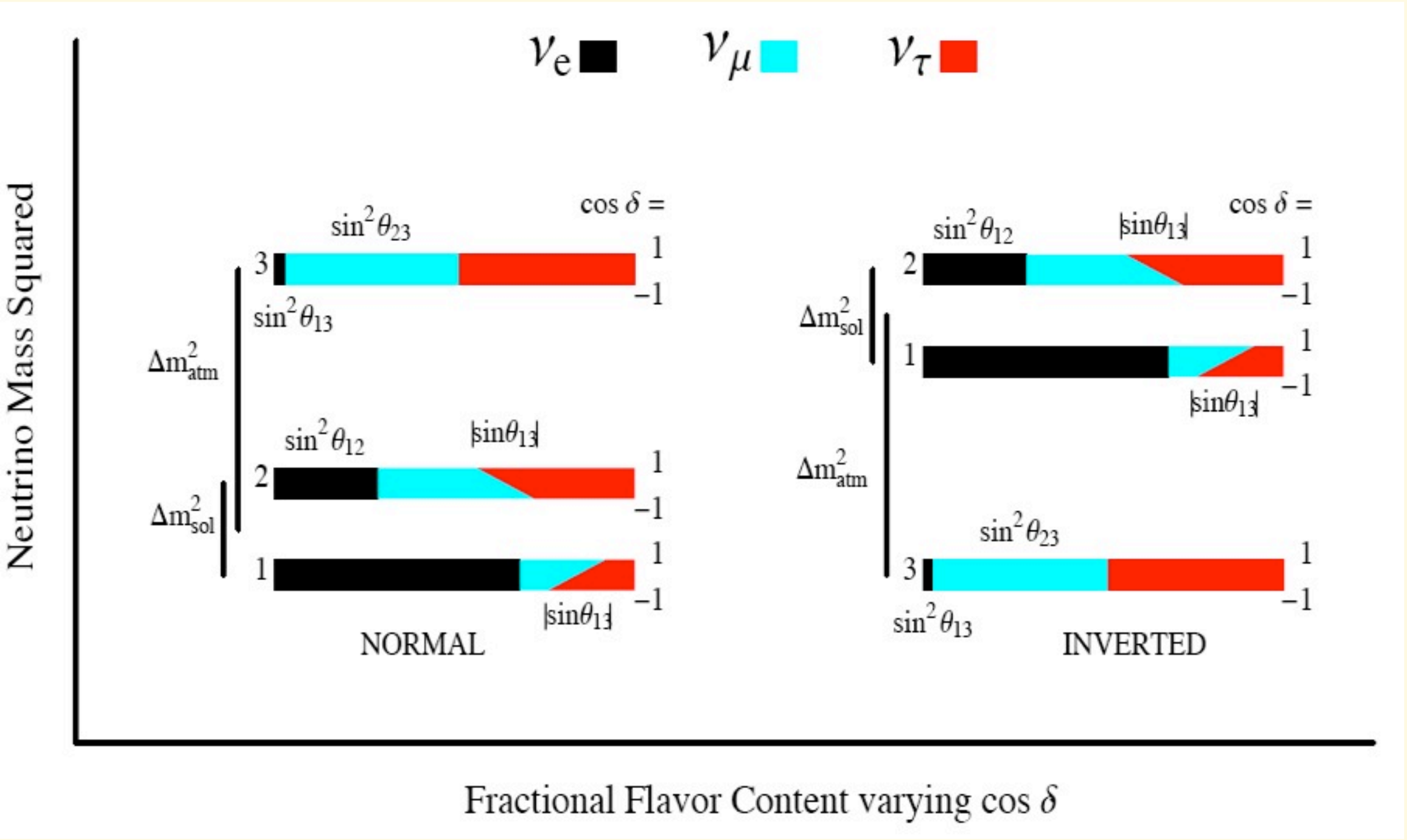

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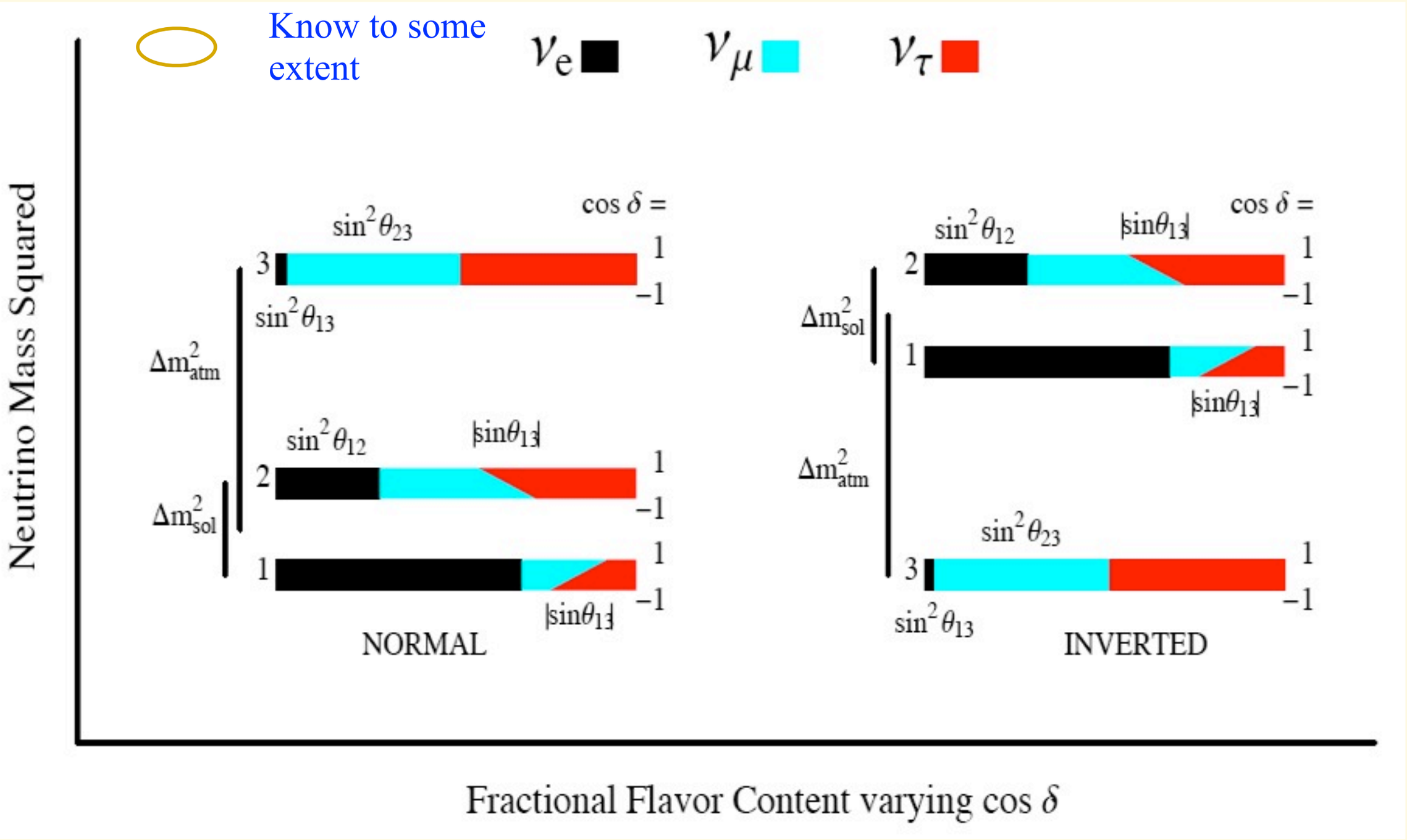

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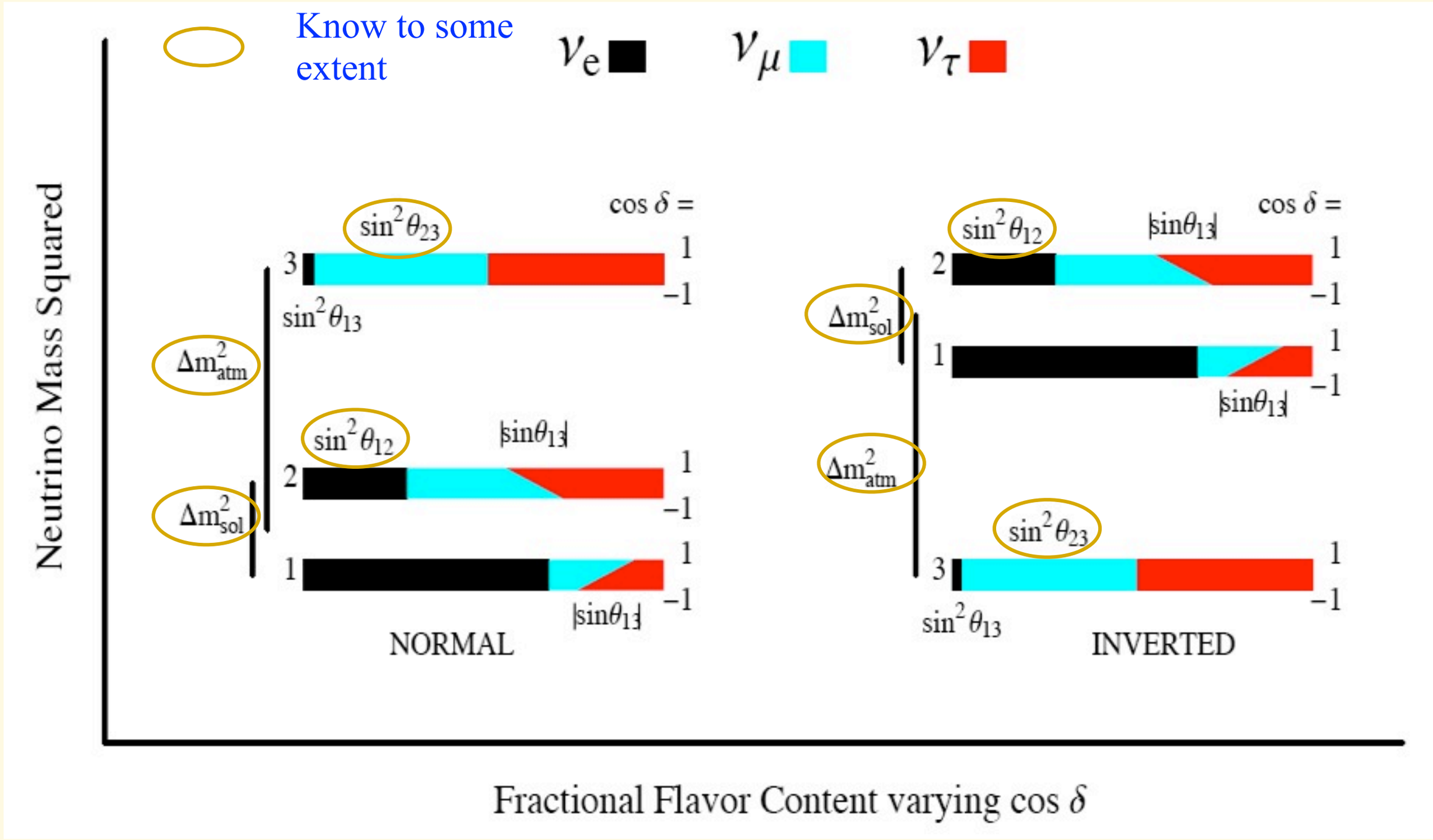

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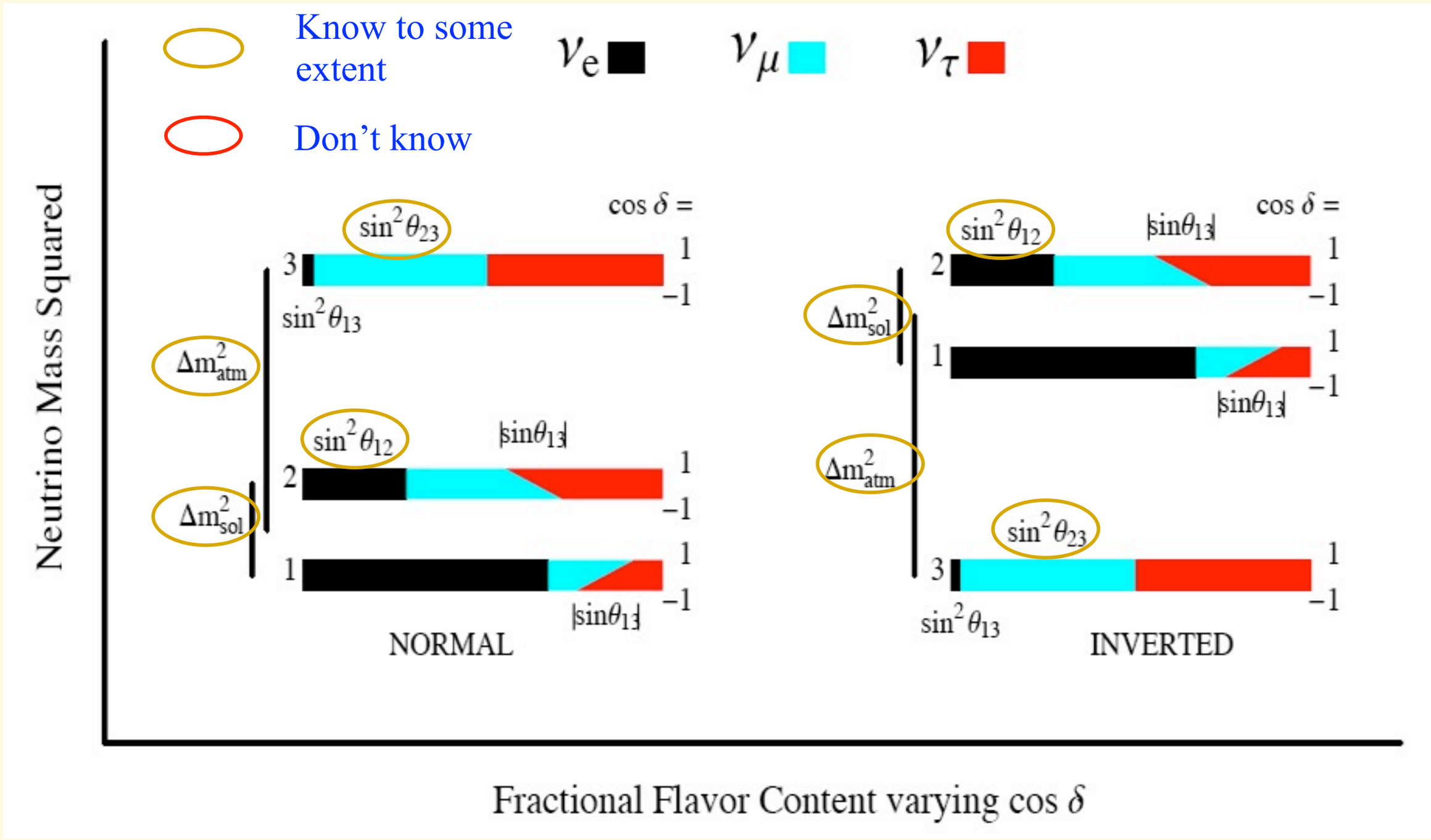

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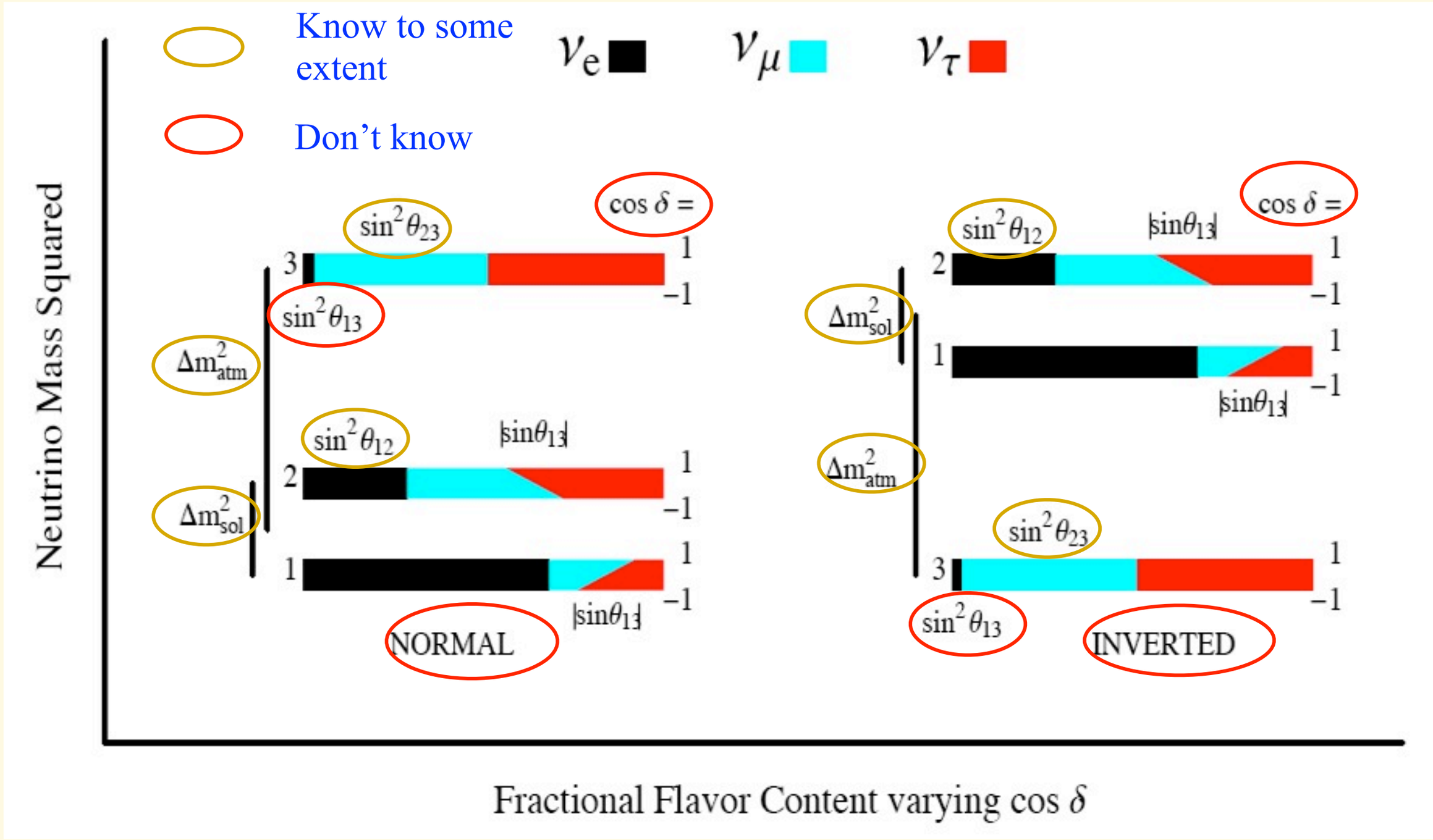

Graphical Representation

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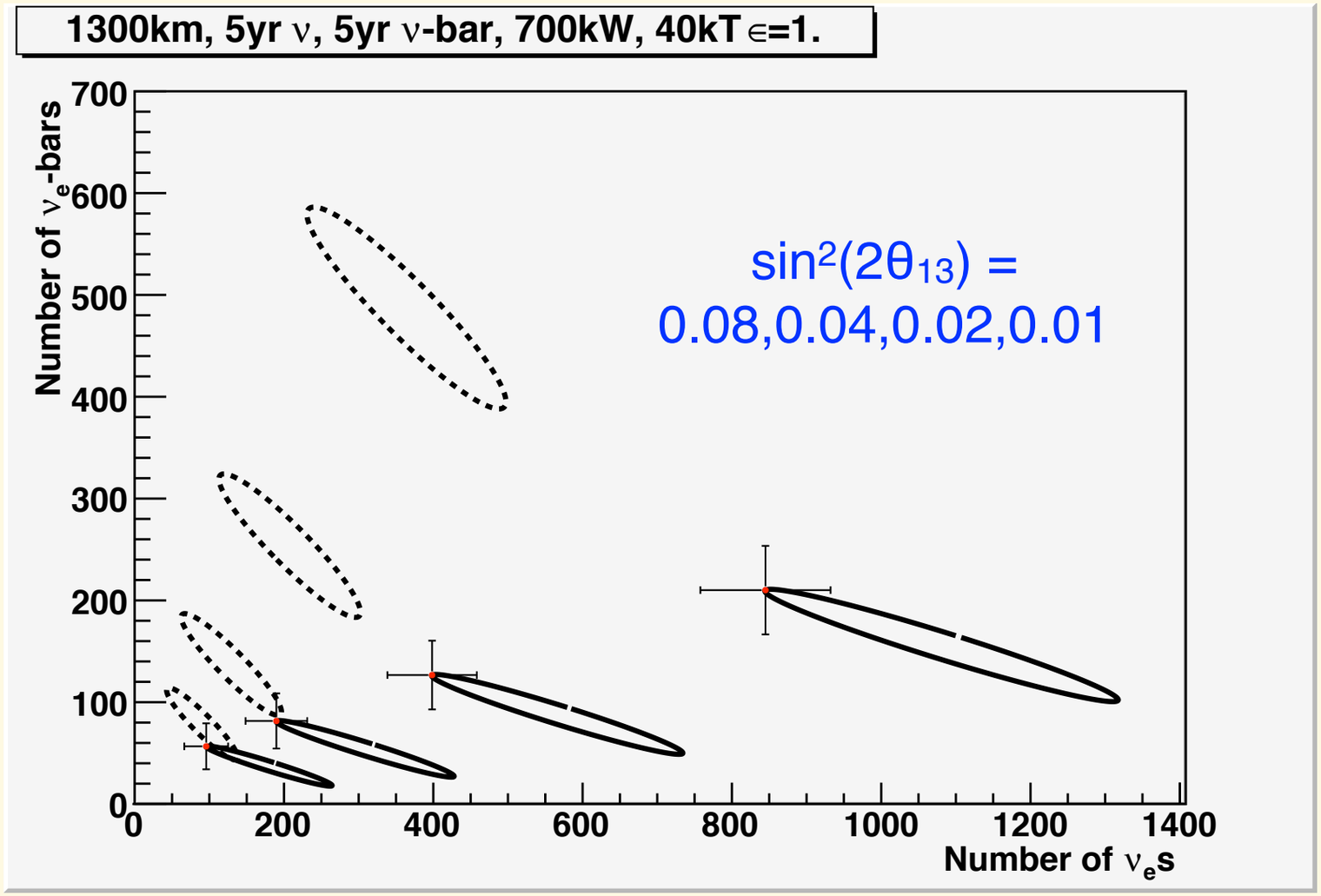
Typical LBNE Sensitivity



Solid: normal hierarchy; dashed: inverted

Ideal detector assumed in all cases

Error bars indicate 3σ; statistics only

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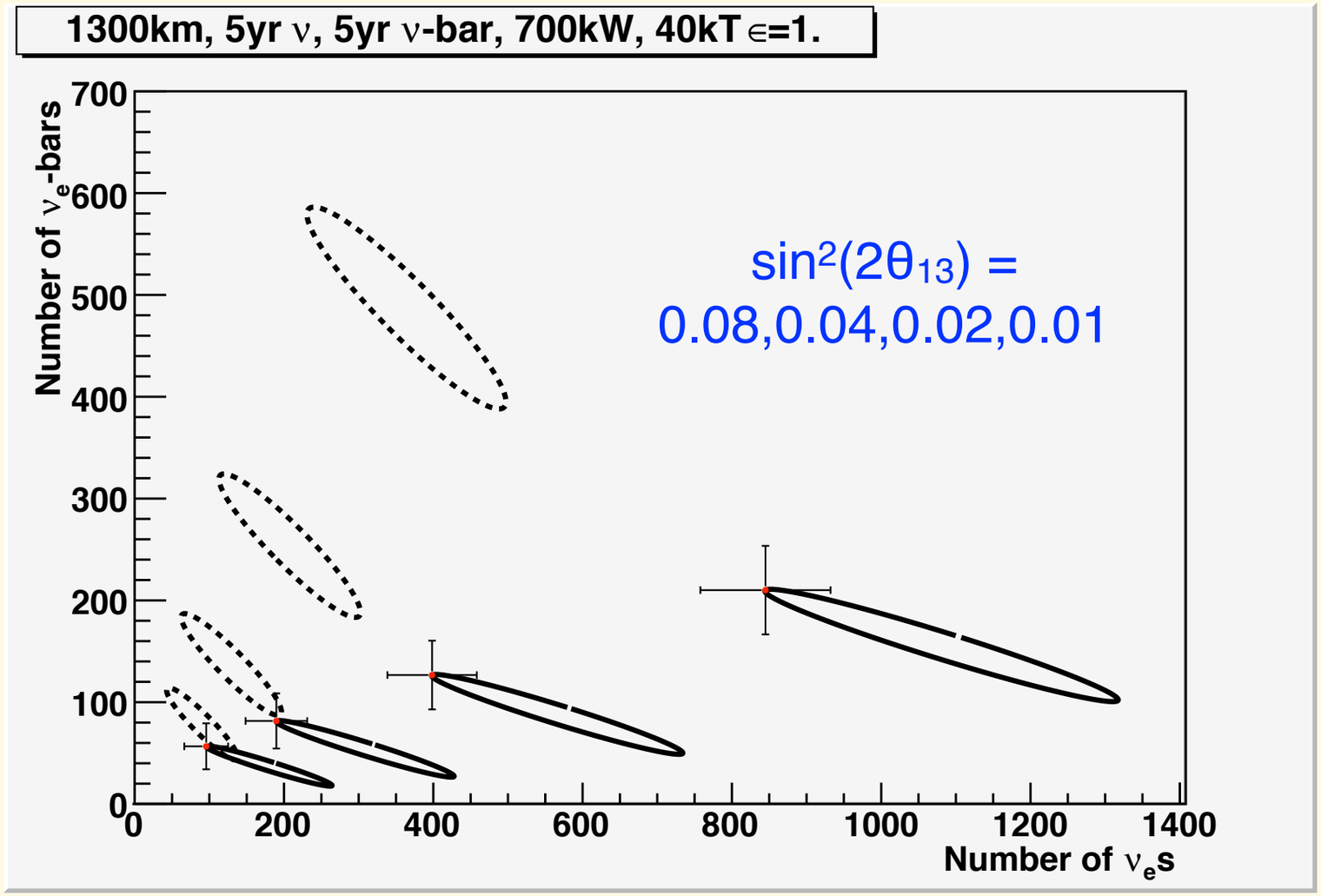

Solid: normal hierarchy; dashed: inverted
Ideal detector assumed in all cases
Error bars indicate 3σ; statistics only

- As θ_{13} increases ellipses move out
- As θ_{13} decreases, the two sets of ellipses become less separated
- The statistical significance of CP violation is independent of the value of $\sin^2(2\theta_{13})$
- But for low values of $\sin^2(2\theta_{13})$ there is ambiguity between hierarchy and δ_{CP}

Fitting for 3 Parameters

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- The other oscillation parameters (θ_{12}, θ_{23}, Δm^2_{12}, Δm^2_{23}) are kept constant at their best measured values
- Later on one might be able to add additional constraints, eg value of θ_{13} from reactors or from NOvA or T2K

Energy Spectra (700kW)

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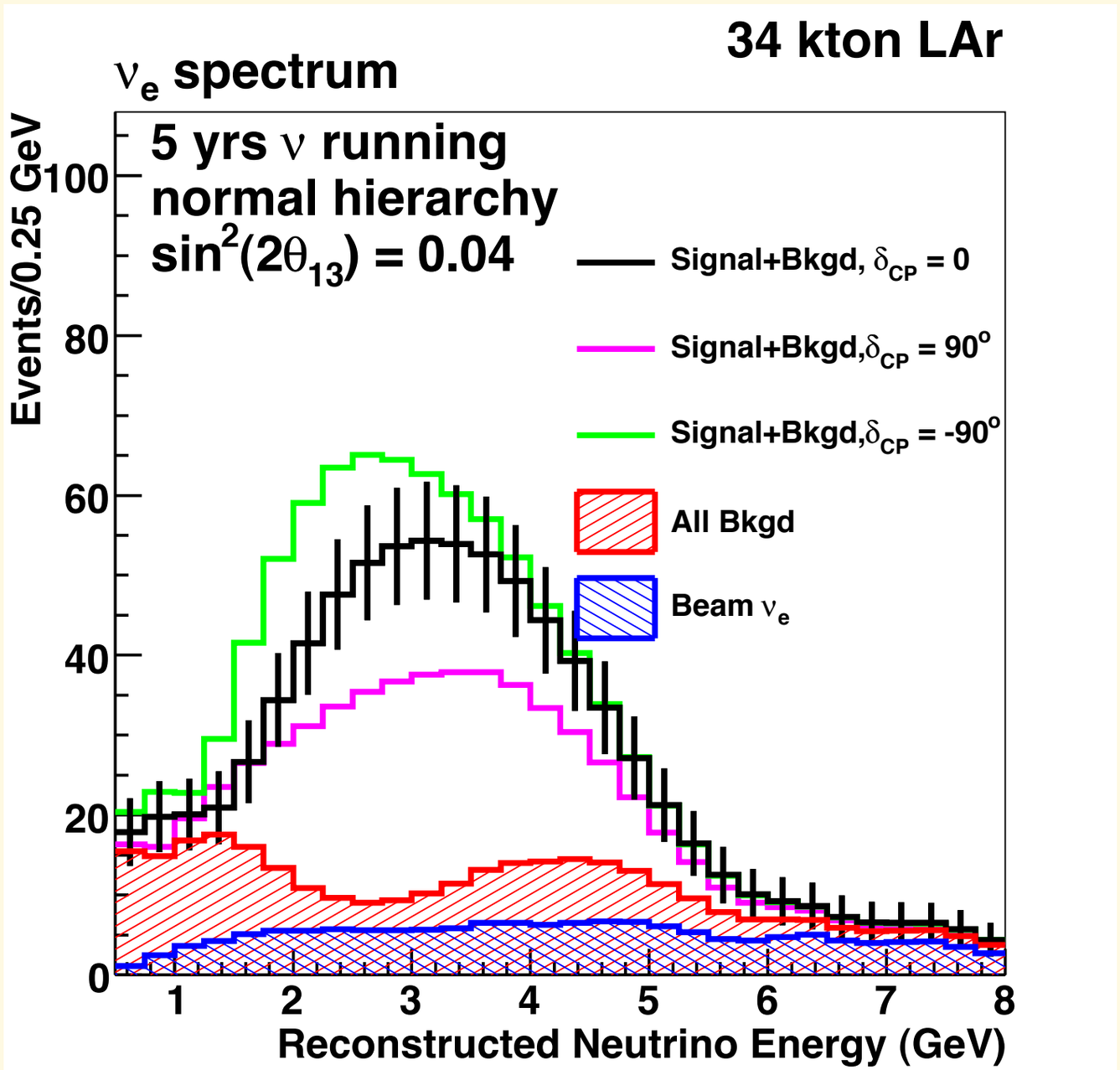
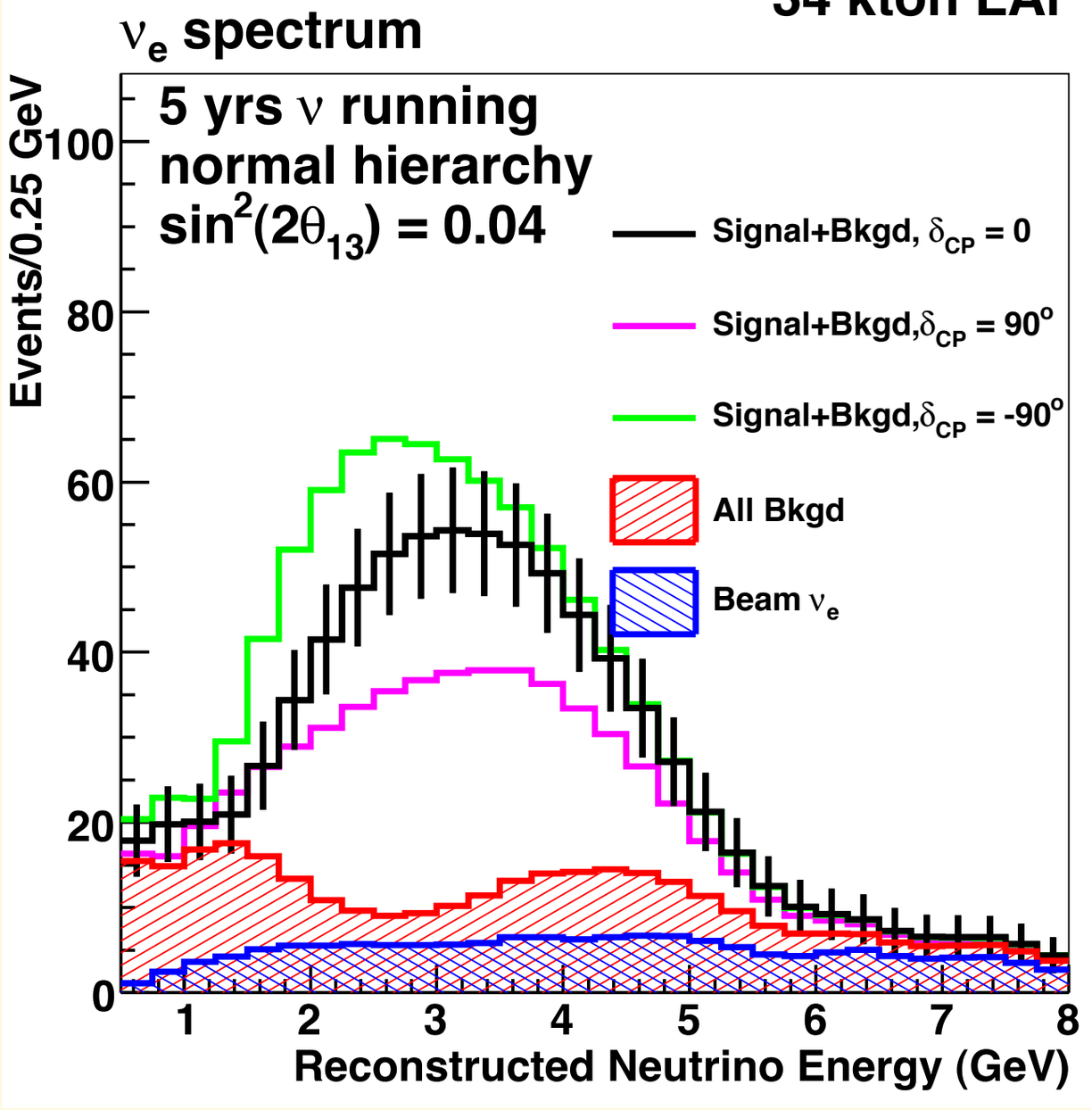
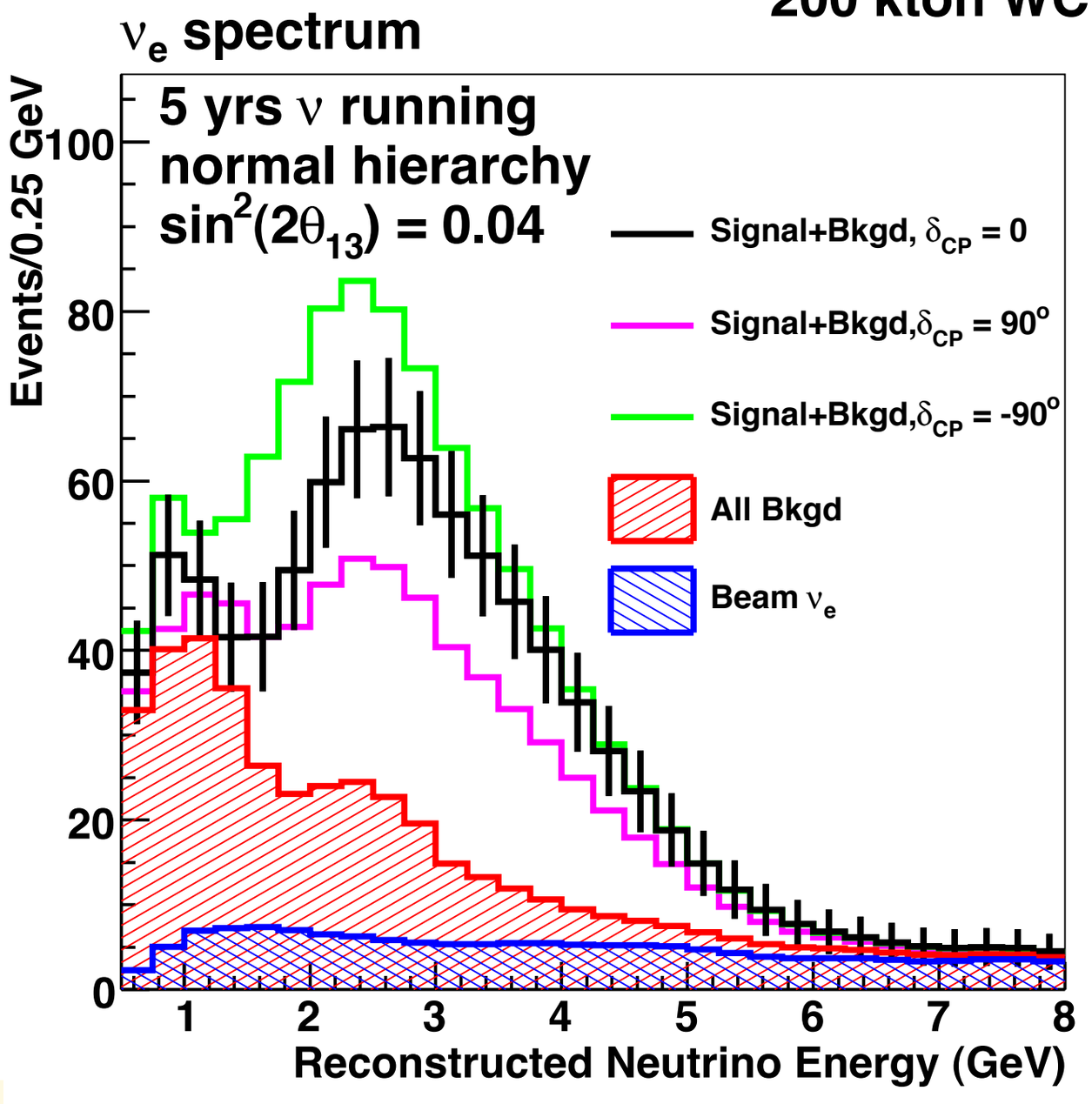


Energy Spectra (700kW)

34 kton LAr



200 kton WC



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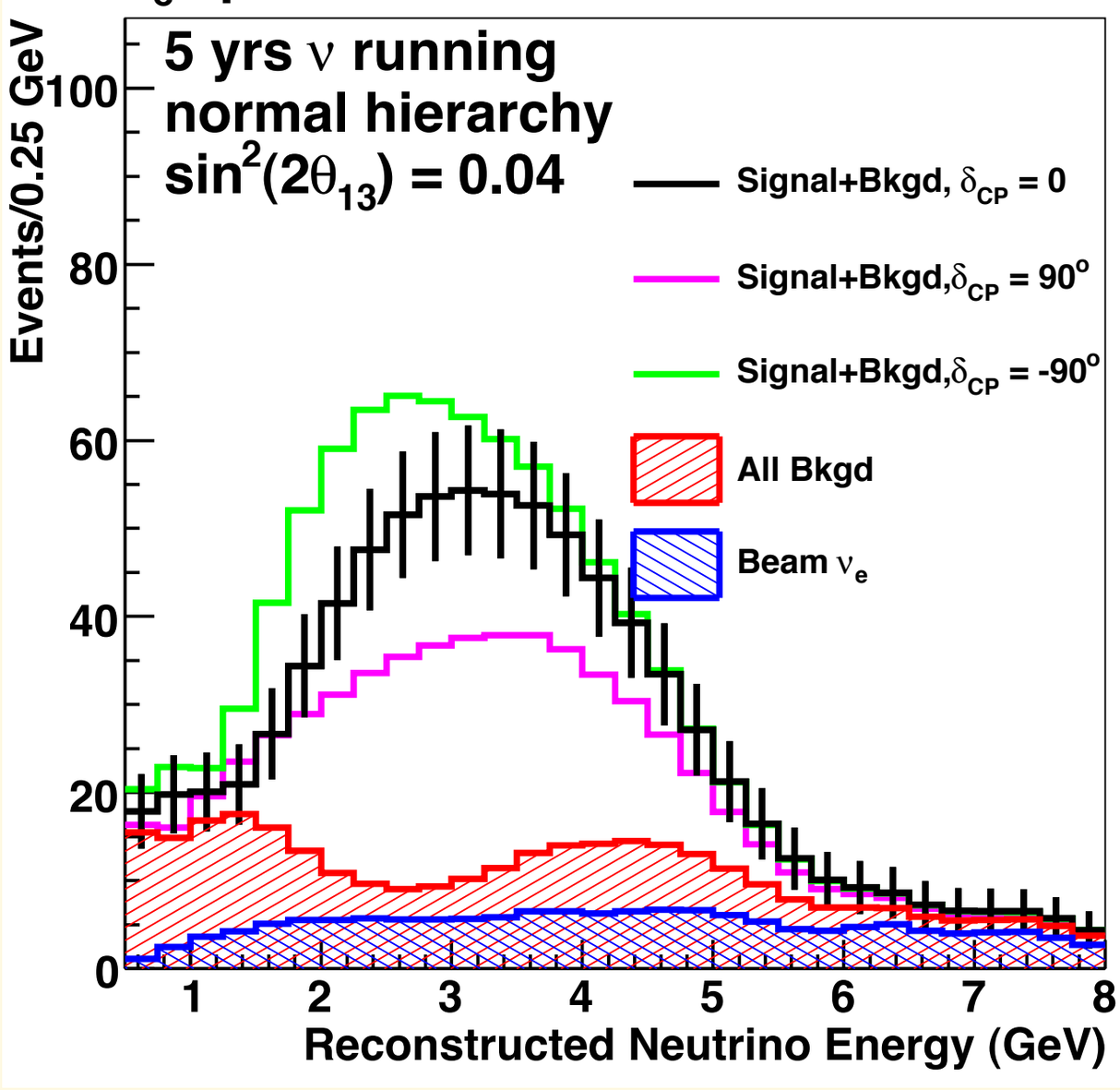

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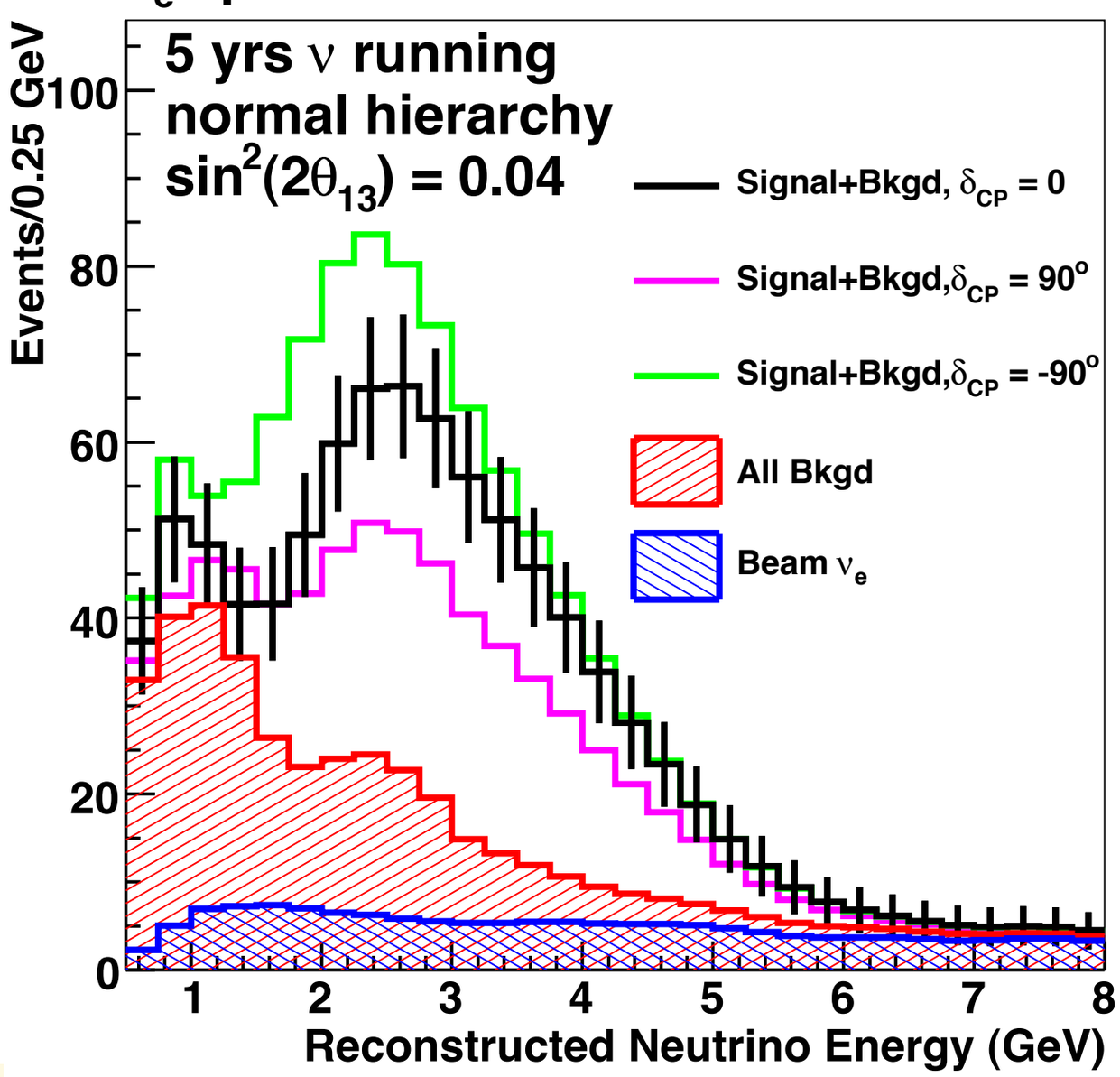

1 kt of LAr gives comparable sensitivity as 6 kt of H_20 mainly due to reduction of NC background

Sensitivity for $\sin^2(2\theta_{13})$

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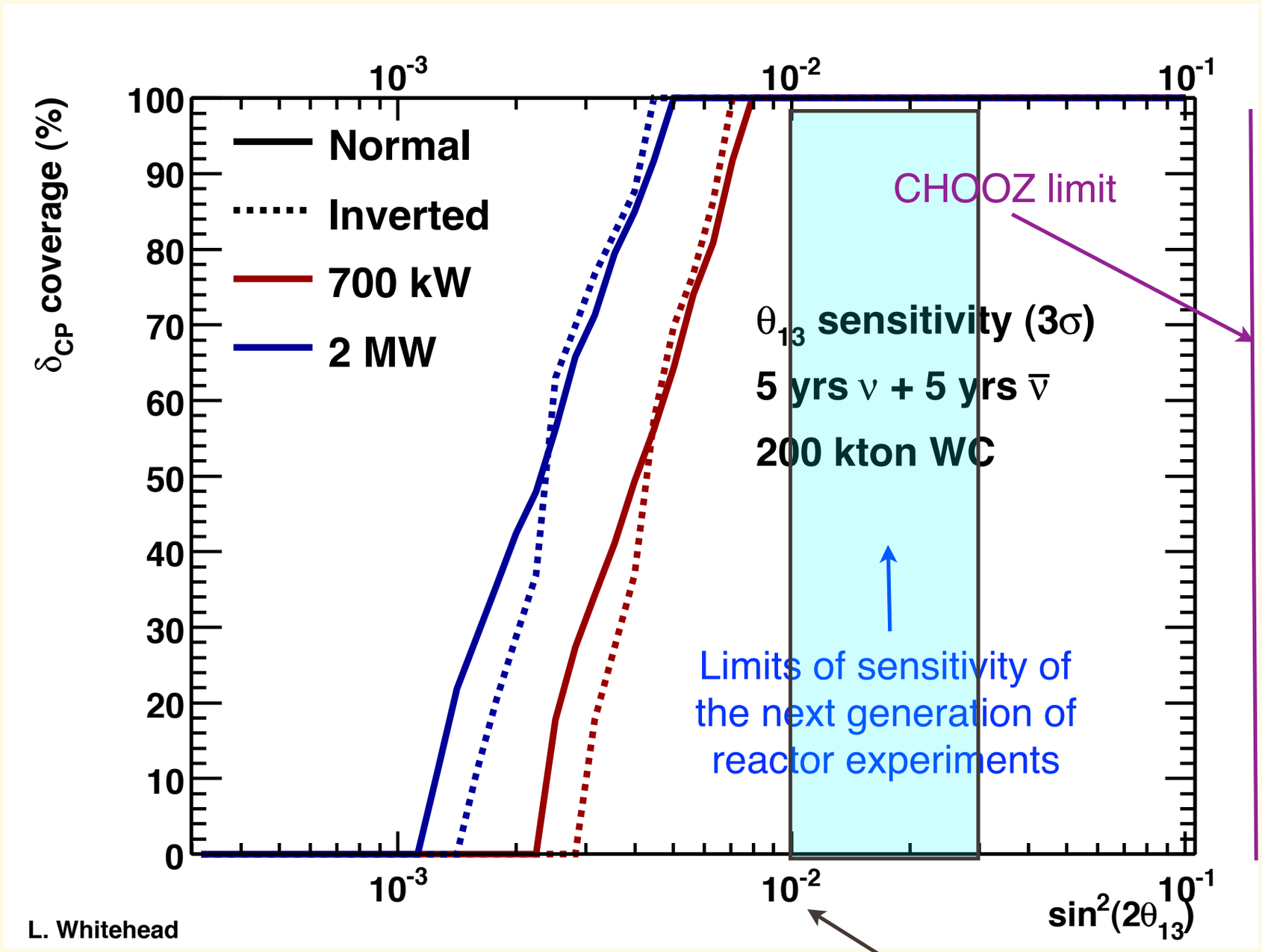
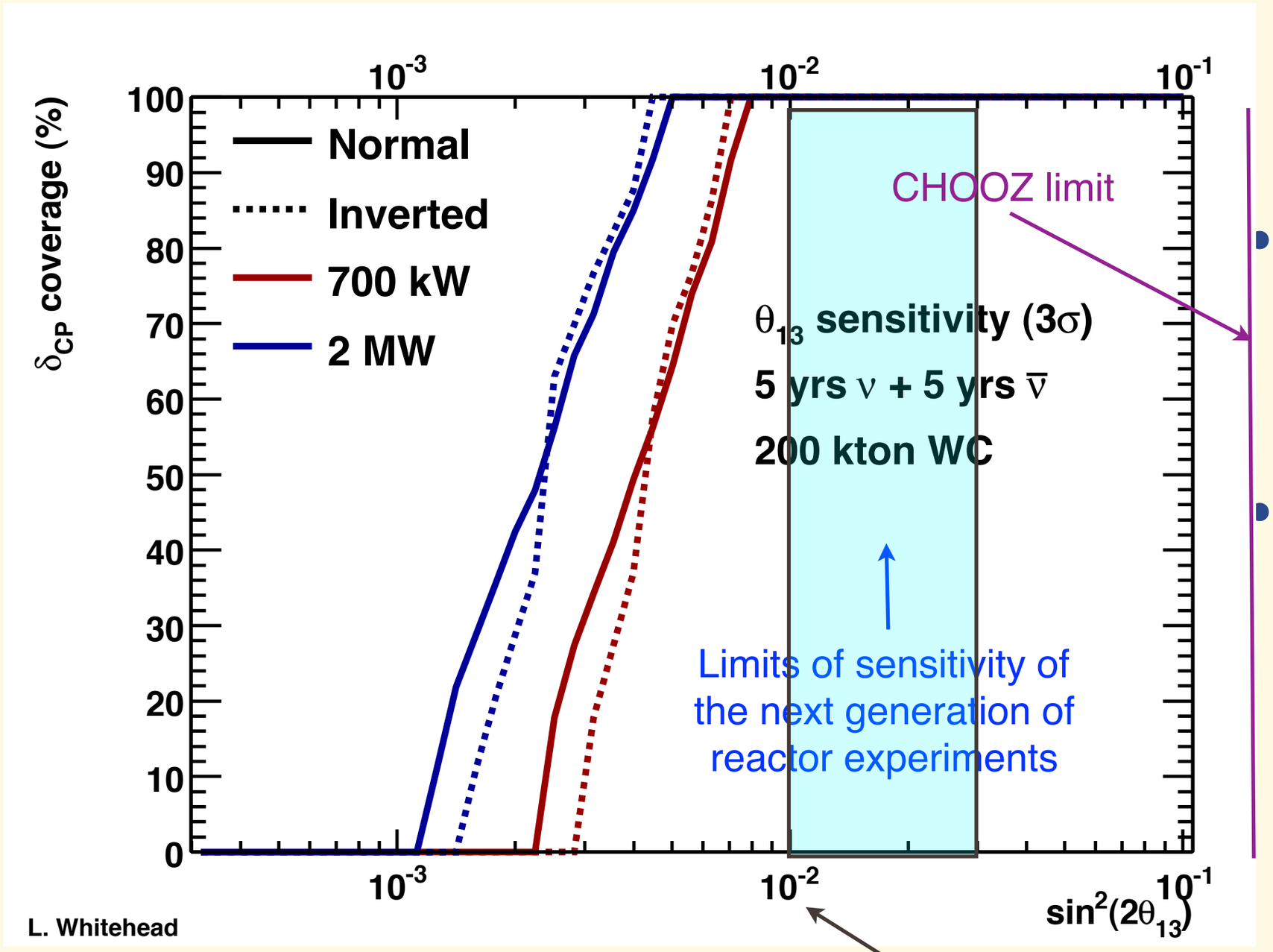


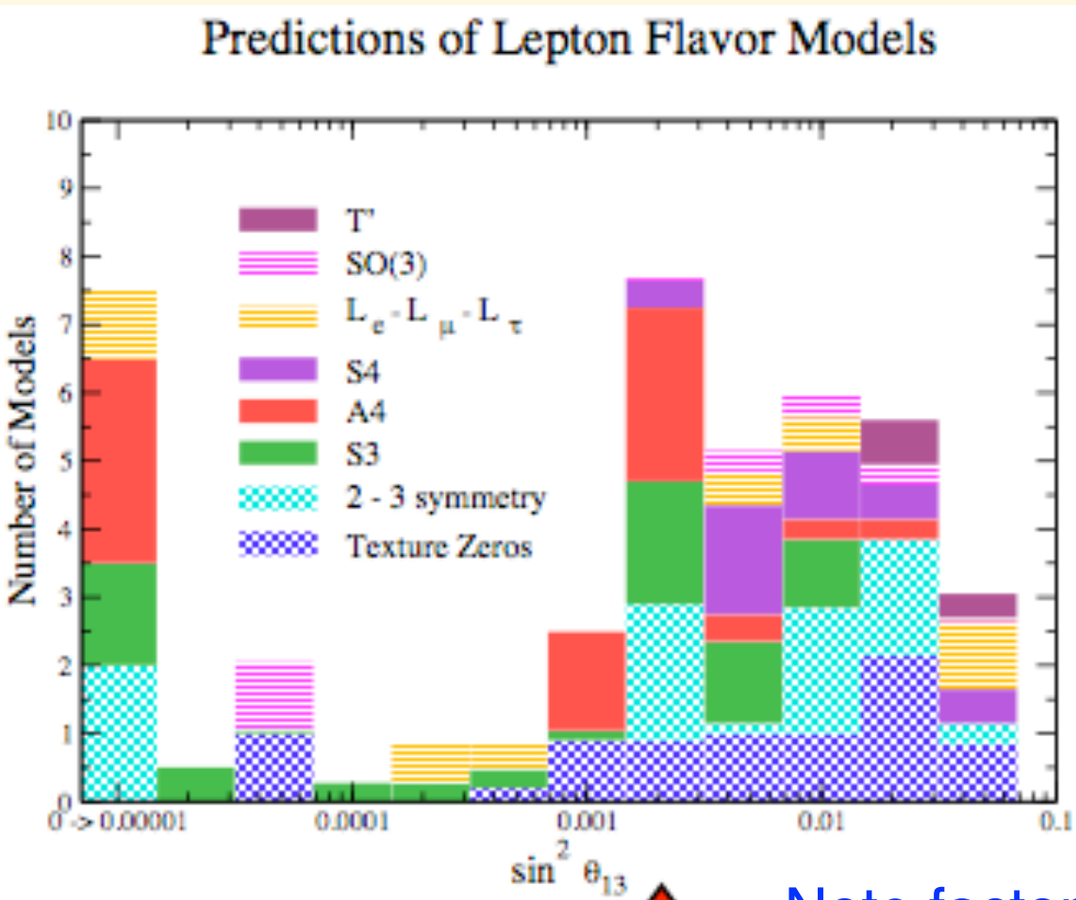
Sensitivity of NOvA and T2K "wiggles" around this value

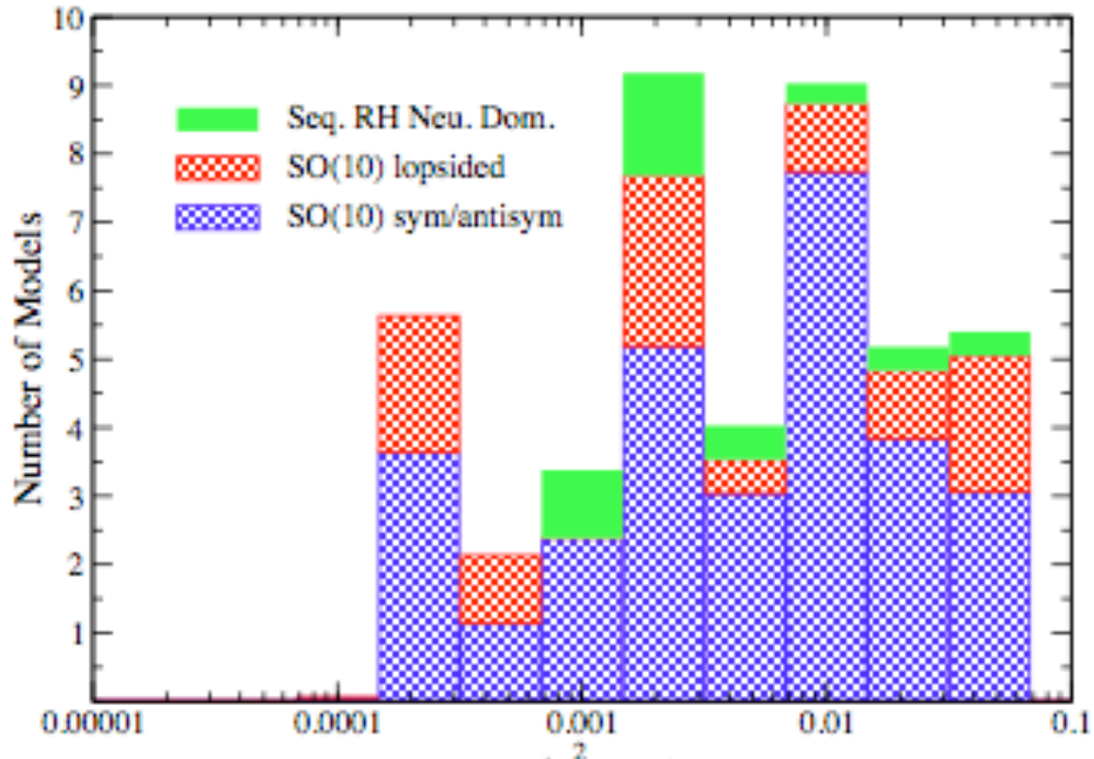
Sensitivity for $\sin^2(2\theta_{13})$



- Project X can extend $\sin^2(2\theta_{13})$ reach by ~2
- This will address predictions of a number of models

Theoretical Predictions





Note factor of 4 difference from previous plot in horizontal scale

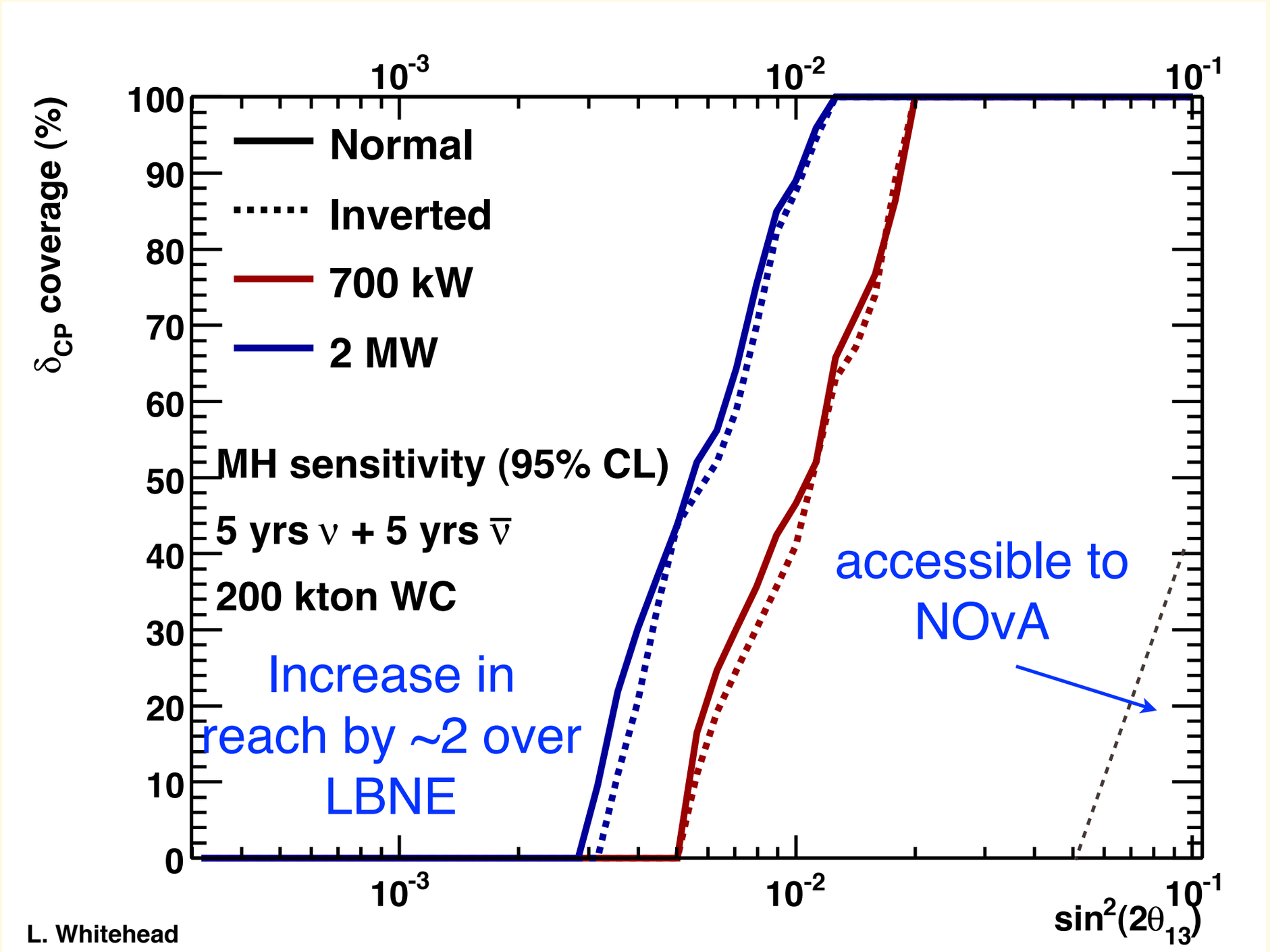
How do we distinguish Models with the same $\sin^2\theta_{13}$?

By relationships with other parameters:
e.g. $\theta_{12} - \theta_{13}\cos(\delta) = \sqrt{1/3}$
but there are many such examples.

This will require precision measurements of $\sin^2\theta_{13}, \sin^2\theta_{12}, \sin^2\theta_{23}$ and δ_{CP}

C. H.Albright International Workshop on Neutrino Telescopes March 10-13, 2009

Sensitivity for Mass Hierarchy



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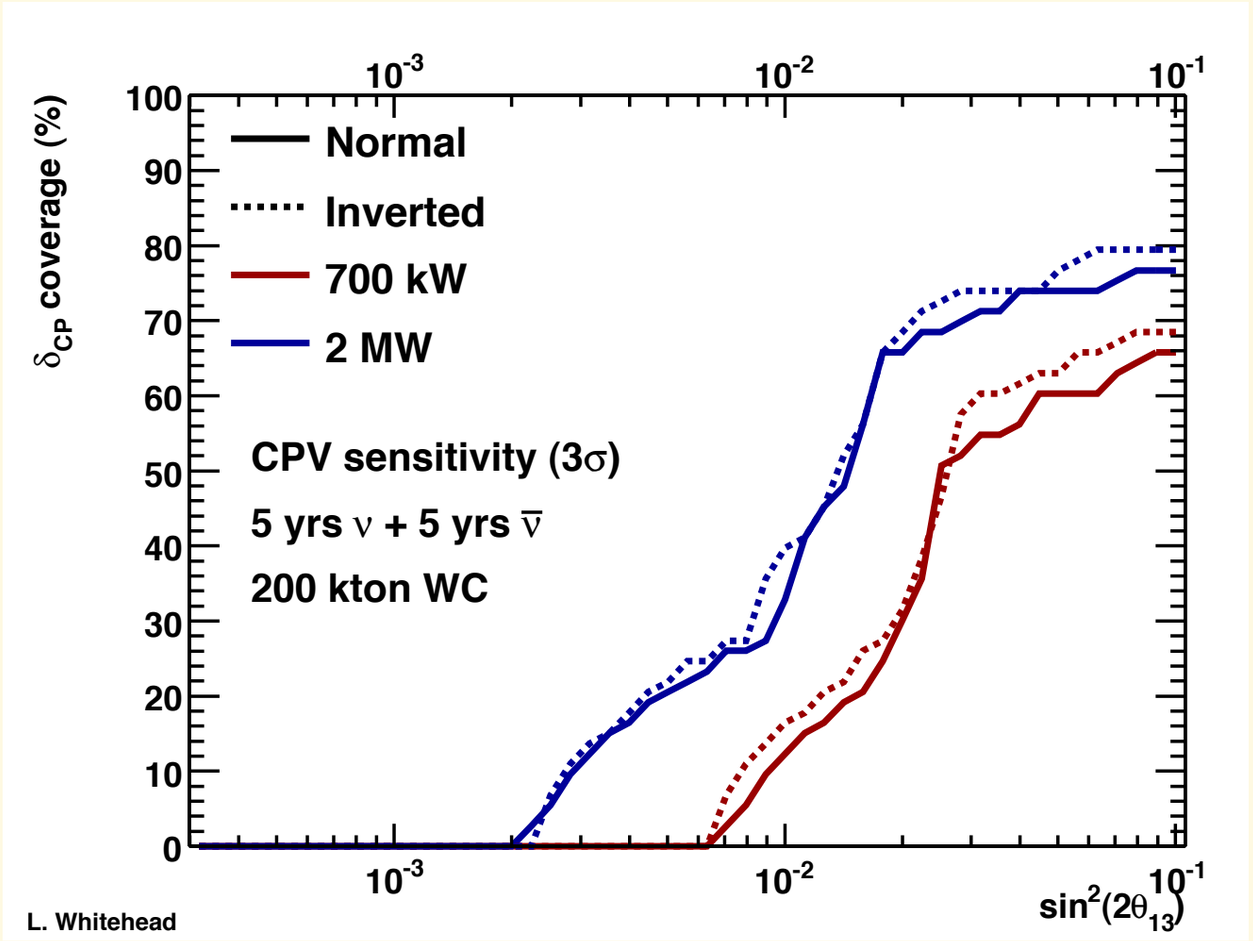

Increase in δ_{CP} coverage by 2-2.5 over LBNE coverage

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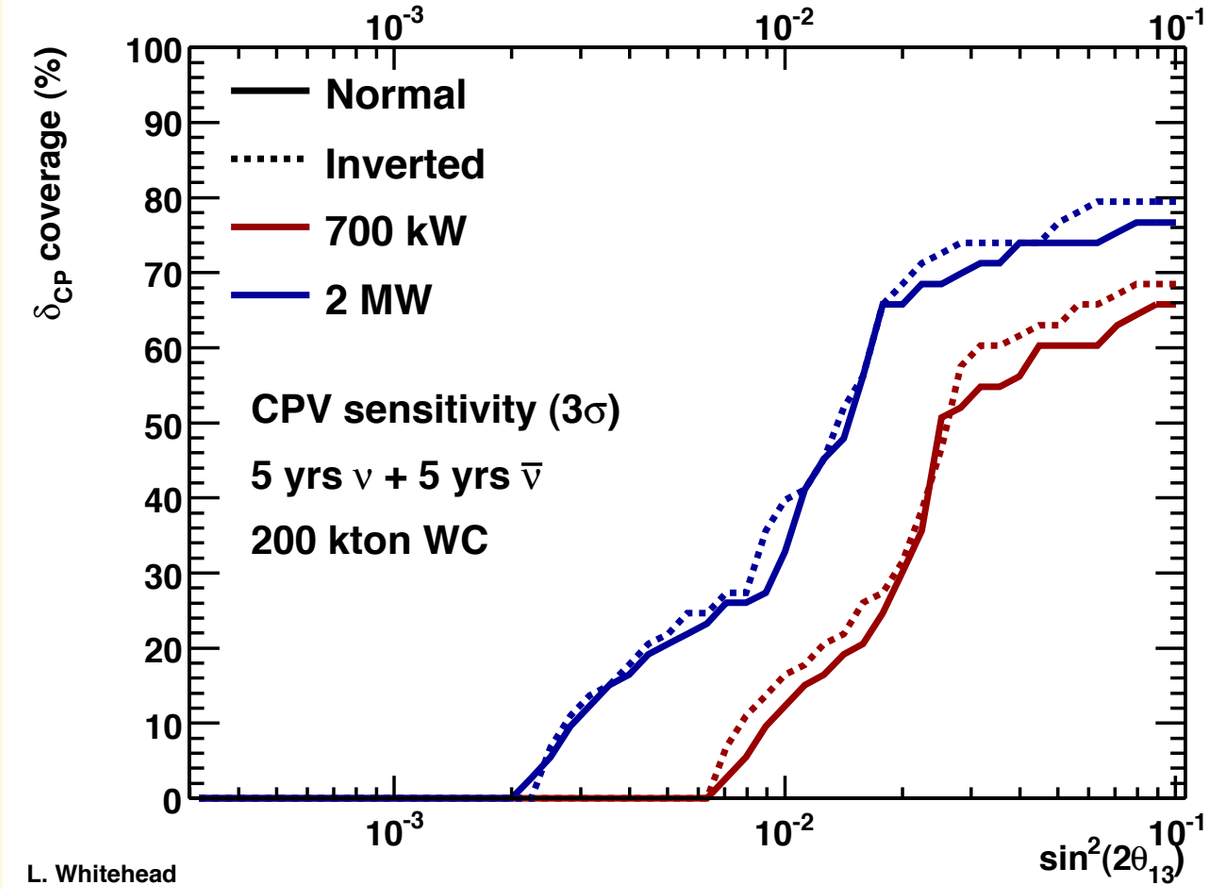

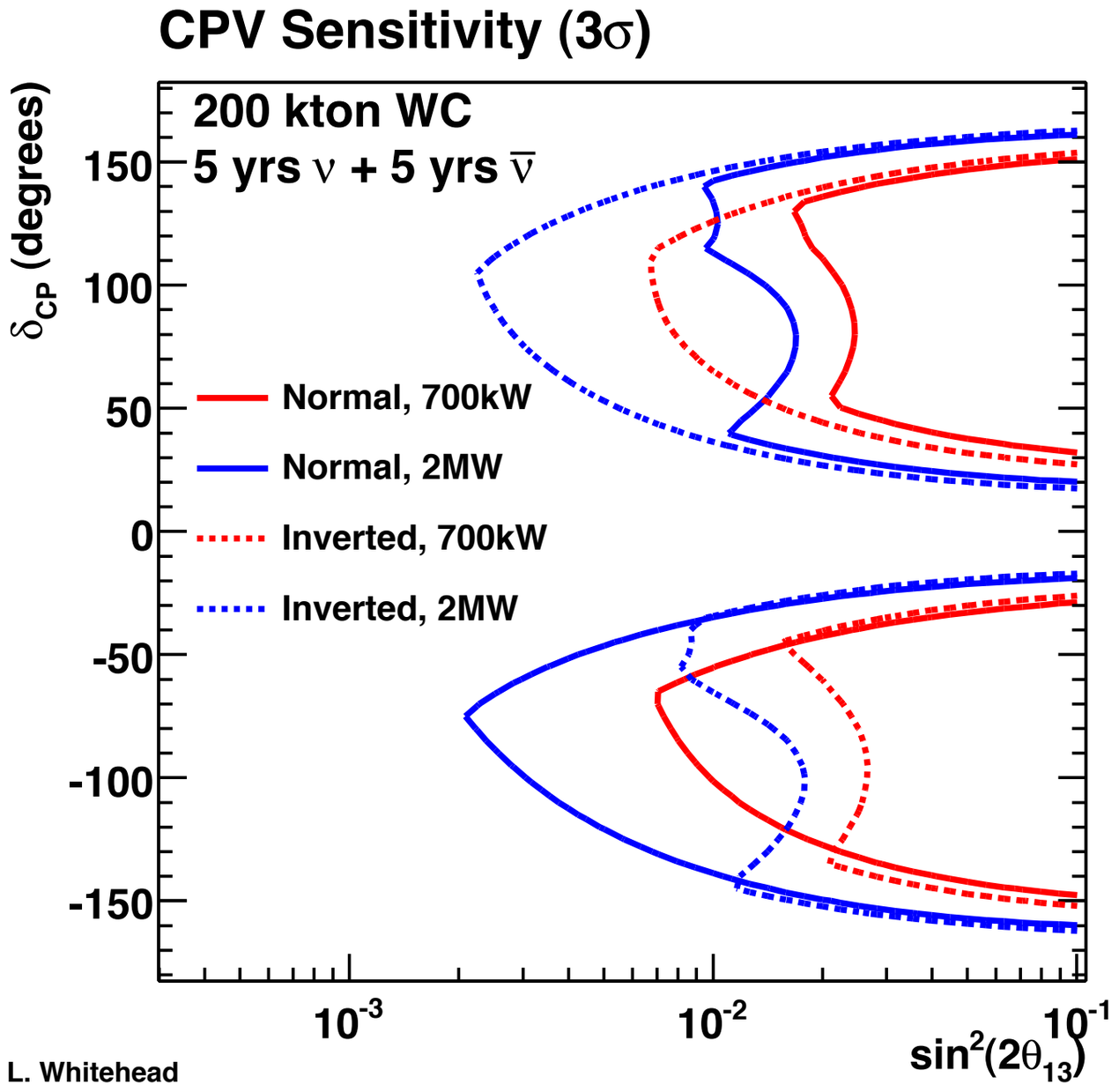

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CP/Hierarchy Ambiguity

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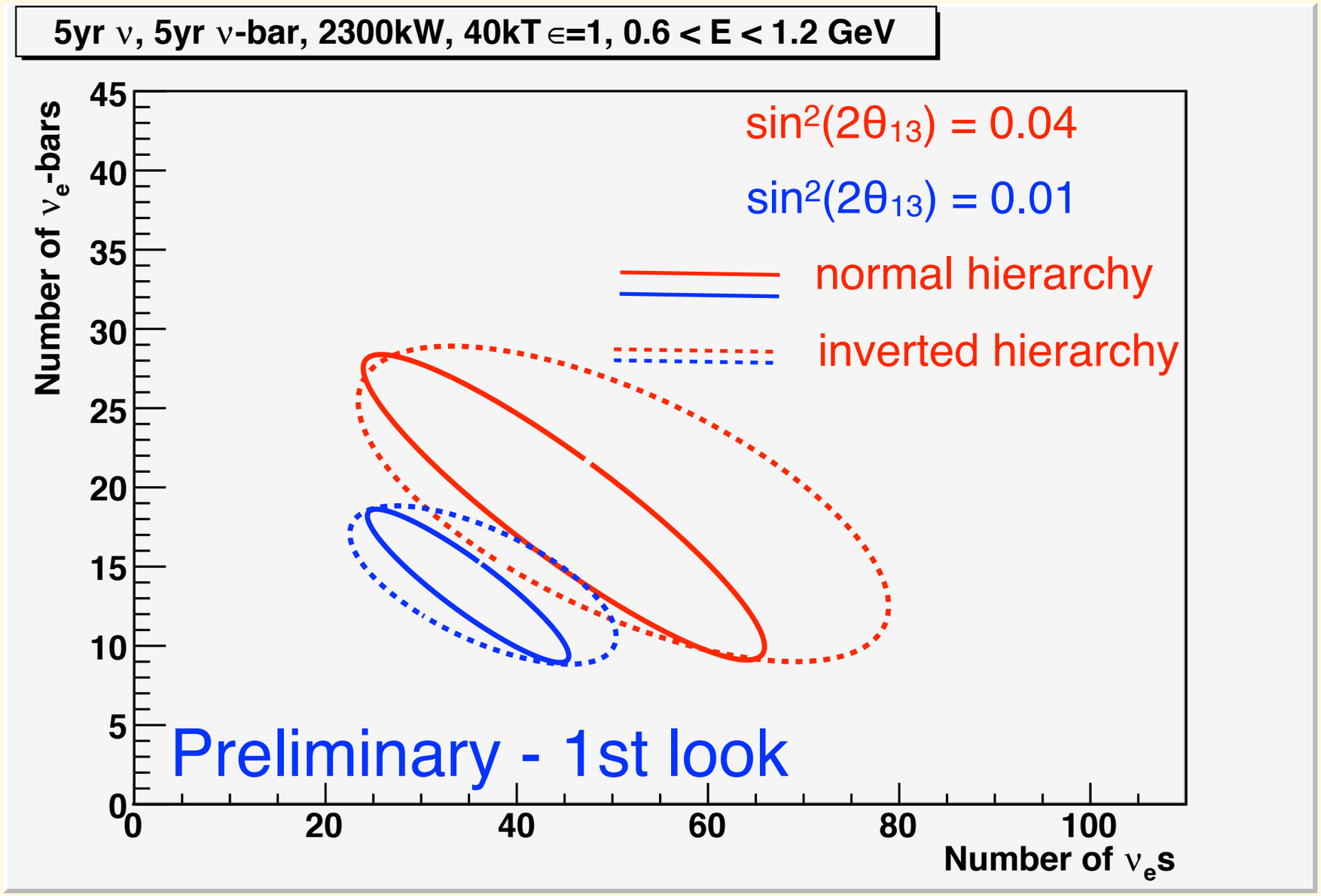
- Resolving this ambiguity is a significant experimental challenge
  - Interesting possibility: study 2nd maximum ($\delta_{CP}=3\pi/2$) CP effects there~3 times larger, matter effects smaller

Ellipses for Low Energy



Relatively small difference between 2 mass hierarchies

For this beam statistics are poor in this limited energy region

The efficiency difference between WC and LAr is less here

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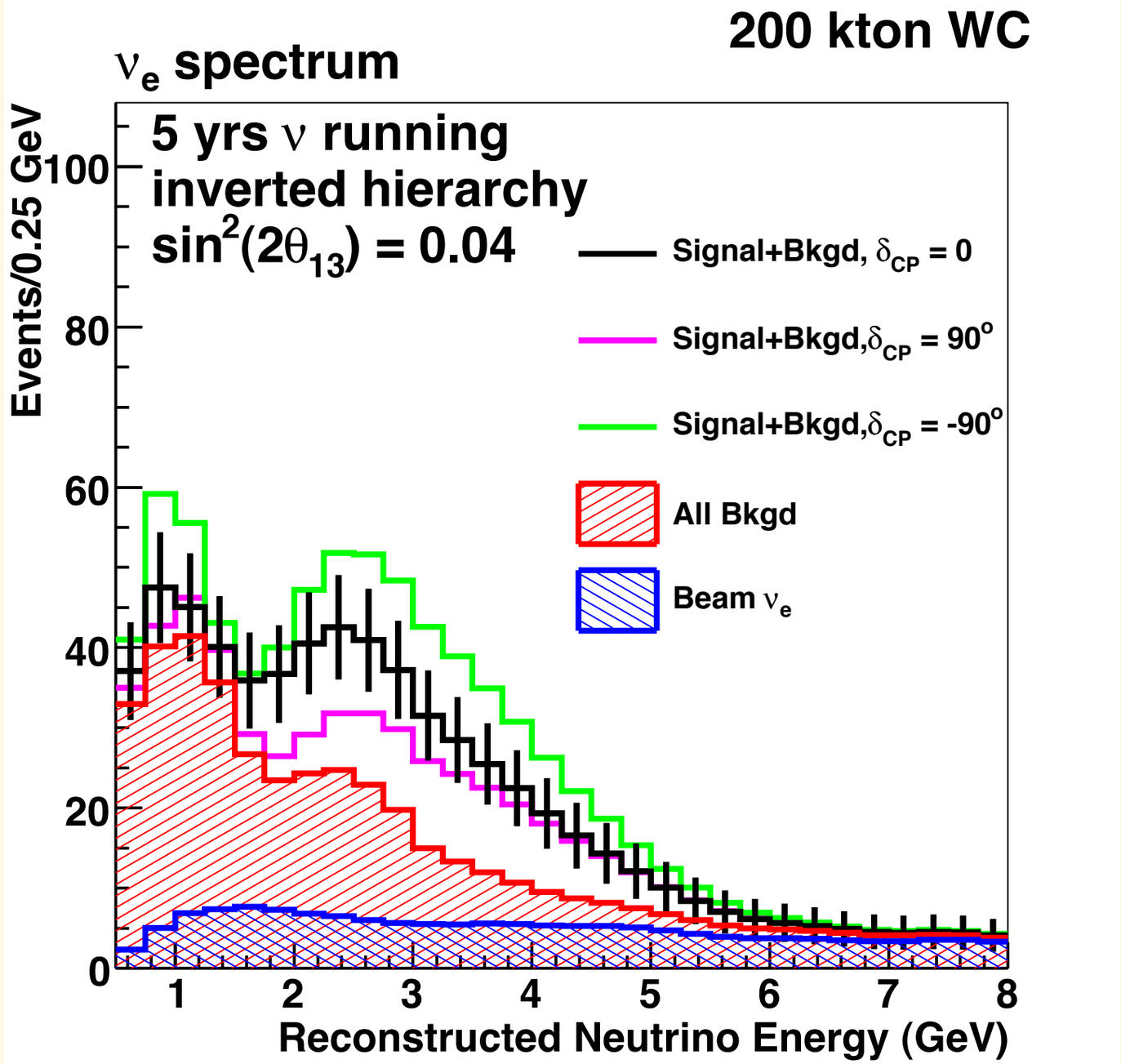

Energy Spectra (700kW)

200 kton WC

ν_e spectrum

5 yrs ν running
inverted hierarchy
$\sin^2(2\theta_{13}) = 0.04$

Signal+Bkgd, $\delta_{CP} = 0$
Signal+Bkgd,$\delta_{CP} = 90^o$
Signal+Bkgd,$\delta_{CP} = -90^o$
All Bkgd
Beam ν_e

Events/0.25 GeV

Reconstructed Neutrino Energy (GeV)

200 kton WC

$\bar{\nu}_e$ spectrum

5 yrs $\bar{\nu}$ running
normal hierarchy
$\sin^2(2\theta_{13}) = 0.04$

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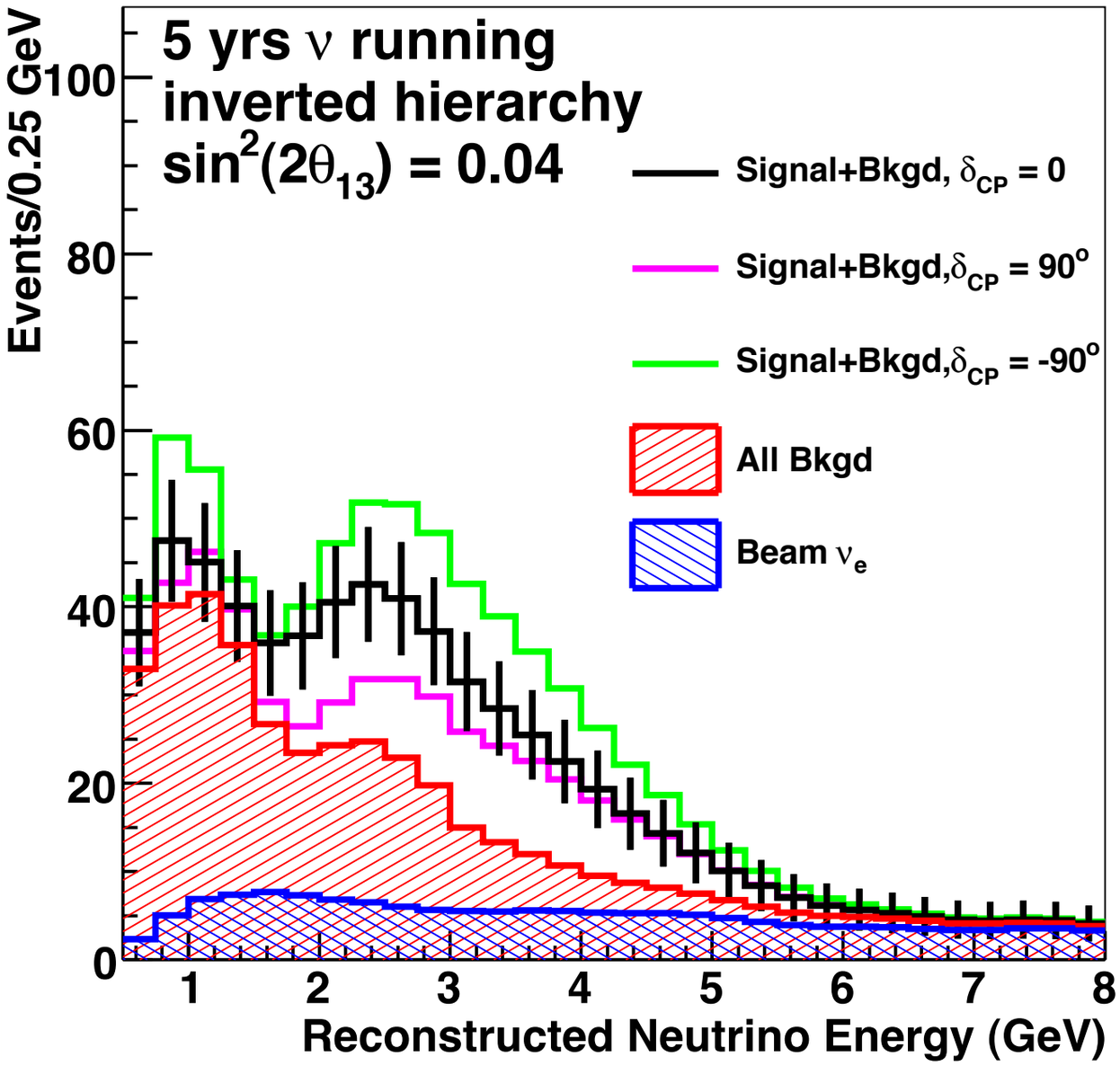
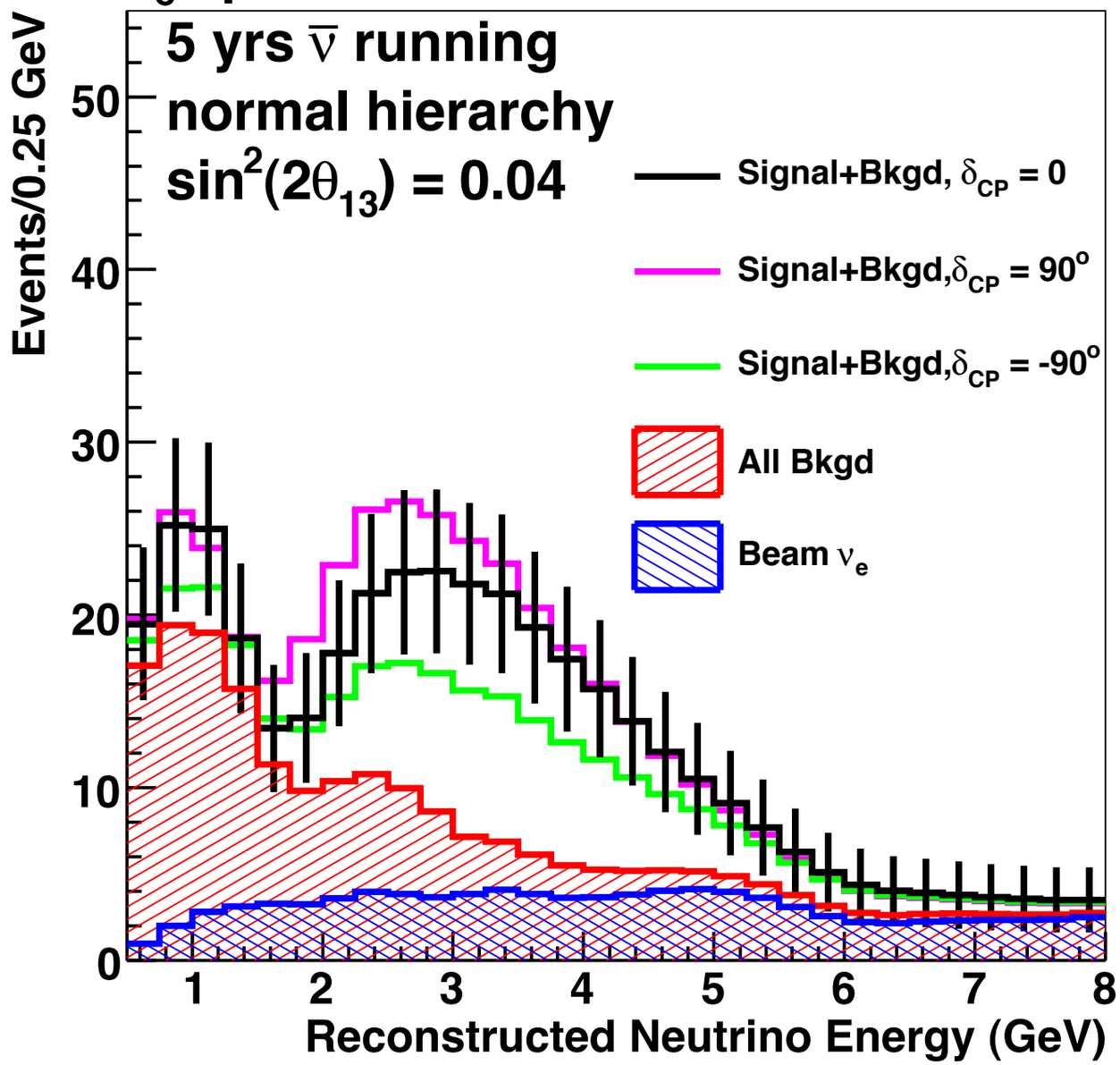


200 kton WC

$\bar{\nu}_e$ spectrum



The statistics at 2nd maximum are rather poor and the backgrounds quite high

ν beam from 8 GeV p's

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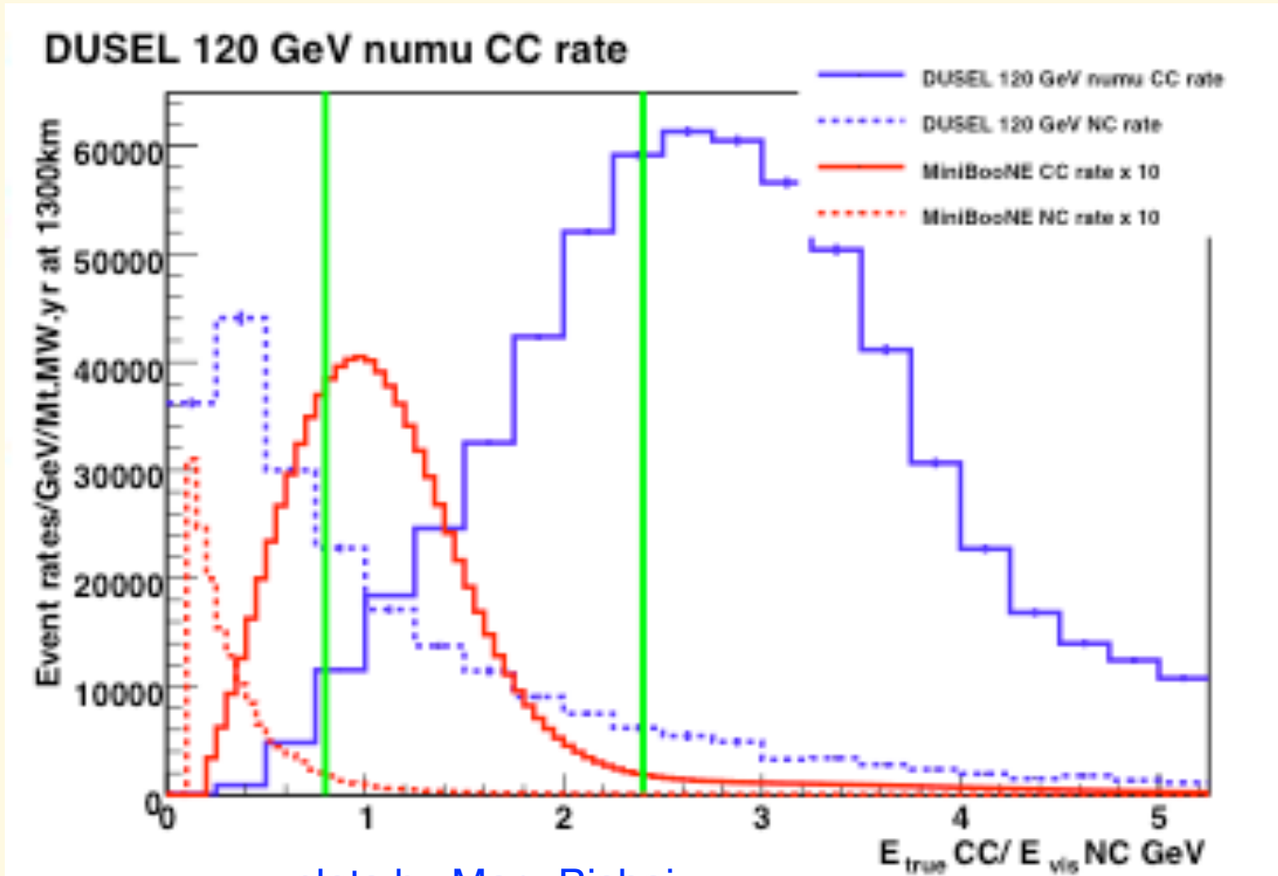


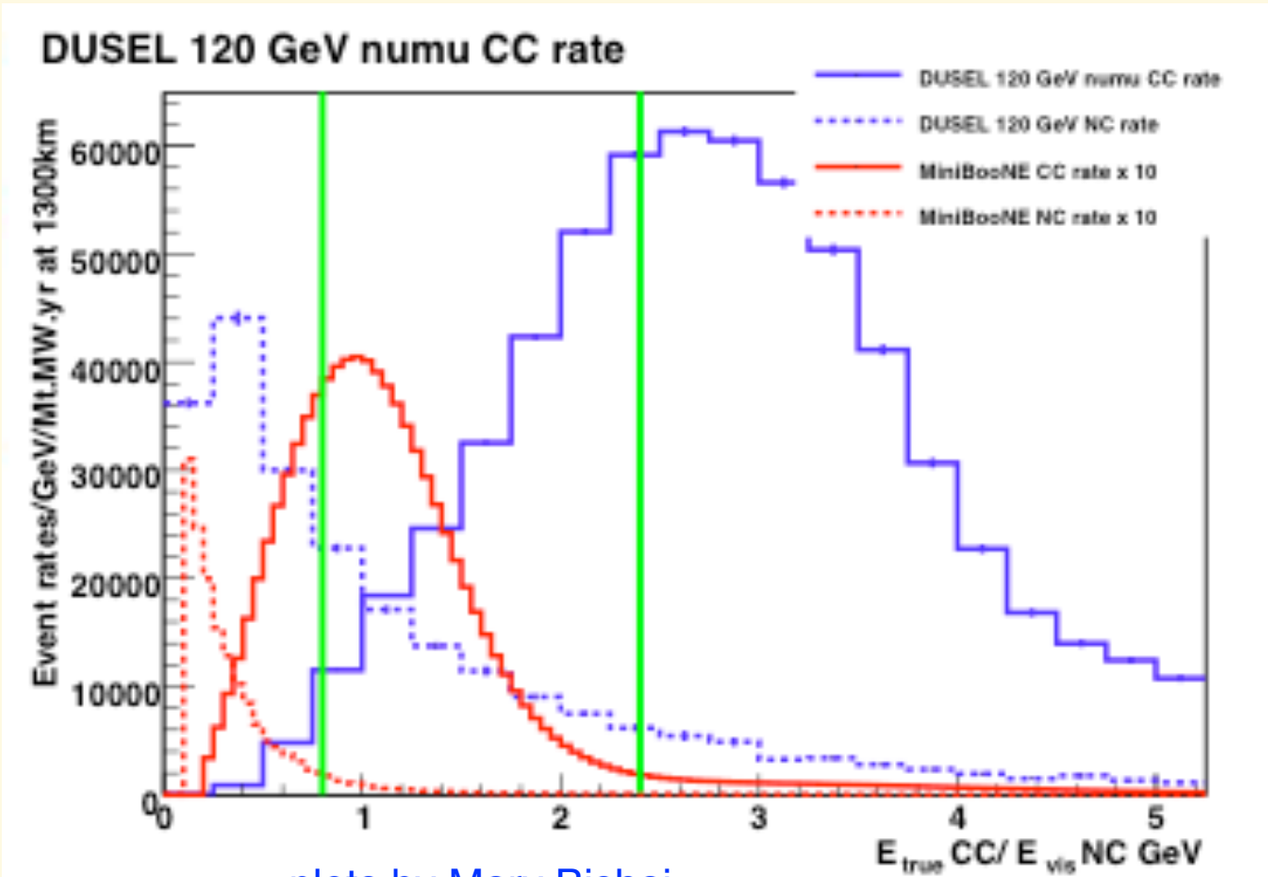
plots by Mary Bishai

ν beam from 8 GeV p's

Advantages

- CC/NC ratio higher by ~50
- Hence NC background down
- Optimized beam design

could decrease ν_e background from μ decays by ~3-4



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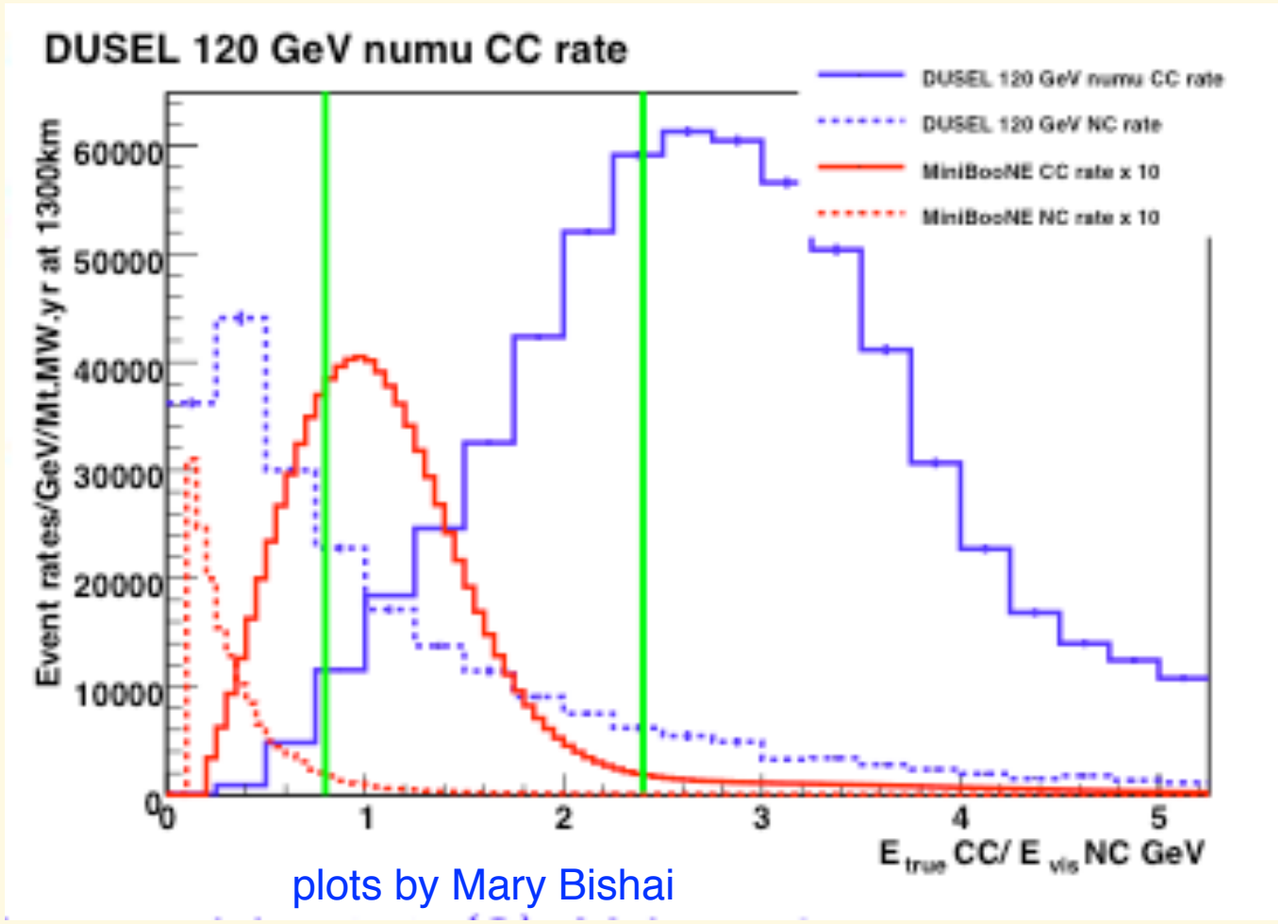

plots by Mary Bishai

So far no detailed studies exist of this option

My "back-of-the-envelope" calculations indicate that for 1MW, 200 kt and 3 yrs one might see ~30-40 ν_e events with low background for $\sin^2(2\theta_{13})=0.01$

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  - Investigation of LSND/MiniBooNE anomaly

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  - Copious source of neutrinos in the 1-4 GeV range (exotica?)
  - Possibilities for specialized experiments in front of Near Detector
- Experiments based on 3 and/or 8 GeV proton beams (versatility of Project X)
  - Investigation of LSND/MiniBooNE anomaly
- Not much work in this area so far

Non-ν_e Oscillation Physics

What is the deep underlying principle that determines the mass splittings and the mixing angles?

We might get some insight into this question by looking for patterns and symmetries eg is $\sin^2(2\theta_{23})$ exactly=1? (analogy: Mendeleev Table)

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The high intensity of the Project X will allow us to probe this question with higher accuracy

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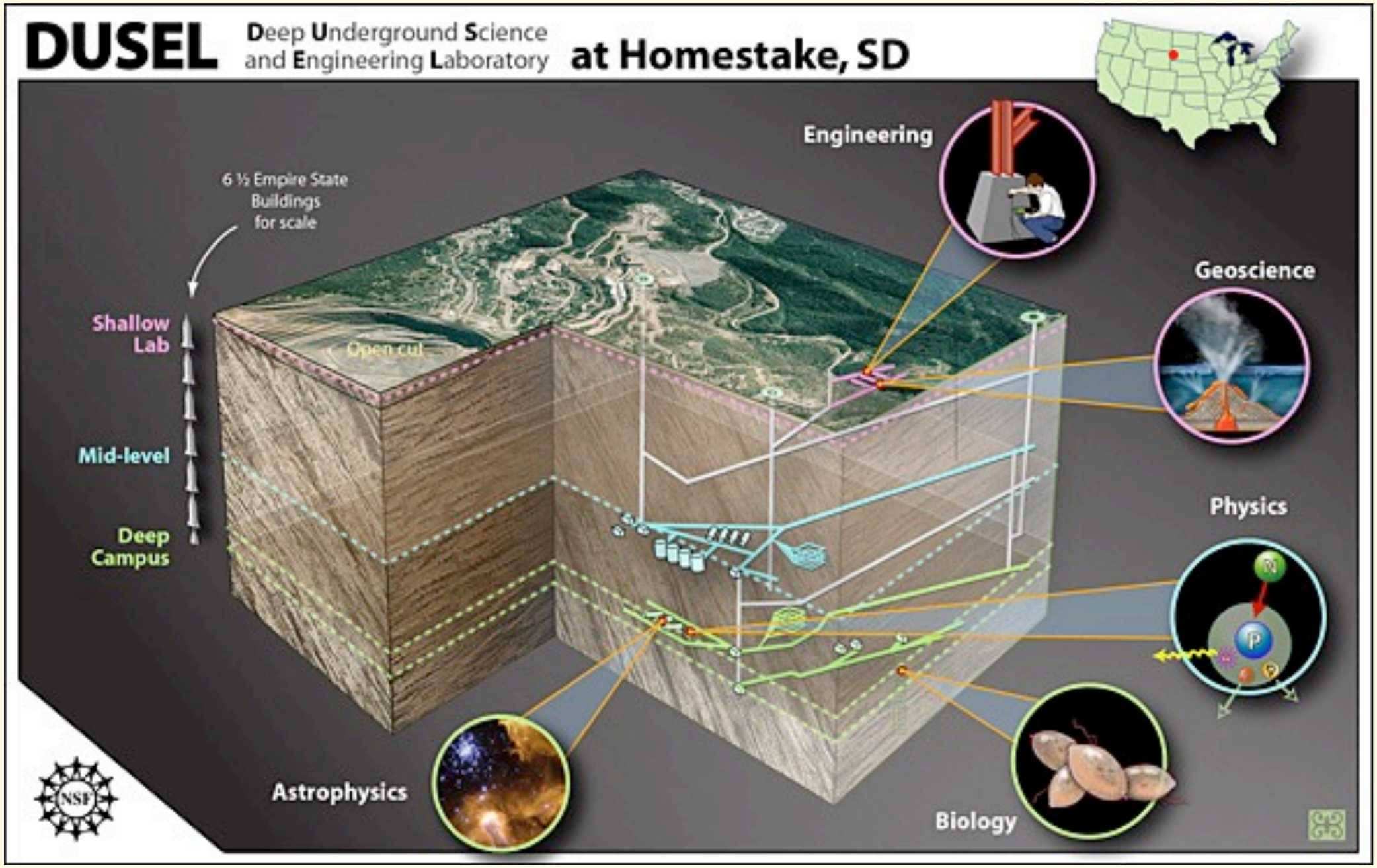
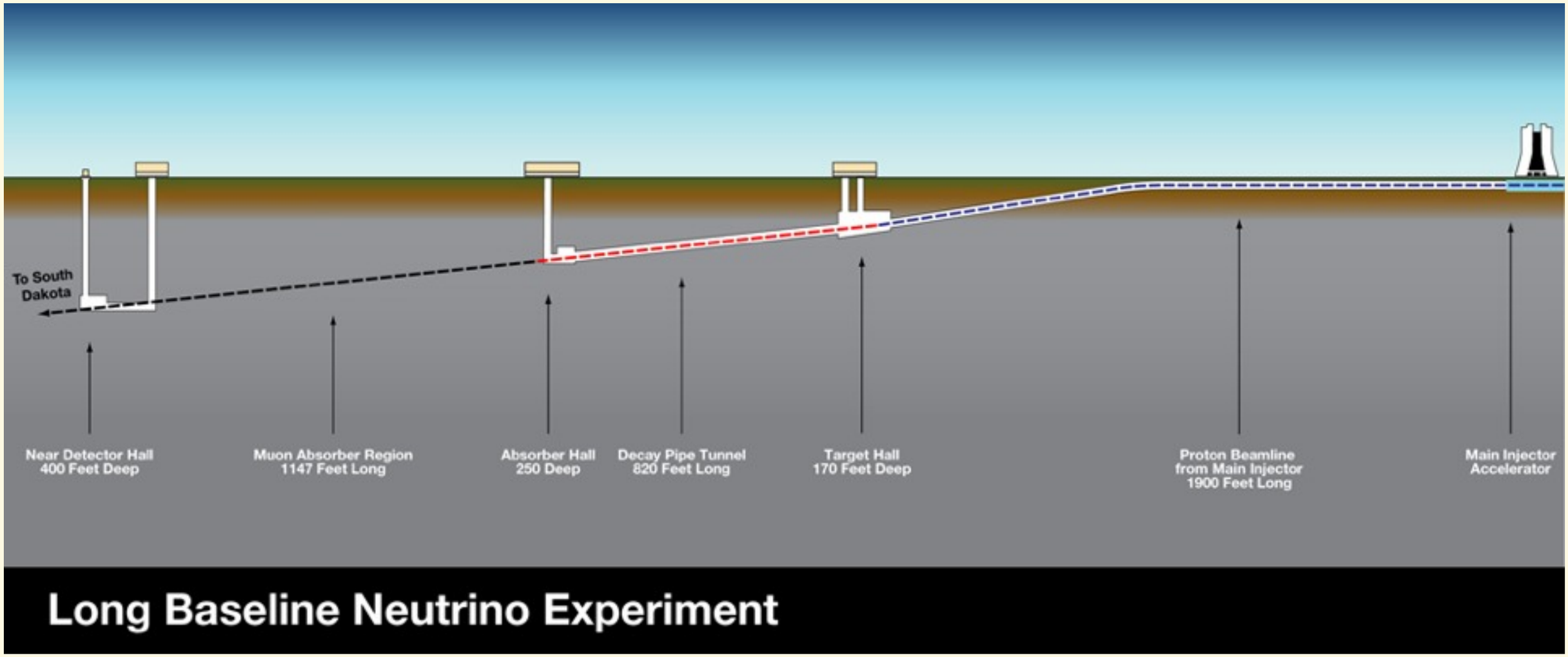
- Potential of beams based on 3 and 8 GeV protons needs to be explored and quantified
- Its versatility will undoubtedly provide a number of other, unexplored opportunities

Backup Slides

A Deep Underground Science and Engineering Laboratory




To South Dakota
Near Detector Hall
400 Feet Deep
Muon Absorber Region
1147 Feet Long
Absorber Hall
250 Deep
Decay Pipe Tunnel
820 Feet Long
Target Hall
170 Feet Deep
Proton Beamline
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1900 Feet Long
Main Injector
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Long Baseline Neutrino Experiment

Transition Probability

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$$P(\nu_\mu \to \nu_e) \approx \mathbf{\sin^2(2\theta_{13})}\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

Main "atmospheric" term

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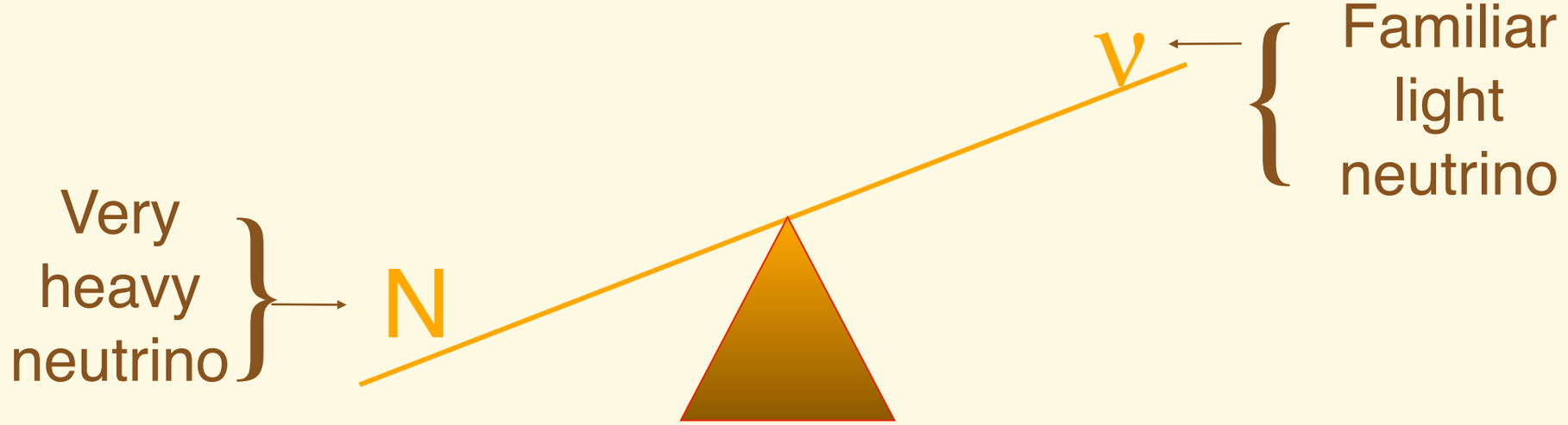
- Interference term proportional to $\sin(2\theta_{13})$, <u>not</u> $\sin^2(2\theta_{13})$

Heavy Neutrino

A natural mechanism to explain the very small mass of the neutrinos is to postulate a ***very heavy neutrino*** and a see-saw mechanism



CP violation in early-universe decays of these ***very heavy neutrinos*** creates a ***lepton-antilepton*** asymmetry.

Standard-Model processes convert part of this ***lepton-antilepton*** asymmetry to a ***nucleon-antinucleon*** asymmetry.

Leptogenesis

Leptogenesis and ***light-neutrino oscillation*** are connected.

Although possible, it would be <u>unnatural</u> for there to be leptogenesis but no light-neutrino CP violation.

CP violation in light-neutrino oscillation would establish leptonic CP violation, and make leptogenesis <u>more plausible</u>.

Graphical Representation

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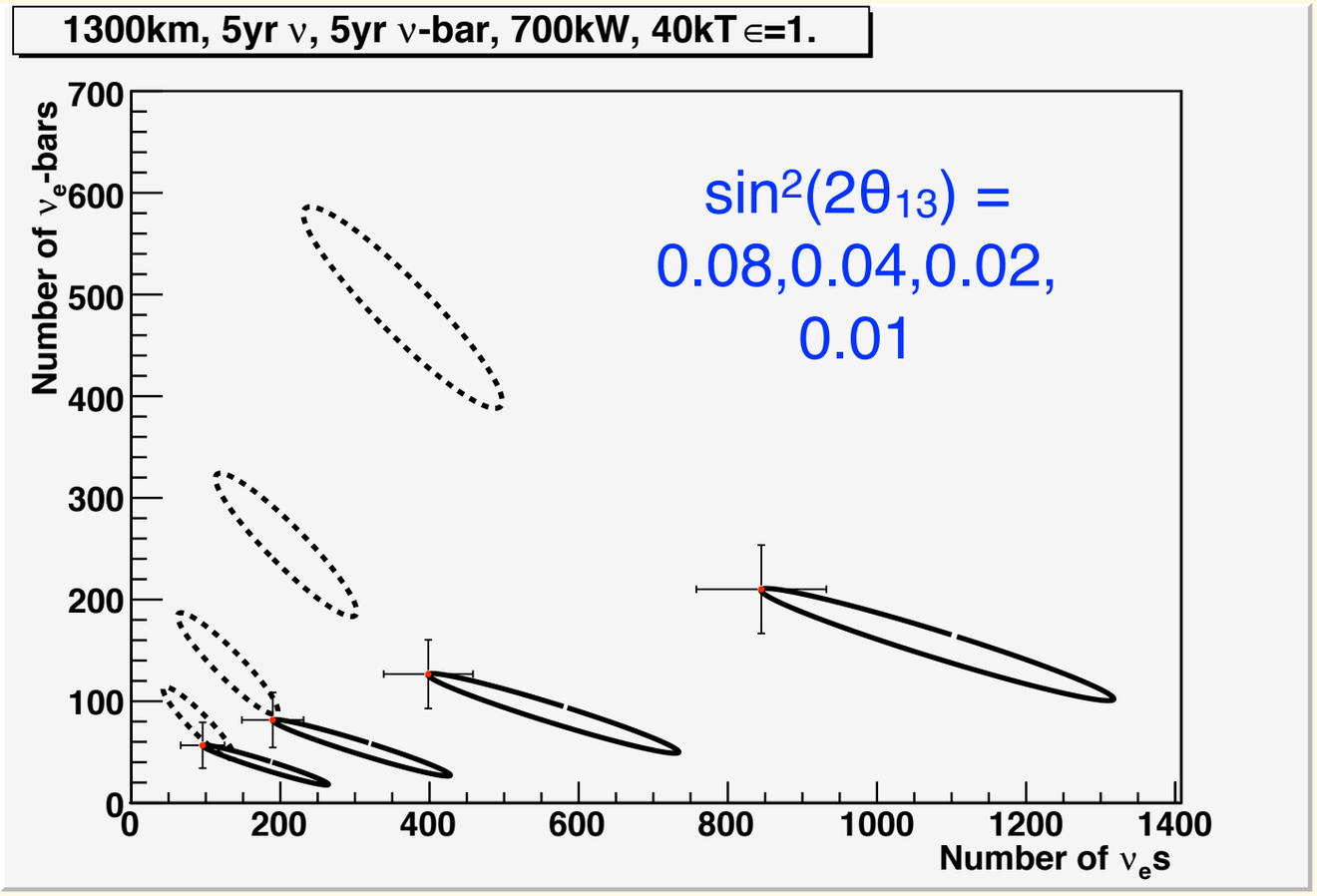
Possible LBNE



Solid: normal mass hierarchy; dashed: inverted

Ideal detector assumed in all cases

Error bars indicate 3σ; statistics only

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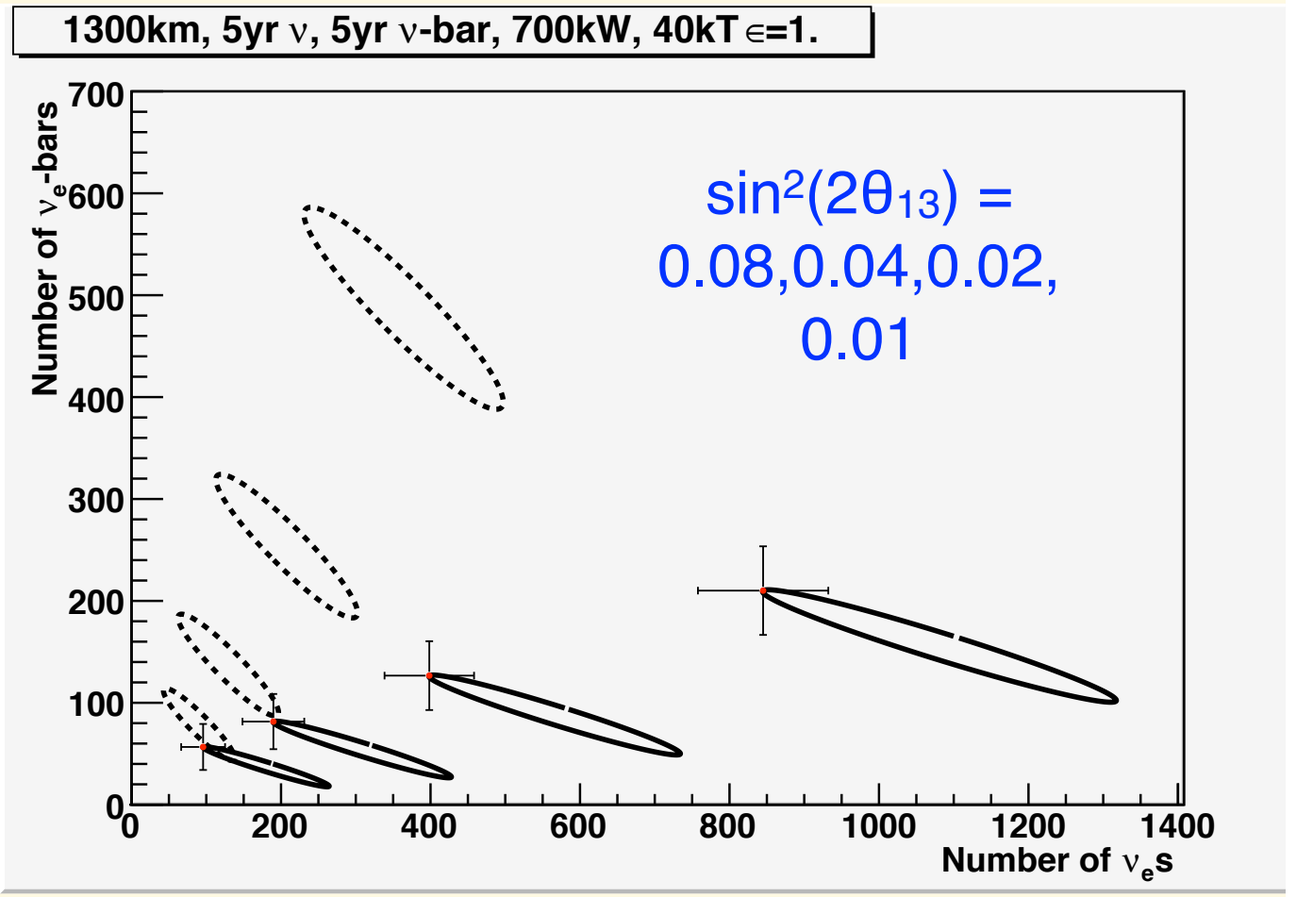
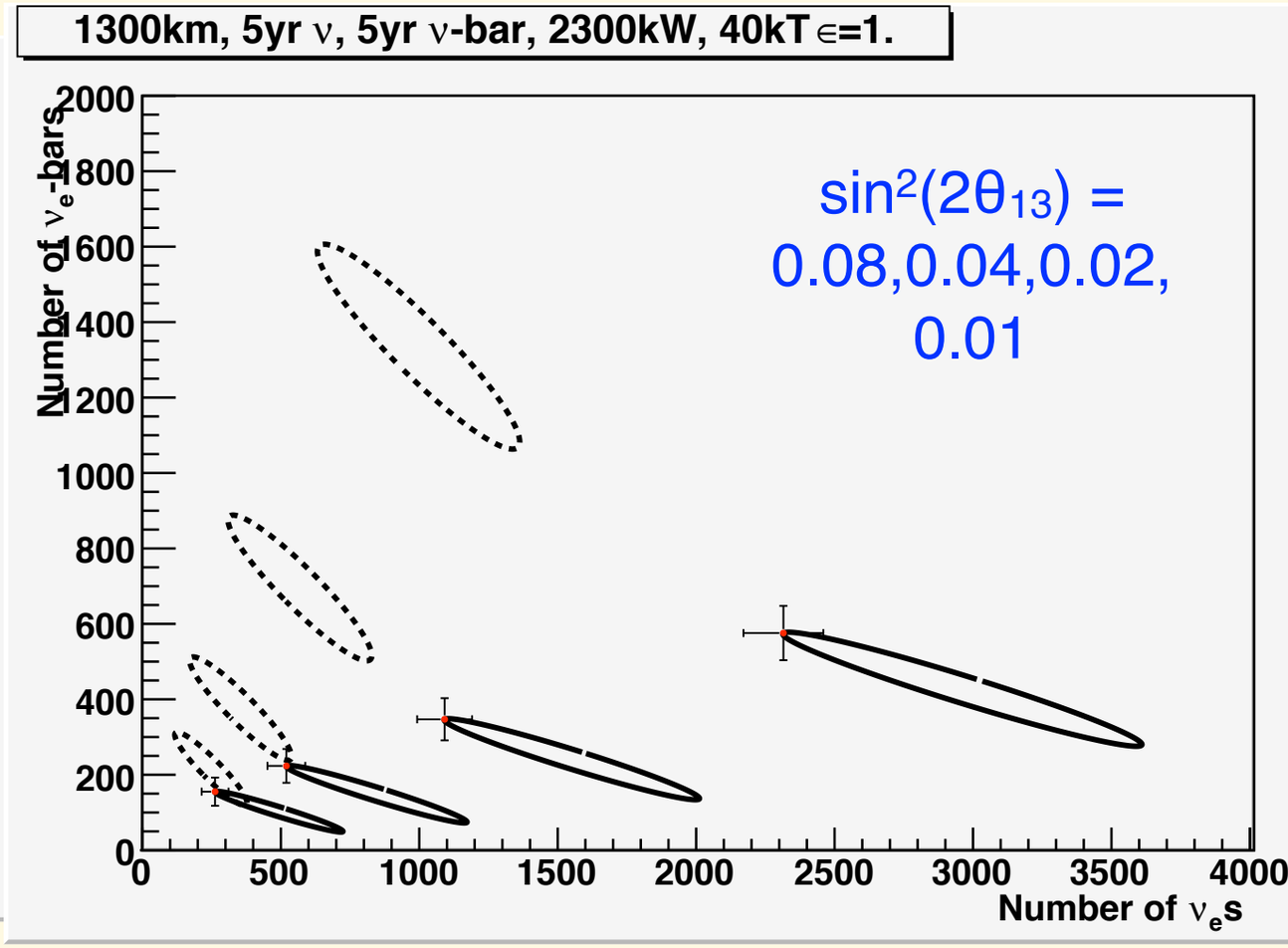


Project X



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$\sin^2\theta_{23}$ dependence

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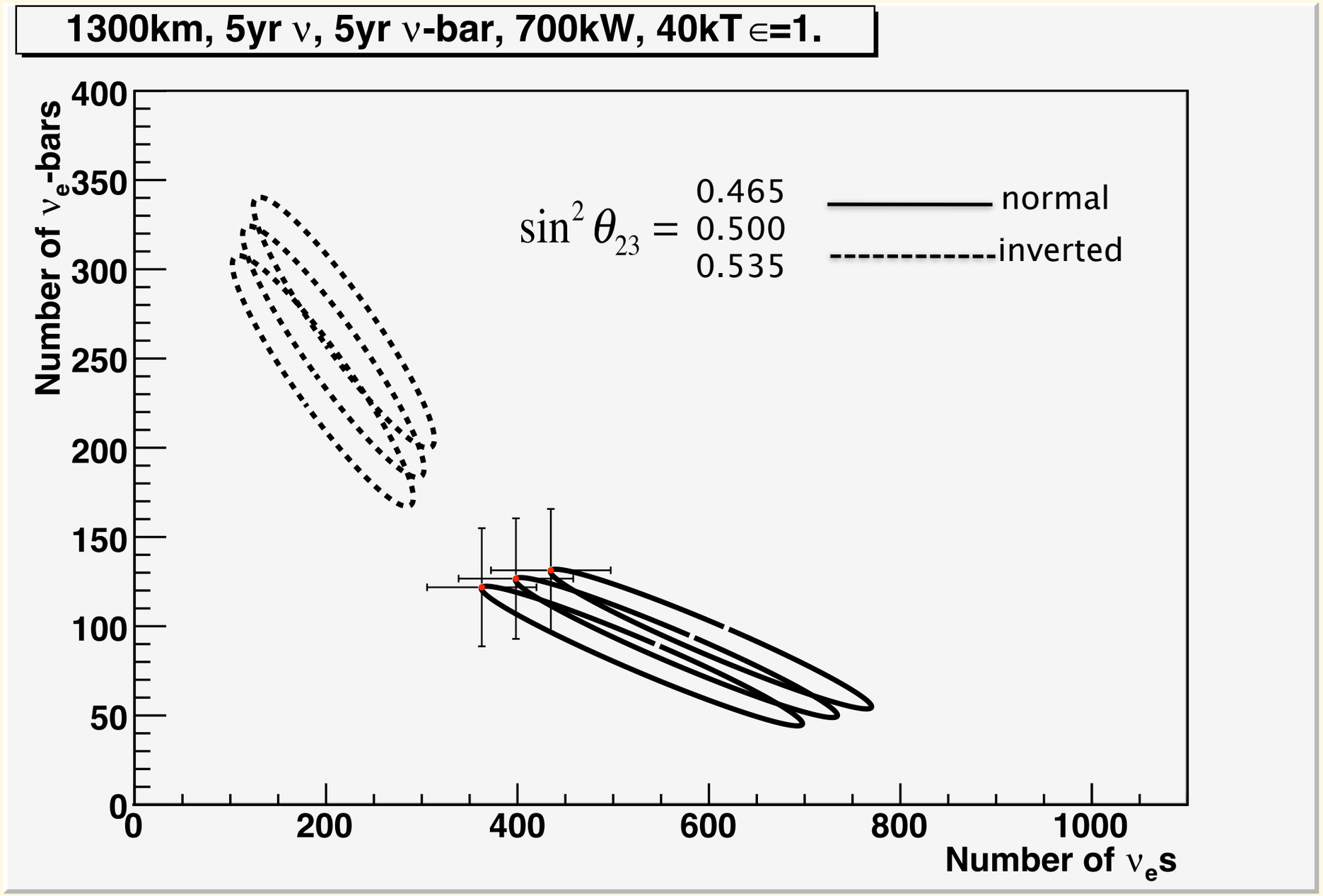

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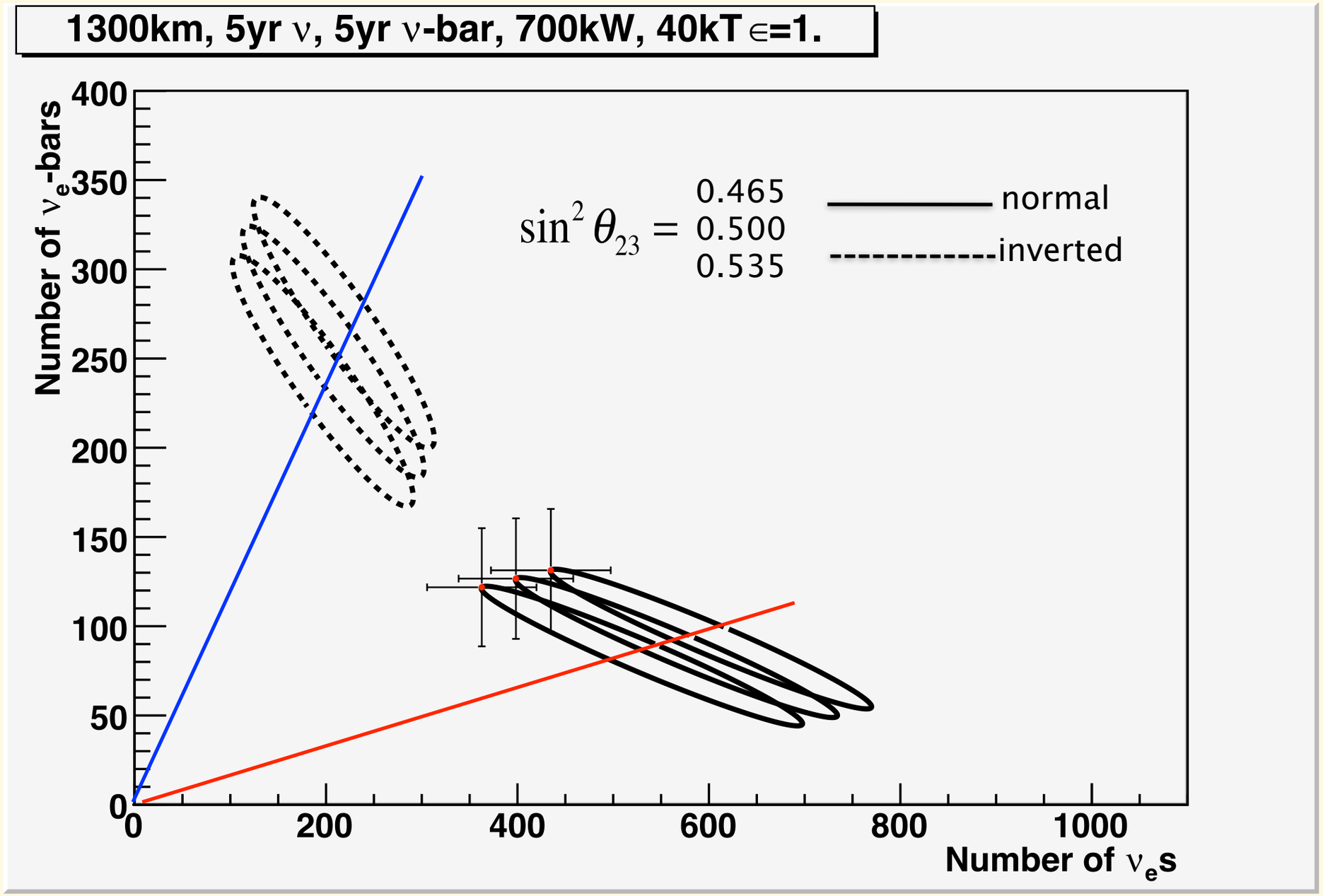
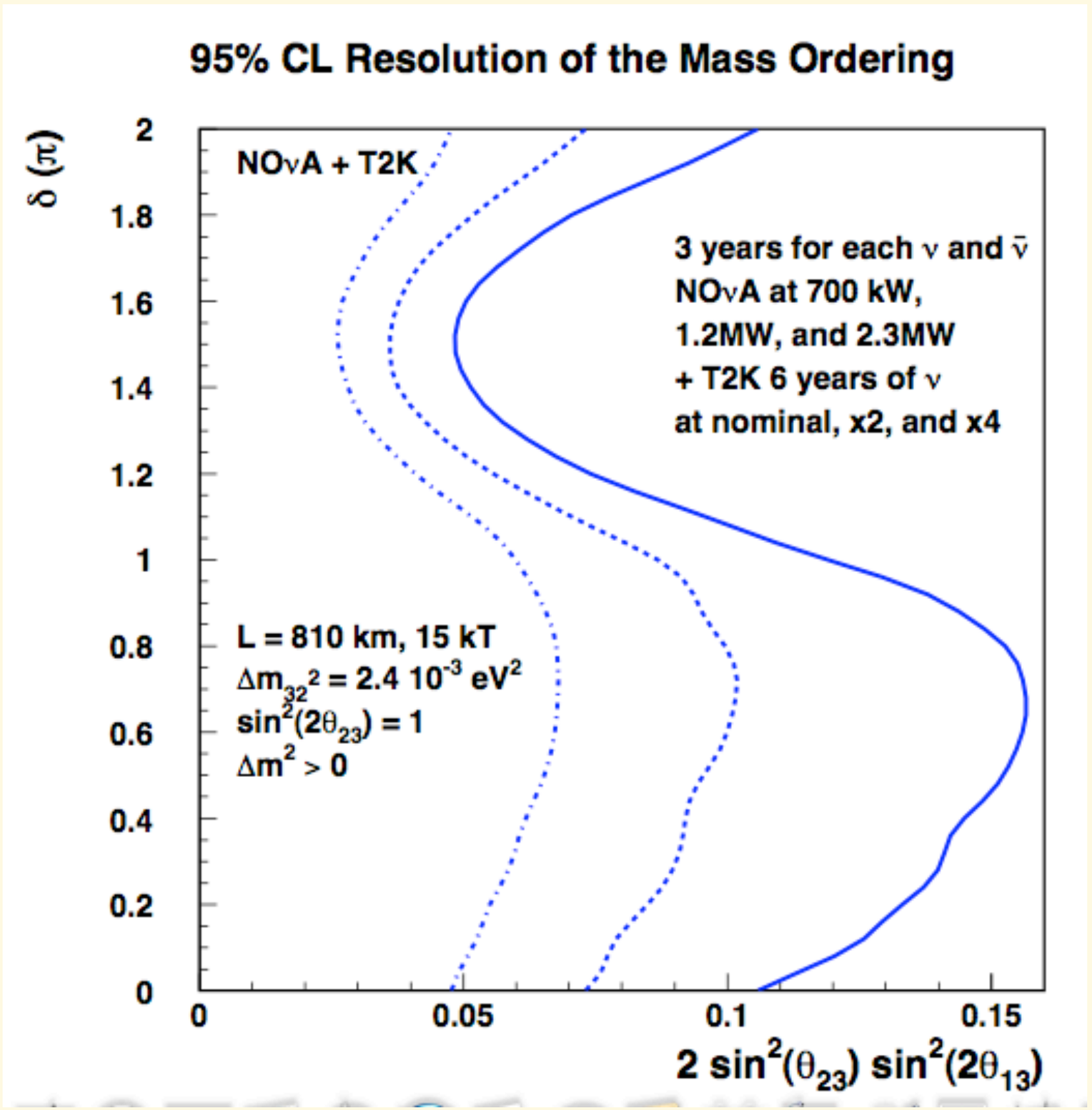


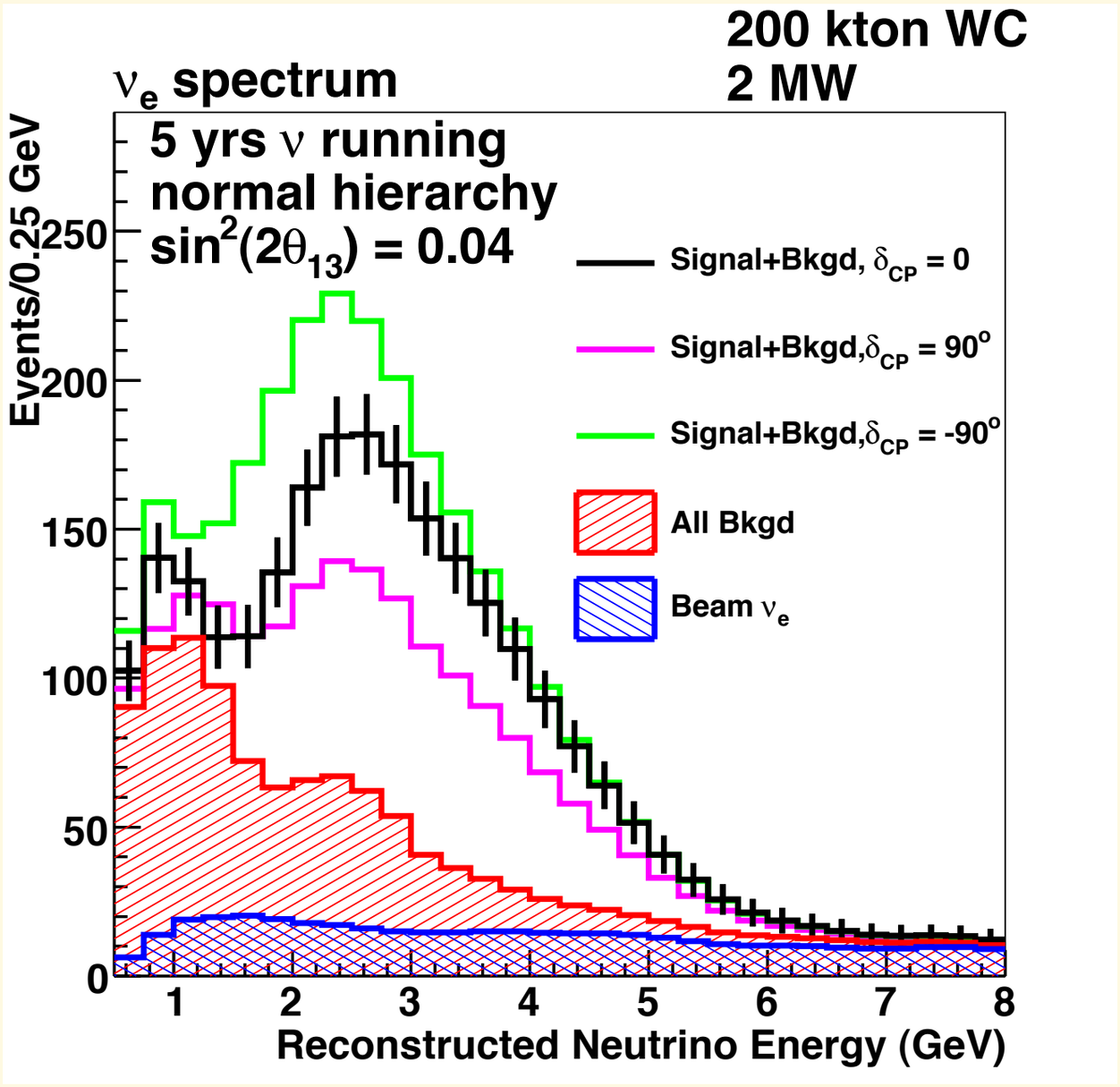
CP sensitivity not affected much by this uncertainty

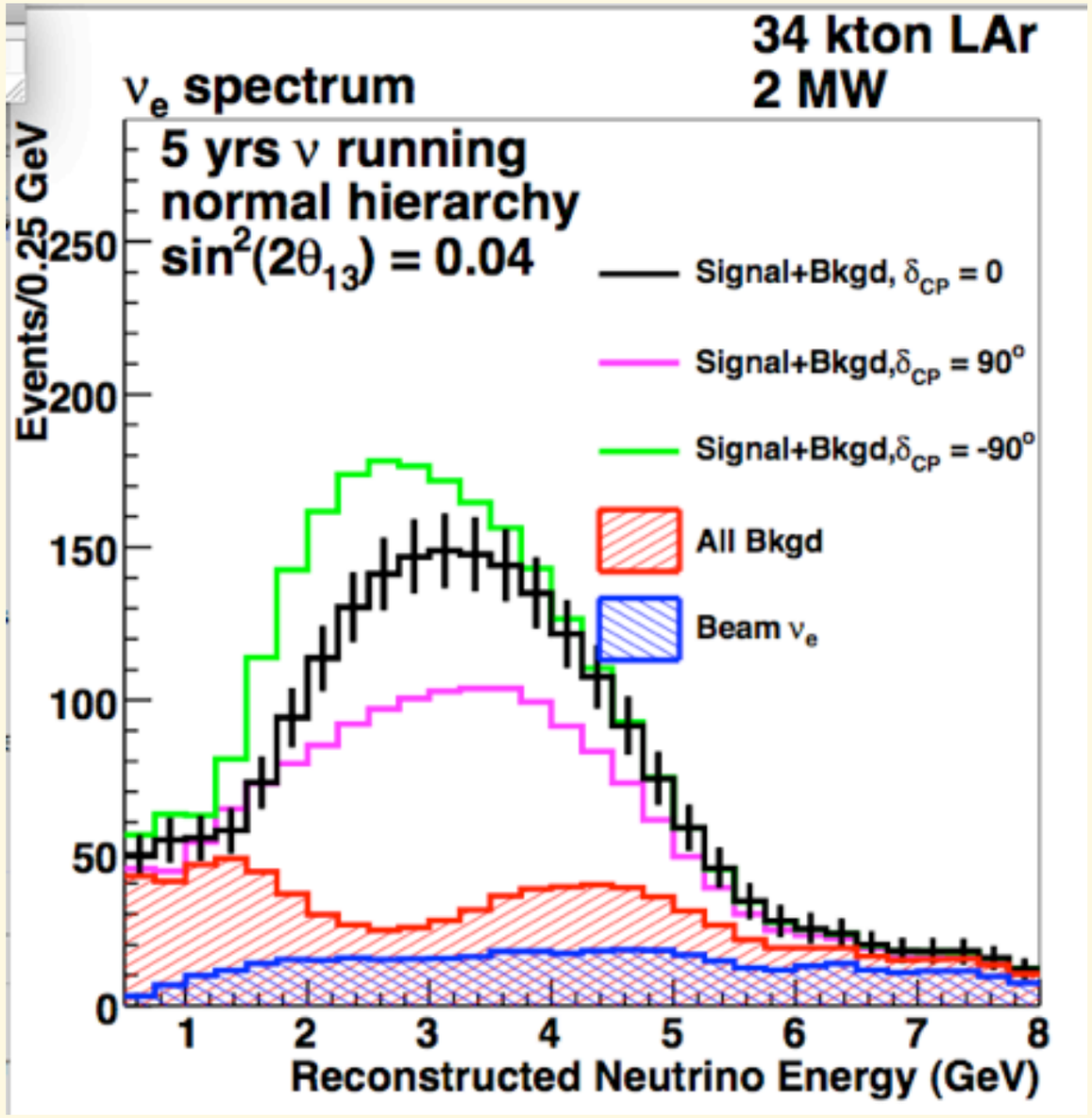
nu/nubar ratio stays relatively constant as $\sin^2\theta_{23}$ is varied

NOvA Reach


95% CL Resolution of the Mass Ordering
NOνA + T2K
3 years for each ν and ν̄
NOνA at 700 kW,
1.2MW, and 2.3MW
+ T2K 6 years of ν
at nominal, x2, and x4
L = 810 km, 15 kT
Δm32² = 2.4 10⁻³ eV²
sin²(2θ23) = 1
Δm² > 0
δ (π)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.05
0.1
0.15
2 sin²(θ23) sin²(2θ13)

Project X Spectra





T2K and NOvA Sensitivities

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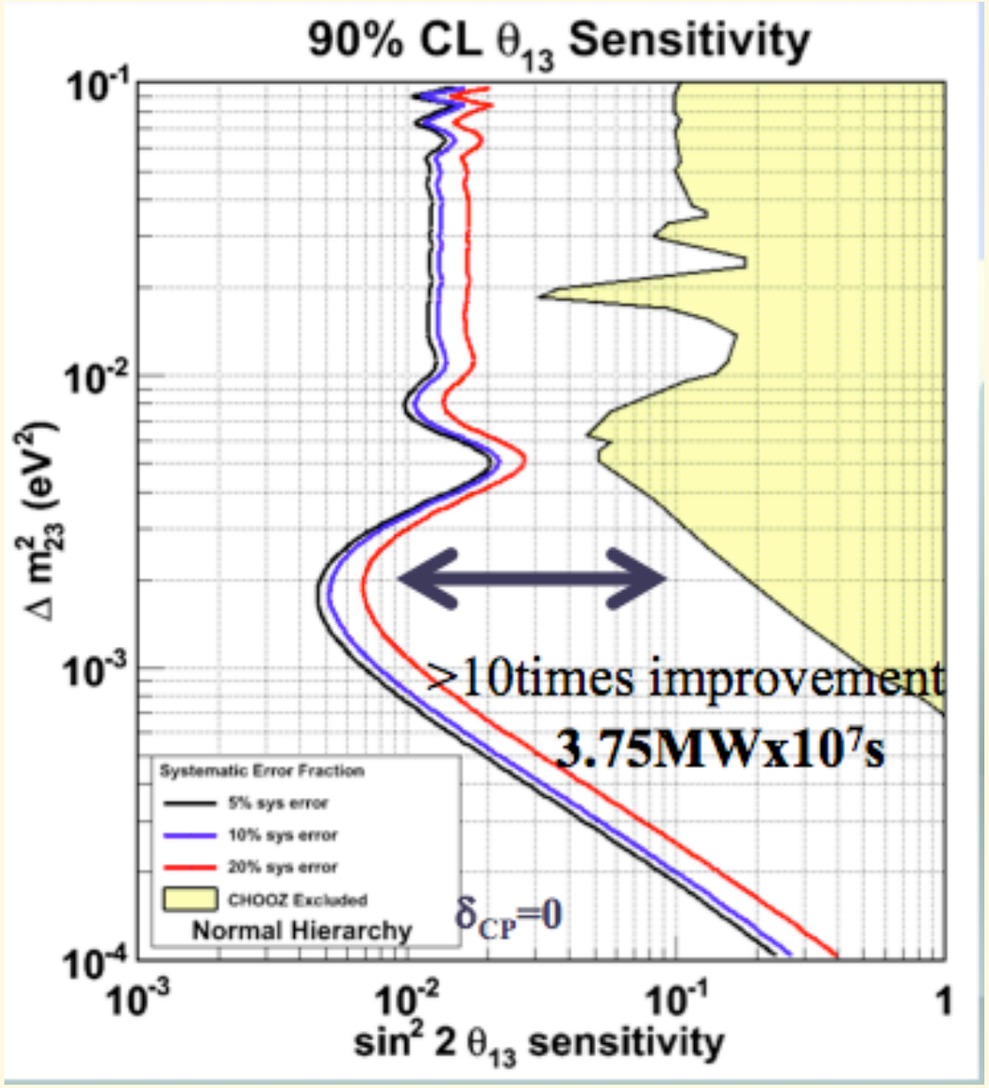
T2K: Assumes 5 years at 750 kW, 22.5 kton fiducial volume



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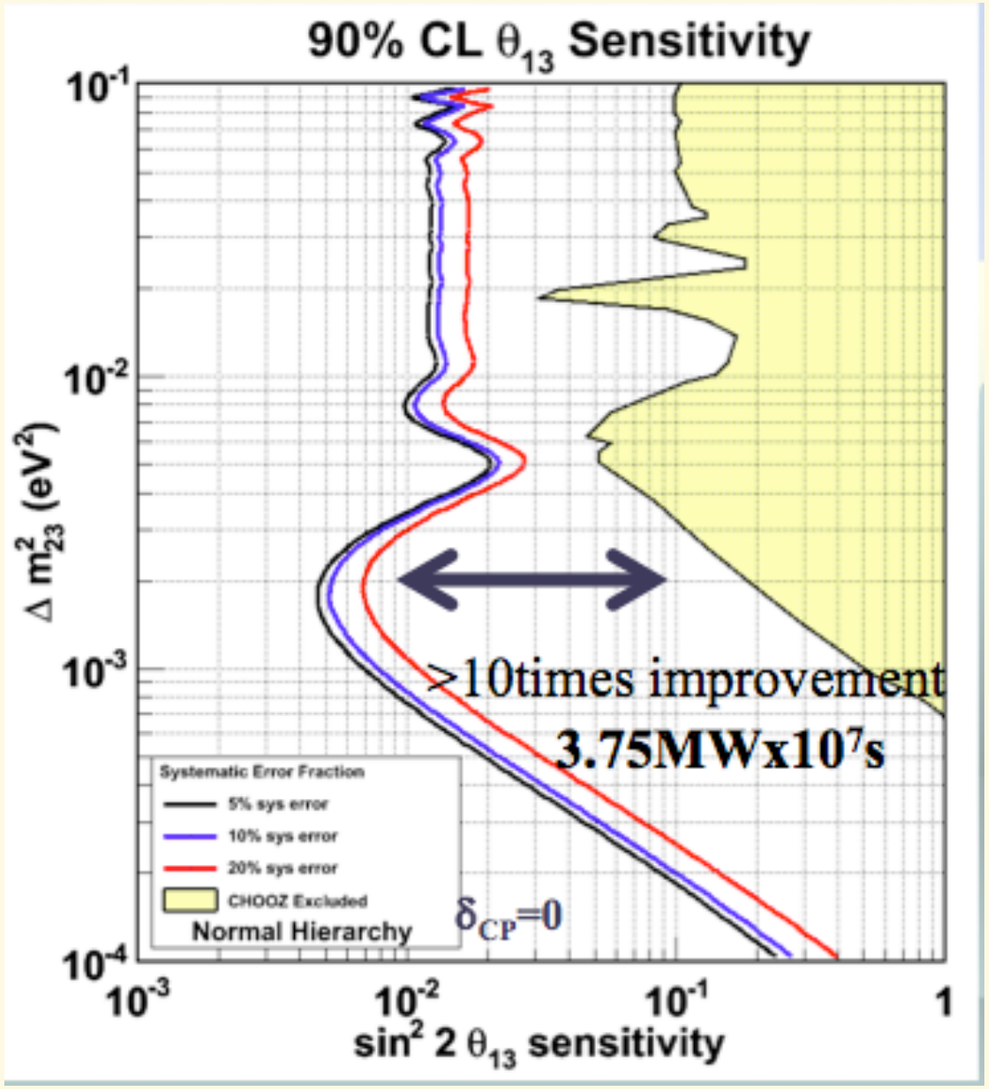
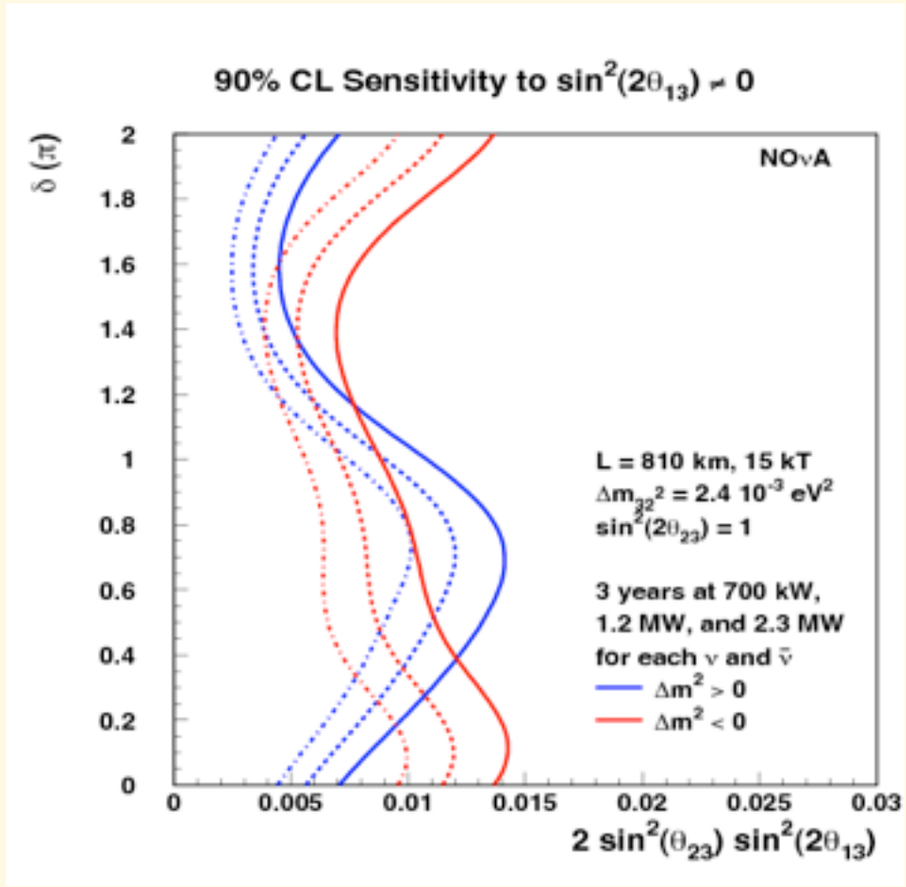
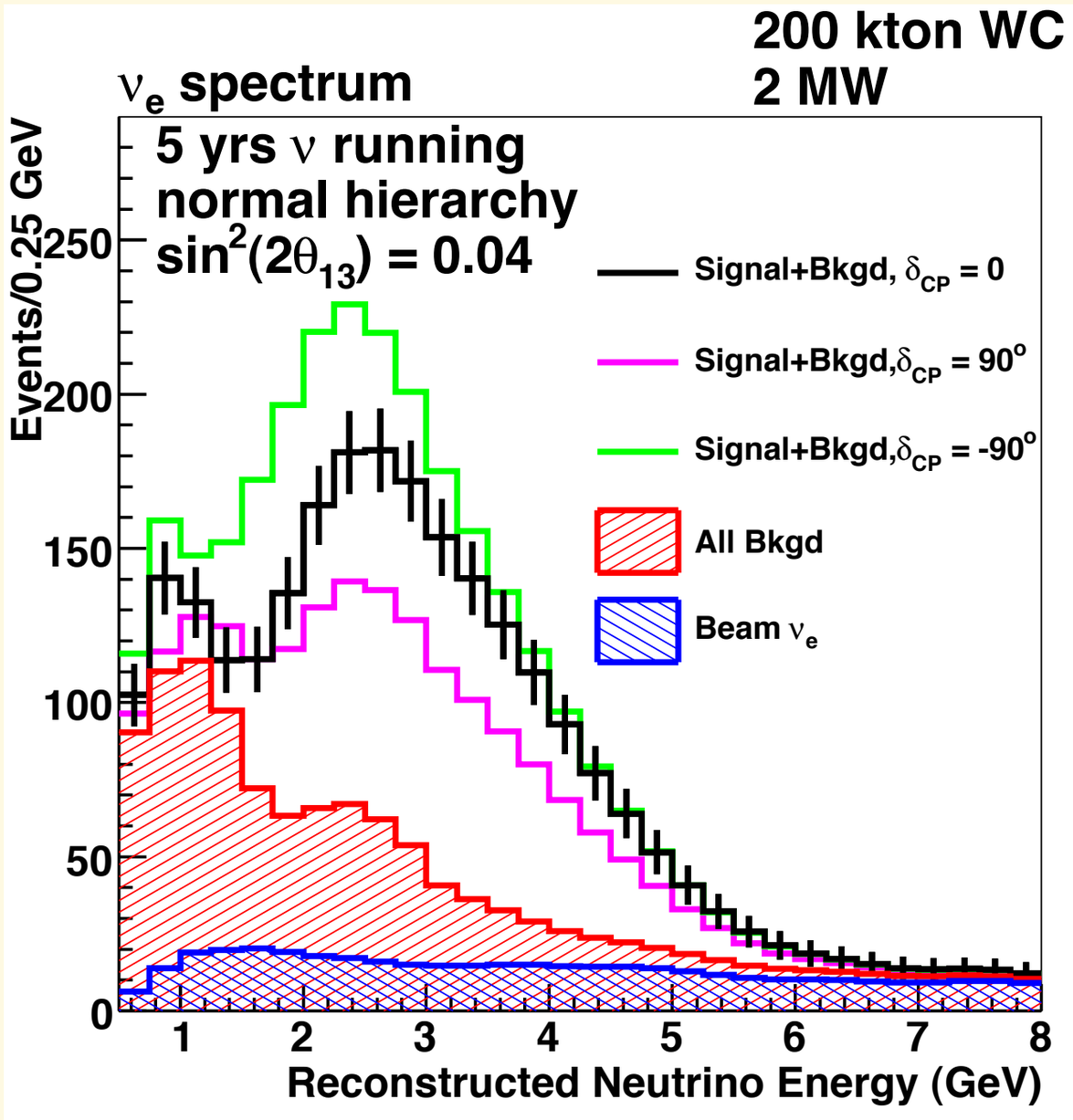
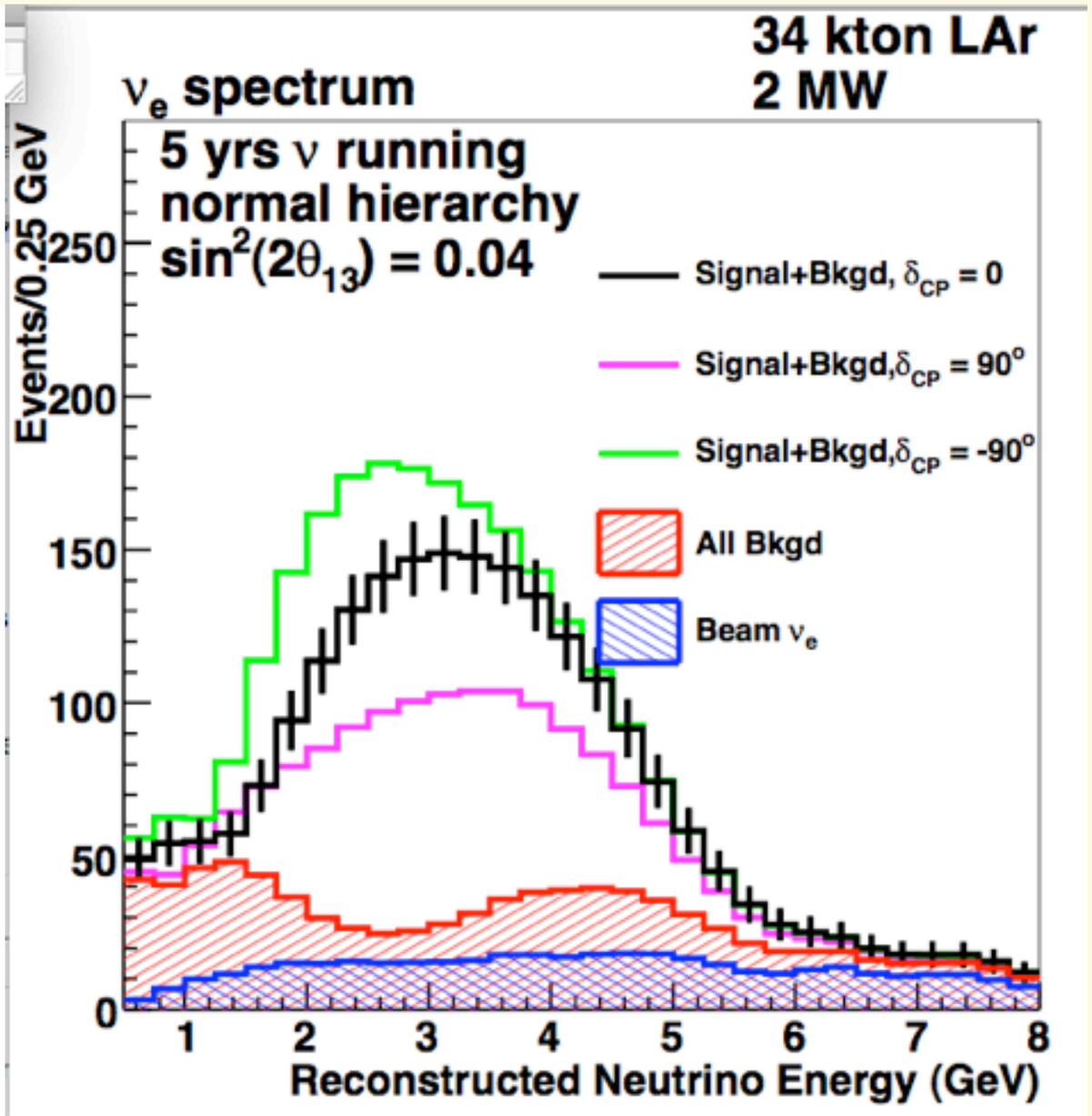


NOvA: Assumes 3 years ν + 3 years anti-ν, 10% systematic, at 700kW



The long distance (810 km) gives it some sensitivity to mass hierarchy

Spectra at 2 MW