Long Baseline Neutrinos - 2

GINA RAMEIKA
FERMILAB

SLAC SUMMER INSTITUTE
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Lecture 2 Outline

- Three neutrinos
  - Oscillation probability
  - Matter effects
- Experimental Techniques :
  - Signals and ambiguities for measuring θ_{13} *and* δ_{CP} and the neutrino mass hierarchy
  - Understanding sensitivity calculations
  - Experiment baseline
  - Neutrino beam configurations
- Experimental Landscape
  - *Reactor Experiments :* $\bar{\nu}_e$ *disappearance* (Ed Blucher lecture)
  - ν_e appearance : T2K, NOvA, LBNE
  - Experiment Timelines

Lecture 2 Outline cont.

- Beyond conventional beams?
- New results to keep an eye on
- Conclusions

Lot's of the plots and numbers in this lecture are for demonstration/education purposes only and don't represent official calculations or status of any particular experiment.

Always check with an experiment's official documentation to get the most up to date information.

Three neutrinos : θ_{13} *and* δ_{CP}

OSCILLATION PROBABILITY

MATTER EFFECTS

Features of the matrix

atmospheric and accelerator ν_μ disappearance

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

solar ν_e and reactor $\bar{\nu}_e$ disappearance

- Two component mixing
- Complex phase δ and θ_{13}

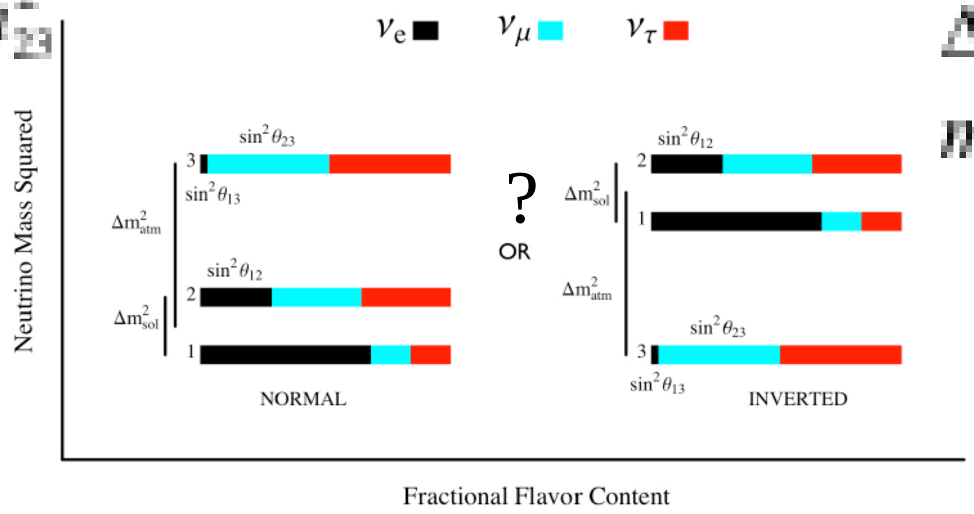
Now consider the case of all three neutrinos :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Current state of knowledge

Δm_{12}^2	$7.59 \pm 0.02 \times 10^{-5}\, eV^2$
Δm_{23}^2	$2.43 \pm 0.13 \times 10^{-3}\, eV^2$
$\sin^2 2\theta_{12}$	0.87 ± 0.03
$\sin^2 2\theta_{23}$	> 0.92
$\sin^2 2\theta_{13}$	$< 0.19 \quad (90\% CL)$

$\Delta m_{12}^2 << \Delta m_{23}^2$



$\Delta m_{13}^2 \approx \Delta m_{23}^2$

$m_1 < m_2$

Oscillation Probability with 3 flavors

$$\alpha, \beta = e, \mu, \tau$$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} L / 4E)$$

$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} L / 2E)$$

$$P(\nu_\alpha \to \nu_\beta) = P_{\alpha\beta}(\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta; E, L)$$

3-ν Oscillation Probability

$$P(\nu_\alpha \to \nu_\beta) = P_{\alpha\beta}(\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta; E, L) \qquad \alpha, \beta = e, \mu, \tau$$

Ignore the small Δm^2_{21}

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \cos^4(\theta_{13}) \sin^2(\Delta m^2_{32} L / 4E)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E)$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} \sin^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E)$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_{13} \cos^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E)$$

3-ν Oscillation Probability

$$P(\nu_\alpha \to \nu_\beta) = P_{\alpha\beta}(\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta; E, L) \qquad \alpha, \beta = e, \mu, \tau$$

And small θ_{13}

1

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \cos^4(\theta_{13}) \sin^2(\Delta m^2_{32} L / 4E)$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E)$$

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} \sin^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E)$$

$$P(\nu_e \to \nu_\tau) = \sin^2 2\theta_{13} \cos^2(\theta_{23}) \sin^2(\Delta m^2_{32} L / 4E)$$

But we need to ask how small θ_{13} really is?
Can we measure it?

Probabilities with θ_{13}

In vacuum

$$P(\nu_\mu \to \nu_e) = P1 + P2 + P3 + P4$$

$$P1 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta m_{32}^2 L/4E)$$

$$P2 = \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta m_{21}^2 L/4E)$$

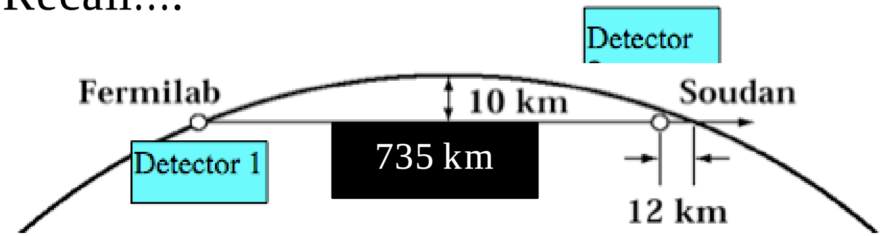
$$P3 = \mp J\sin\delta\sin(\Delta m_{32}^2 L/4E)$$

$$P4 = J\cos\delta\cos(\Delta m_{32}^2 L/4E)$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$
$$\times\sin(\Delta m_{32}^2 L/4E)\sin(\Delta m_{21}^2 L/4E)$$

Propagation through matter

Recall....



Doesn't matter to ν_μ or ν_τ

ν_e's (and $\overline{\nu_e}$) "see" the electrons in the Earth which affects the oscillation probability

And the probability equation is quite complicated.........

There are a number of different ways that it can be expressed using approximations and expansions....

A popular approximation

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T4$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim 1/30 \qquad \Delta = \Delta m^2_{31} L / 4E \qquad x = 2\sqrt{2} G_F N_e / \Delta m^2_{31}$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-x)\Delta}{(1-x)^2}$$

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

Anti-neutrinos
$\delta \to -\delta; x \to -x$

http://pdg.lbl.gov/2009/reviews/rpp2009-rev-neutrino-mixing.pdf

Easiest way to understand it – code it up and make some plots……

One more……

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta)$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$\Delta_{ab} = \Delta m_{ab}^2 \, L/4E \simeq 1.27\,\Delta m_{ab}^2(eV^2)\frac{L(km)}{E(GeV)}$$

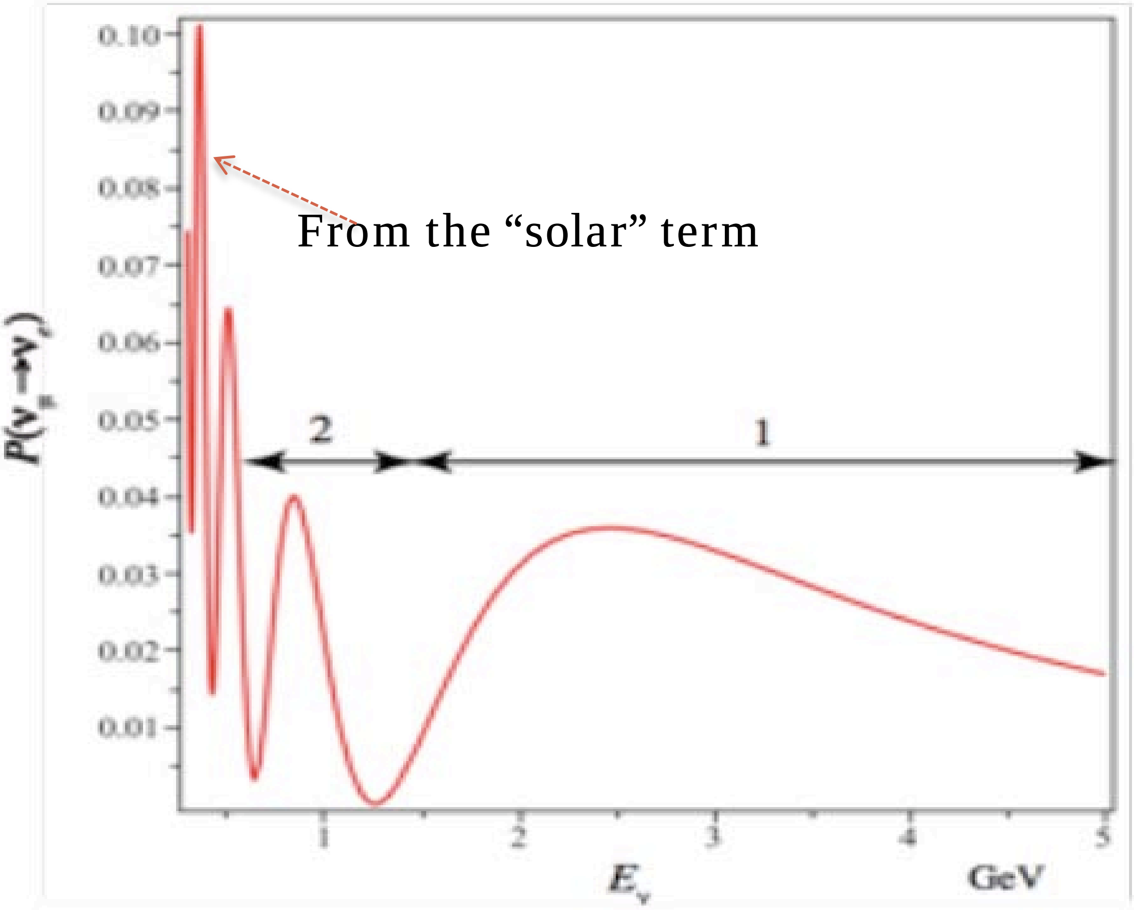
$$a = G_F N_e / \sqrt{2}$$

Code it up and plot it….

arXiv:0710.0554v2(2008)
Nunokawa, Parke, Valle
CP Violation and Neutrino Oscillations

$\nu_\mu \rightarrow \nu_e$ appearance probability

L = 1300 km



1st and 2nd oscillation maximum

Experimental Implications

IS $\theta_{13} \neq 0$?

AMBIGUITIES

SENSITIVITY CALCULATIONS

THE EXPERIMENT BASELINE

NEUTRINO BEAM CONFIGURATIONS

Can an experiment determine if $\theta_{13} \neq 0$?

- What would we expect to measure if $\theta_{13} = 0$? (null)
  - Intrinsic ν_e in the beam
  - ν_e from the θ_{12} mixing
  - Background events that fake ν_e
- Calculate what we would expect to measure for a particular value of θ_{13} and δ
- Need a significance of events above the null expectation

$$\chi^2 = \frac{(N_{null}^{pred} - N_{\theta_{13},\delta}^{pred})^2}{\sigma^2}$$

Statistical and systematic uncertainty in the prediction

The Experimental Landscape for measuring θ_{13}

REACTOR EXPERIMENTS

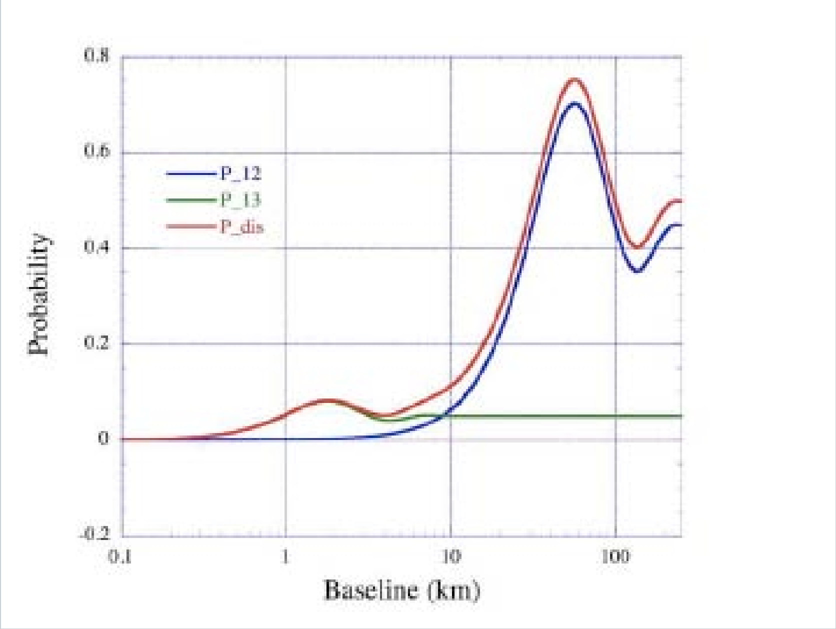
ACCELERATOR LONG BASELINE :

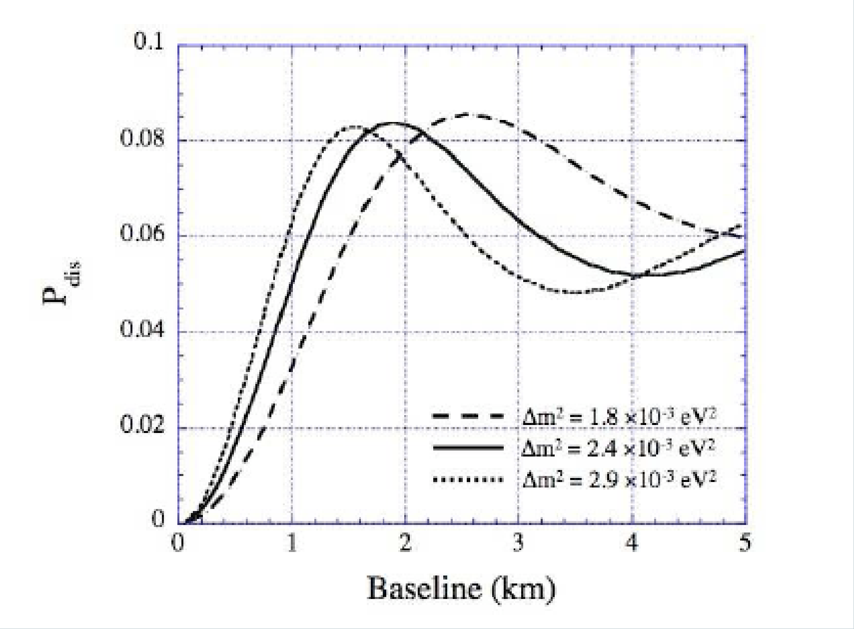
T2K, NOVA

Reactor Experiments

- Measure $P(\bar{\nu}_e \to \bar{\nu}_e)$
- $P_{sur} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$

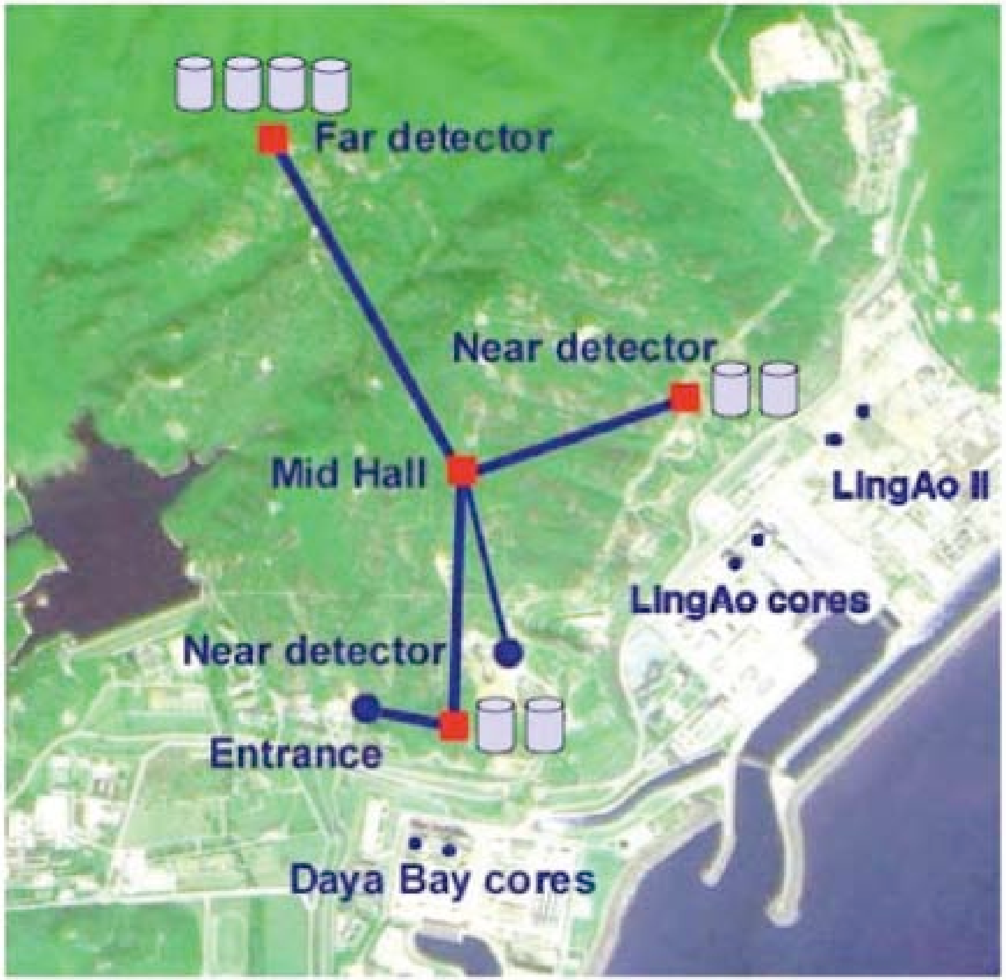
Independent of δ and θ_{23}





Double Chooz, Northeast France

Daya Bay, China



RENO – Yonggwang, Korea

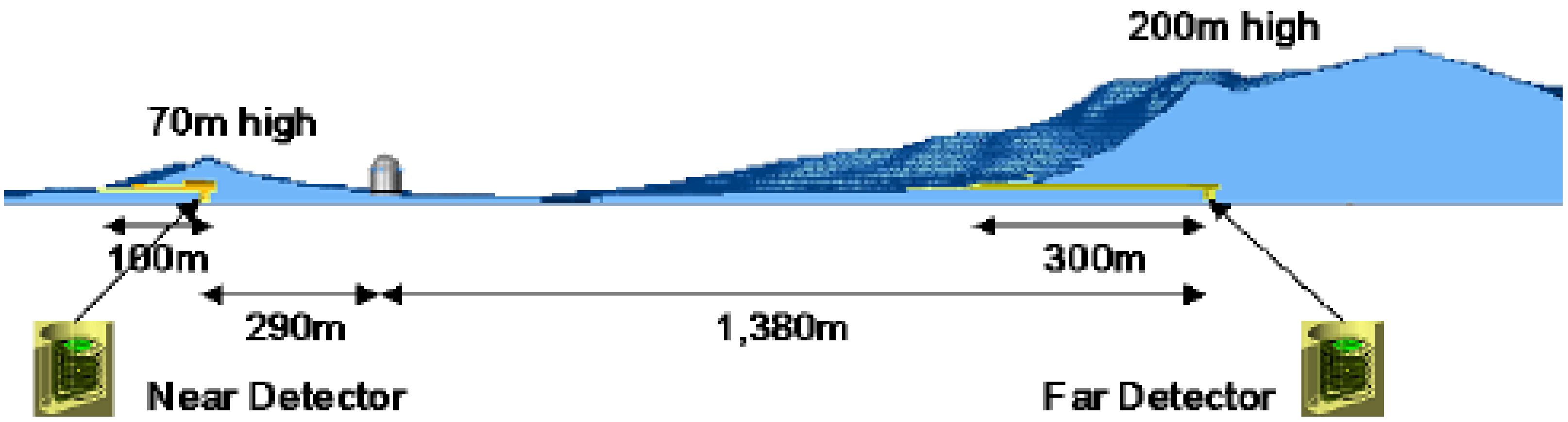


Figure 1. A schematic layout of the RENO experiment.

Double Chooz sensitivity

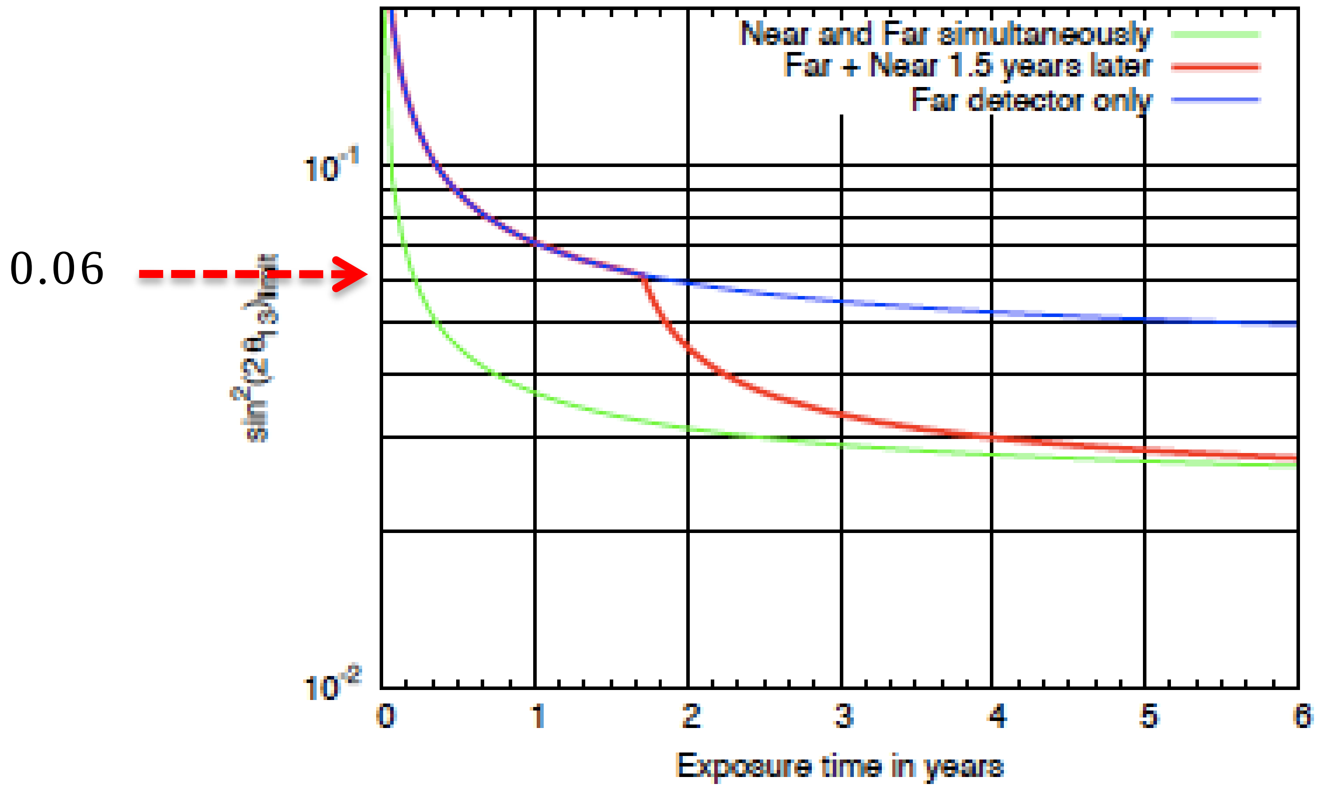


Figure 18: $\sin^2(2\theta_{13})$ sensitivity limit for the detectors installation scheduled scenario

A positive result from Double Chooz ➔ $\sin^2 2\theta_{13}$ is relatively large

Long-baseline experiments

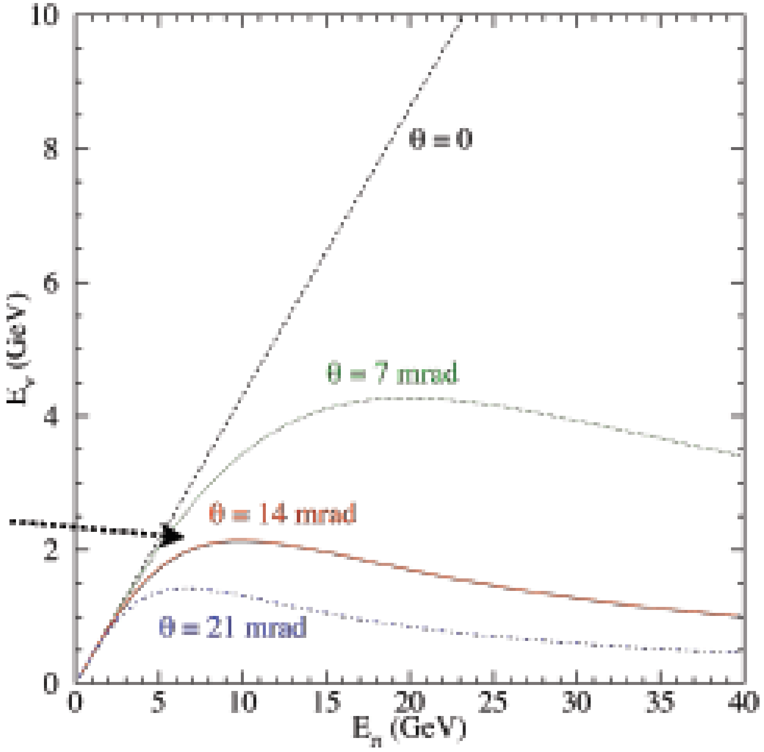
T2K AND NOVA

Off-axis Beams

Recall, the neutrinos come from pion decay….

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

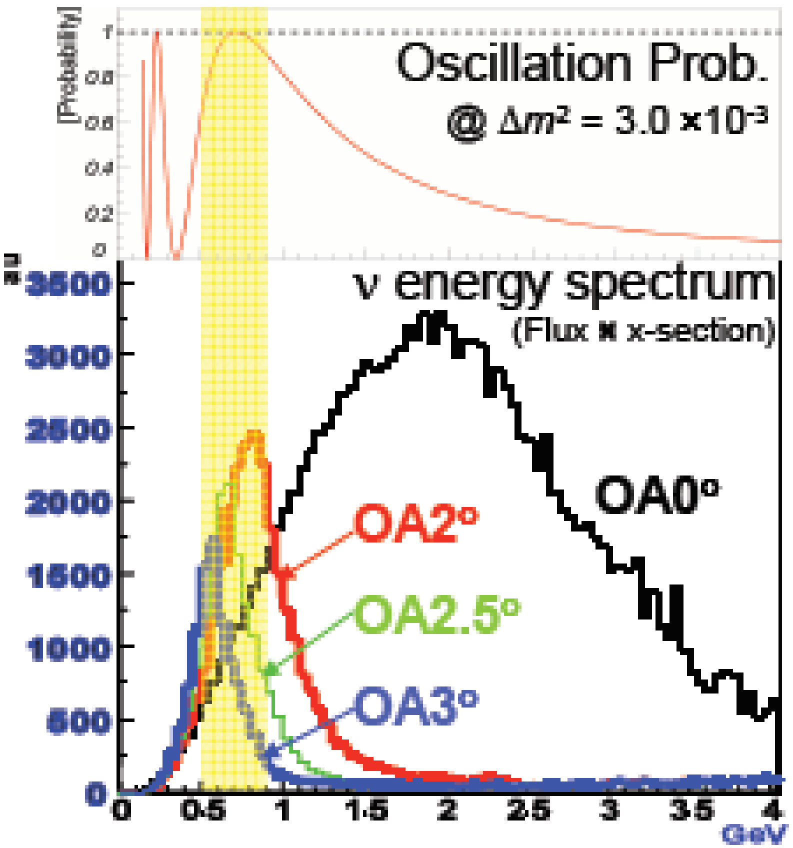
$$\gamma = E_\pi / m_\pi$$

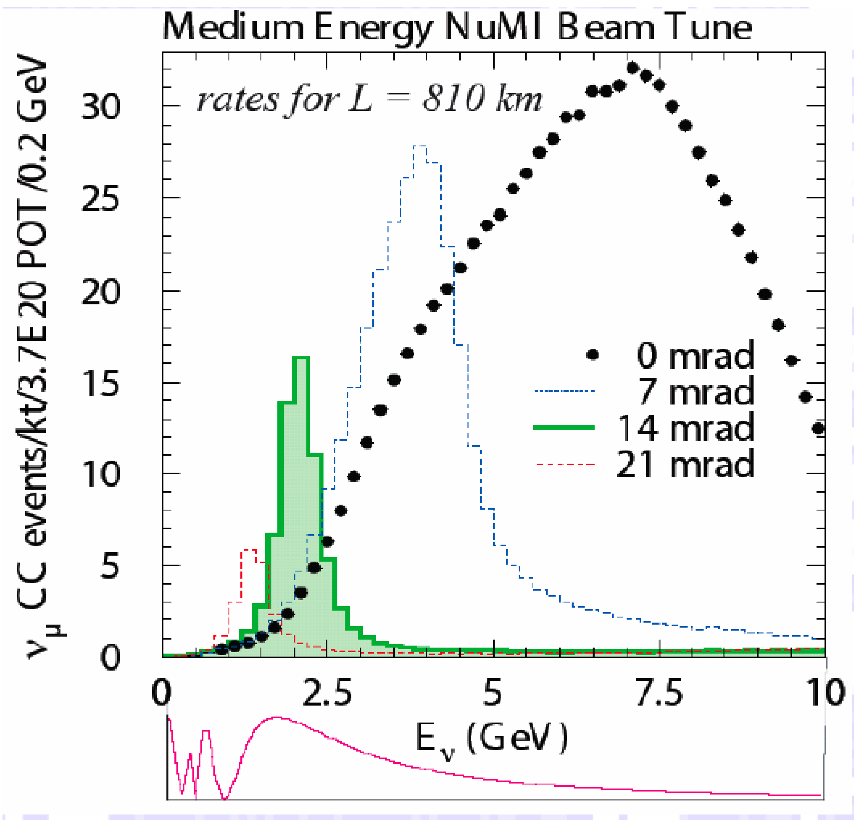


Neutrino energy is relatively independent of the parent pion energy :
enhances low energy, suppresses high energy

Why Off-Axis Beams?

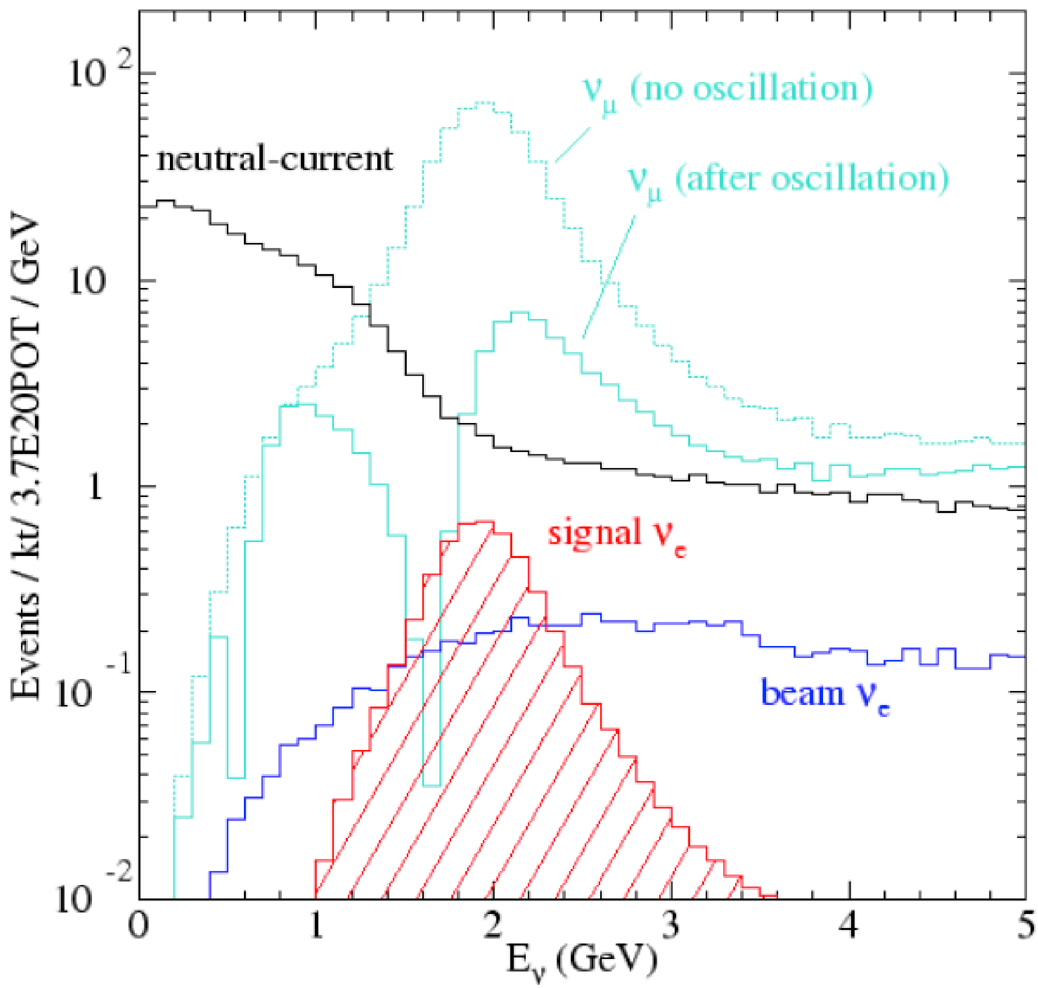
L=285km JPARC 2 Super-K





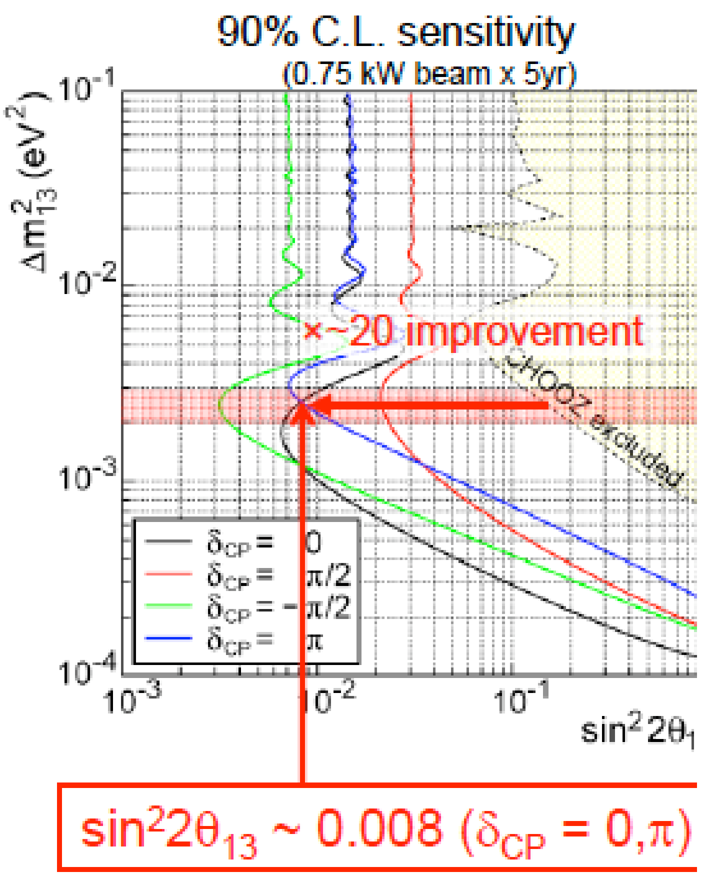
Signals and Backgrounds

NOvA

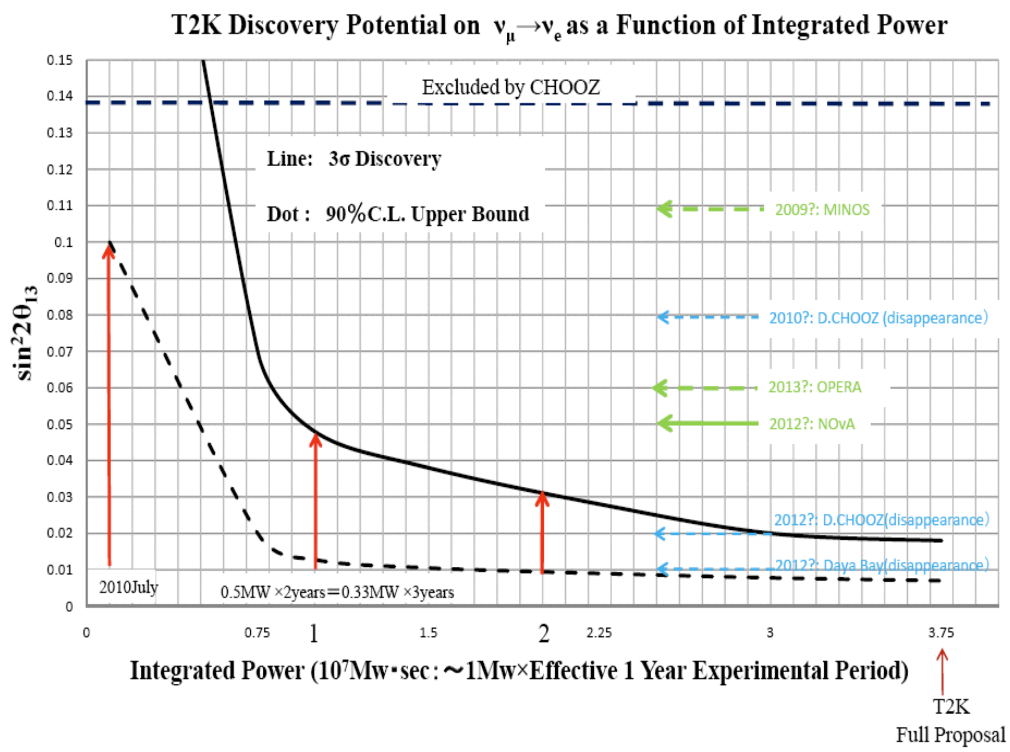


Tokai to Kamiokande : T2K

T2K

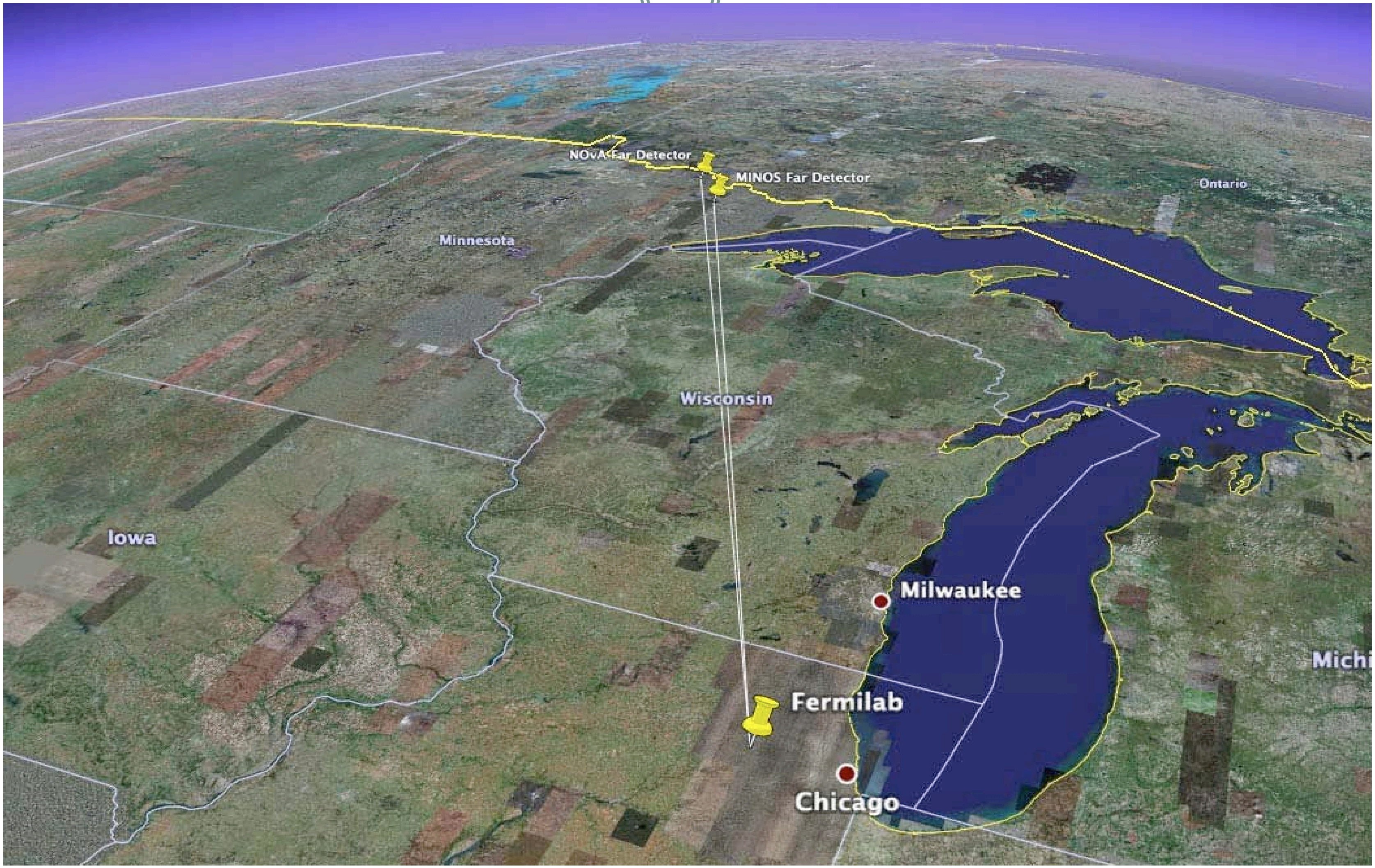


90% C.L. sensitivity
(0.75 kW beam x 5yr)
×~20 improvement
CHOOZ excluded
sin²2θ13 ~ 0.008 (δCP = 0,π)

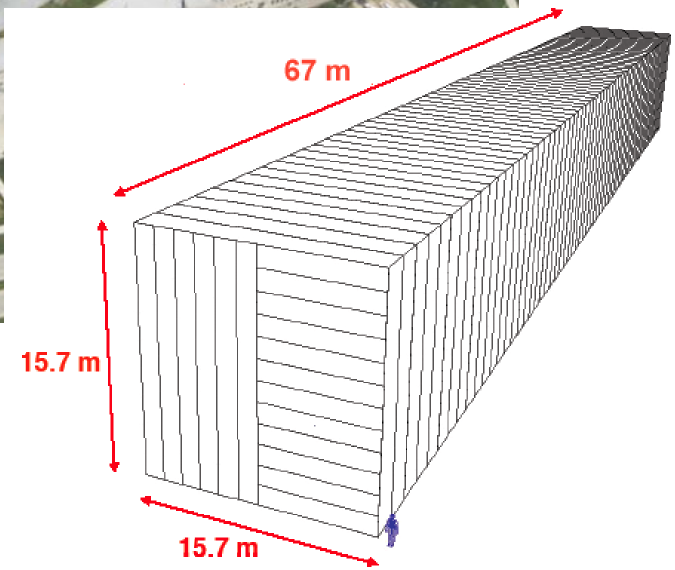


T2K Discovery Potential on νμ→νe as a Function of Integrated Power
Excluded by CHOOZ
Line: 3σ Discovery
Dot : 90%C.L. Upper Bound
2009?: MINOS
2010?: D.CHOOZ (disappearance)
2013?: OPERA
2012?: NOvA
2012?: D.CHOOZ(disappearance)
2012?: Daya Bay(disappearance)
2010July
0.5MW ×2years=0.33MW ×3years
Integrated Power (10⁷Mw·sec : ~1Mw×Effective 1 Year Experimental Period)
T2K Full Proposal

NOvA


NOvA Far Detector
MINOS Far Detector
Ontario
Minnesota
Wisconsin
Iowa
Milwaukee
Michi
Fermilab
Chicago

NOvA

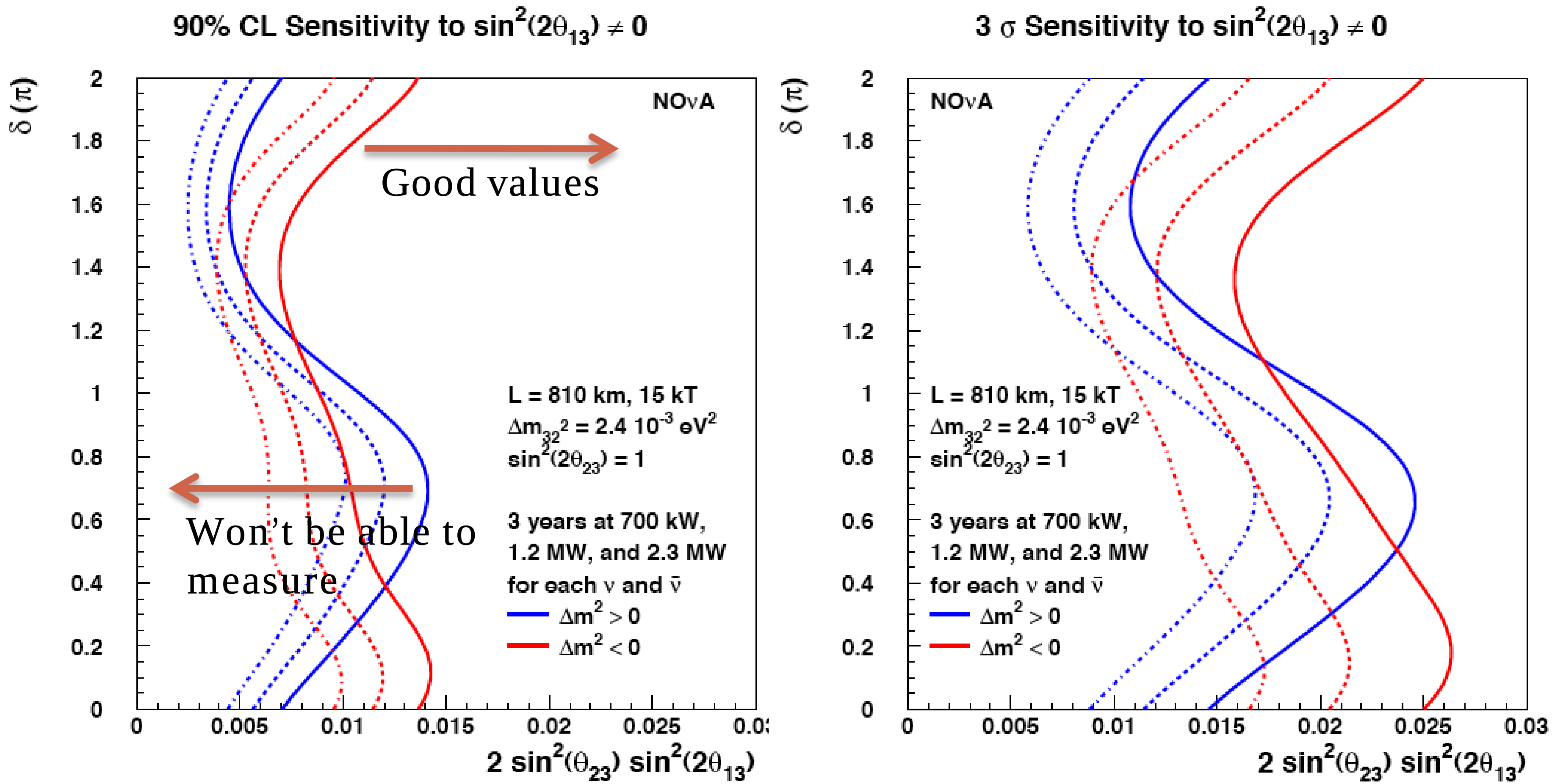


14 kilotons Liquid scintillator in PVC extrusions

Under construction at Ash River

Commissioning in 2012-13; data 2013 - 2019

Sensitivity to $\sin^2 2\theta_{13} \neq 0$



Dotted lines ➔intensity upgrades (more neutrinos) that probably won't happen

Experiment Timelines for limits on θ_{13}

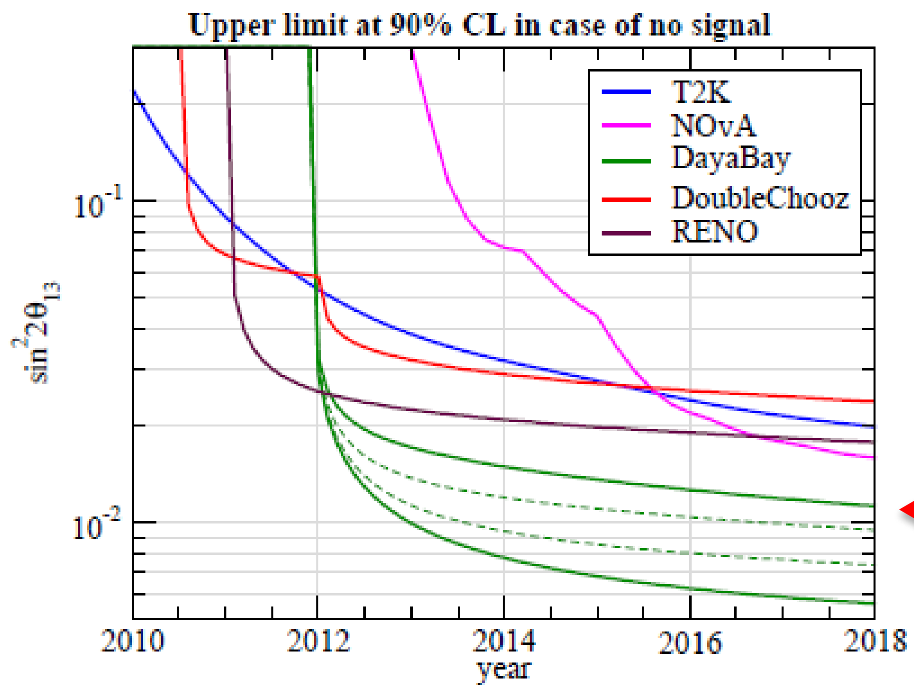


Figure 18. Evolution of the θ_{13} sensitivity limit as a function of time (90% CL), i.e., the 90% CL limit which will be obtained if the true θ_{13} is zero. The four curves for Daya Bay correspond to different assumptions on the achieved systematic uncertainty, from weakest to strongest sensitivity: 0.6% correlated among detector modules at one site, 0.38% correlated, 0.38% uncorrelated among modules, 0.18% uncorrelated.

M.Mezzetto, T.Schwetz, arXiv:1003.5800v1 [hep-ph] 30 Mar 2010

If $\sin^2 2\theta_{13}$ > 0.01 the current "Phase I" experiments should be able to determine this

Bottom line

- θ_{13} needs to be non-zero in order to have a CP-violating phase δ
- Measuring determining that δ has a value (not 0 or π) such that $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, says that neutrinos violate *CP* which may have a connection to *CP* violation in the early universe, and hence to the observed matter-anti-matter asymmetry……
- Experimental challenge – we want to measure the parameter, δ

Beyond θ_{13}

MATTER EFFECTS

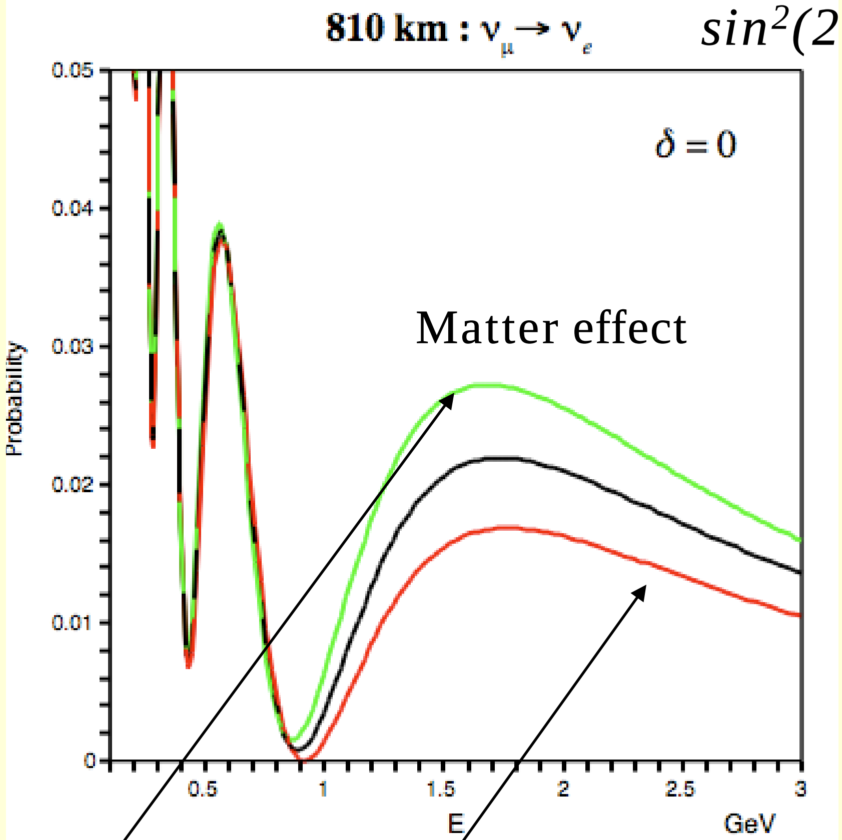
MASS HIERARCHY

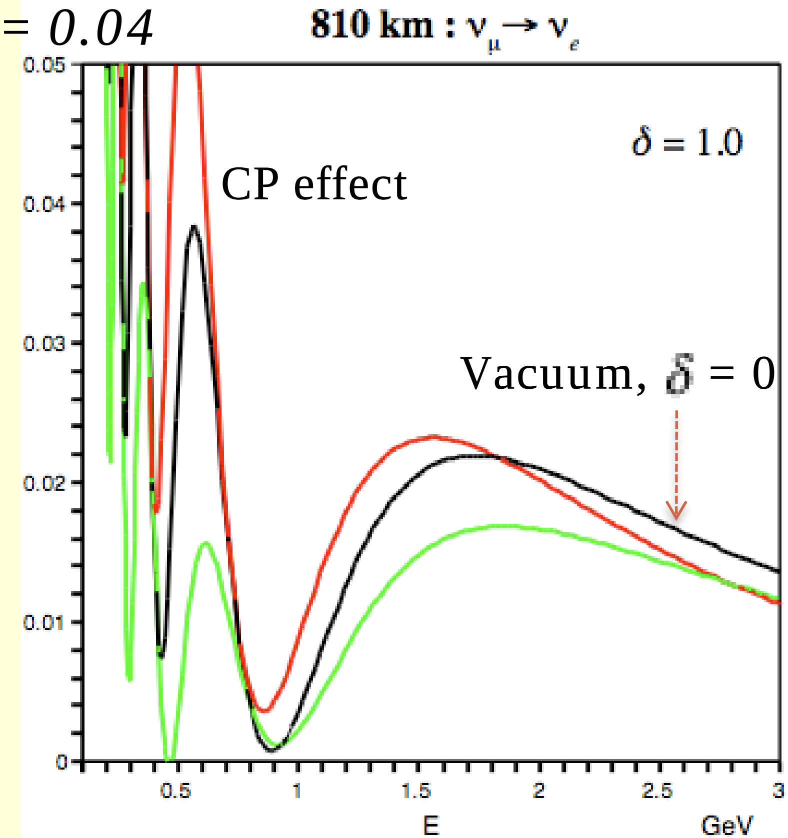
AMBIGUITIES AND δ_{CP}

Matter Effects and CP

Normal hierarchy

$sin^2(2\cup_{13}) = 0.04$



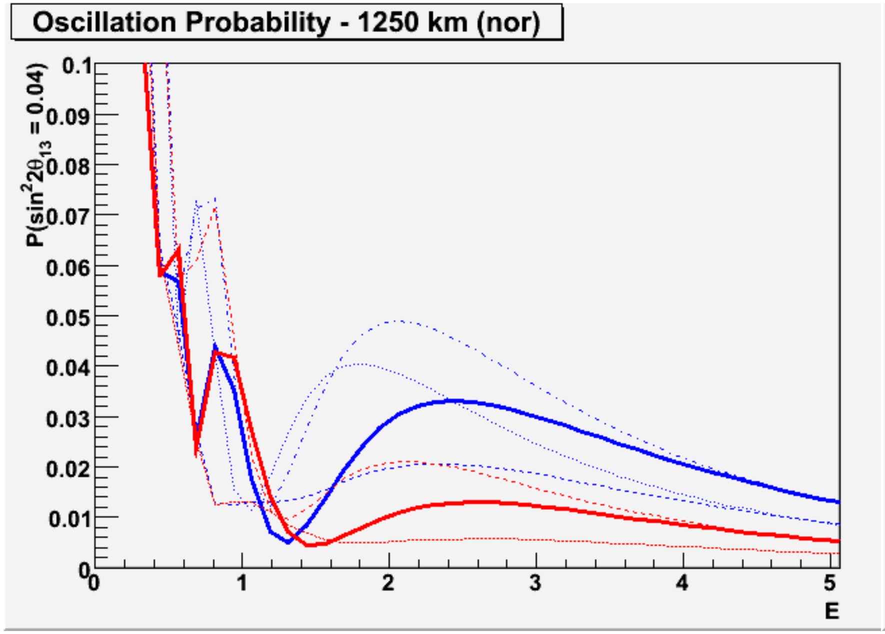


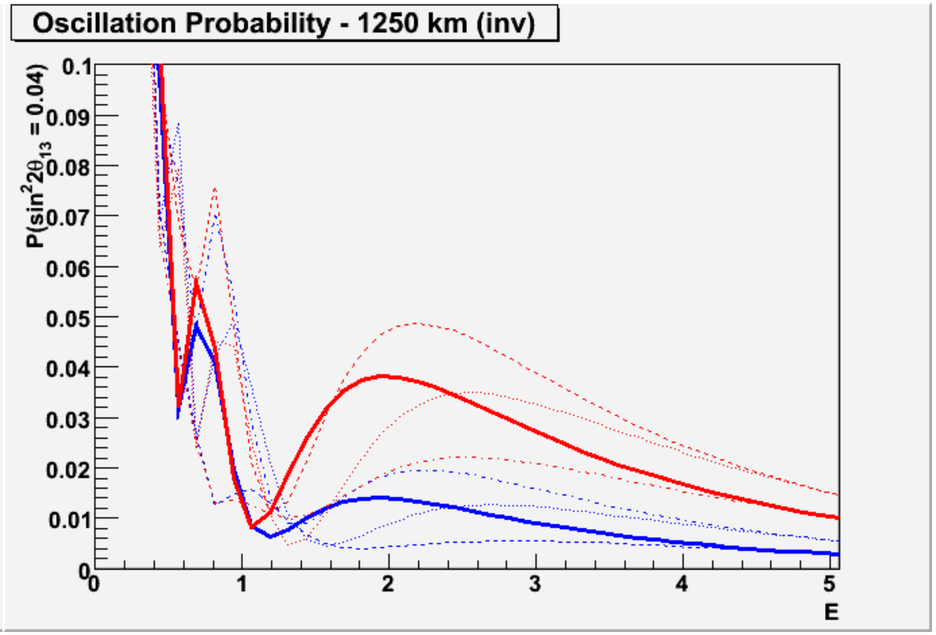
{'s

anti-{'s

Matter and the hierarchy

Neutrinos – blue
Anti-neutrios - red

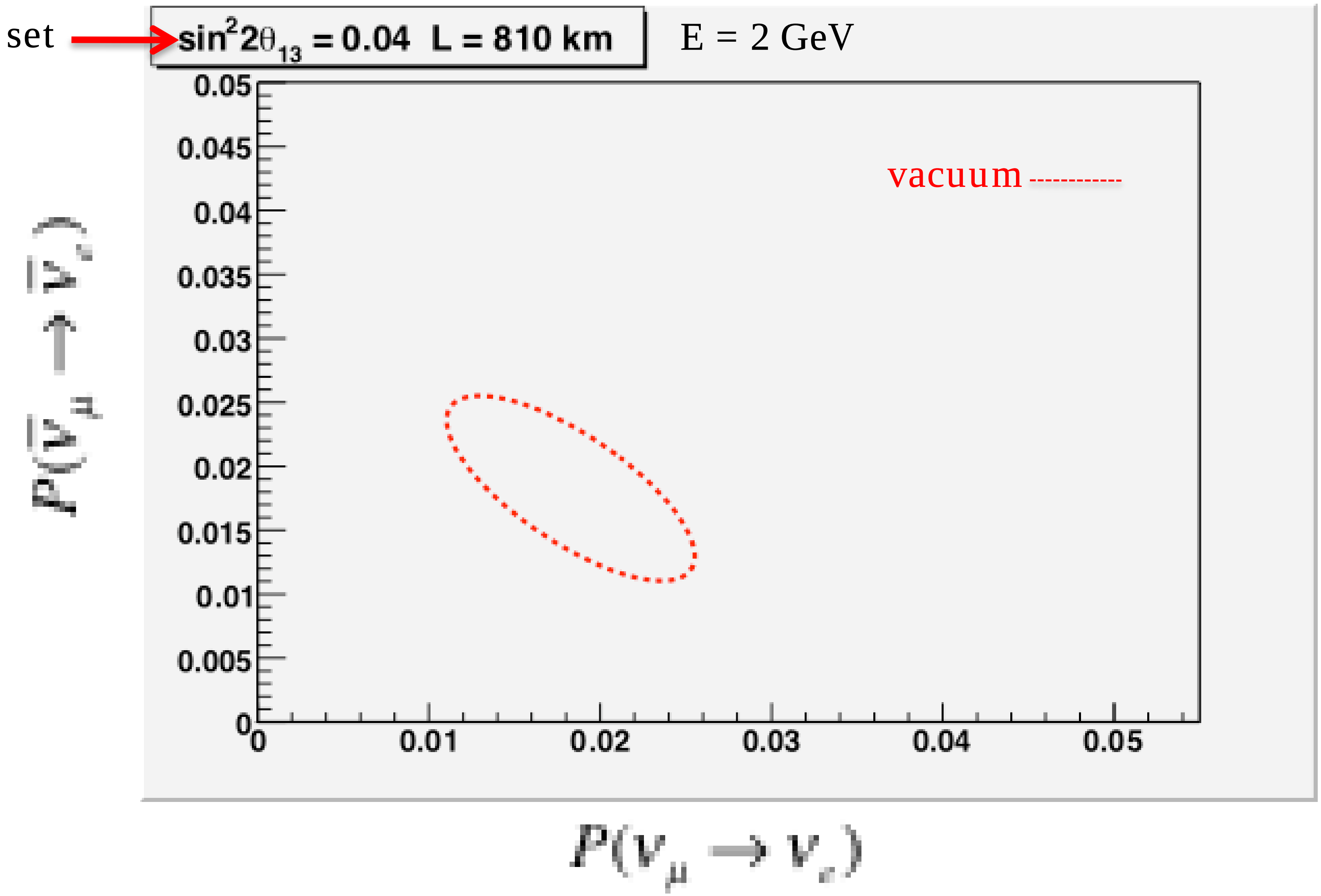




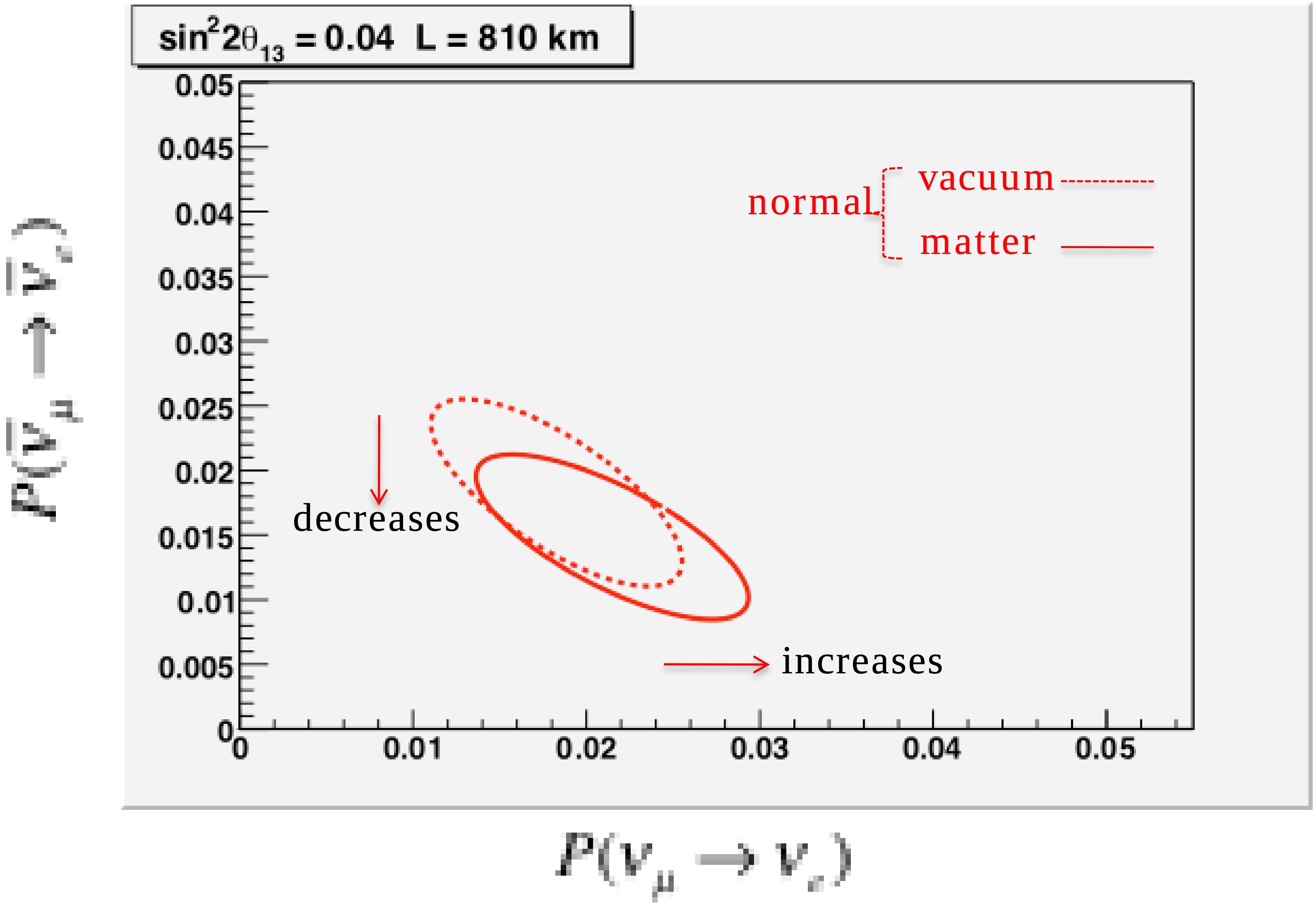
Neutrinos – enhanced
Anti-neutrinos - suppressed

Anti-neutrinos – enhanced
Neutrinos - suppressed

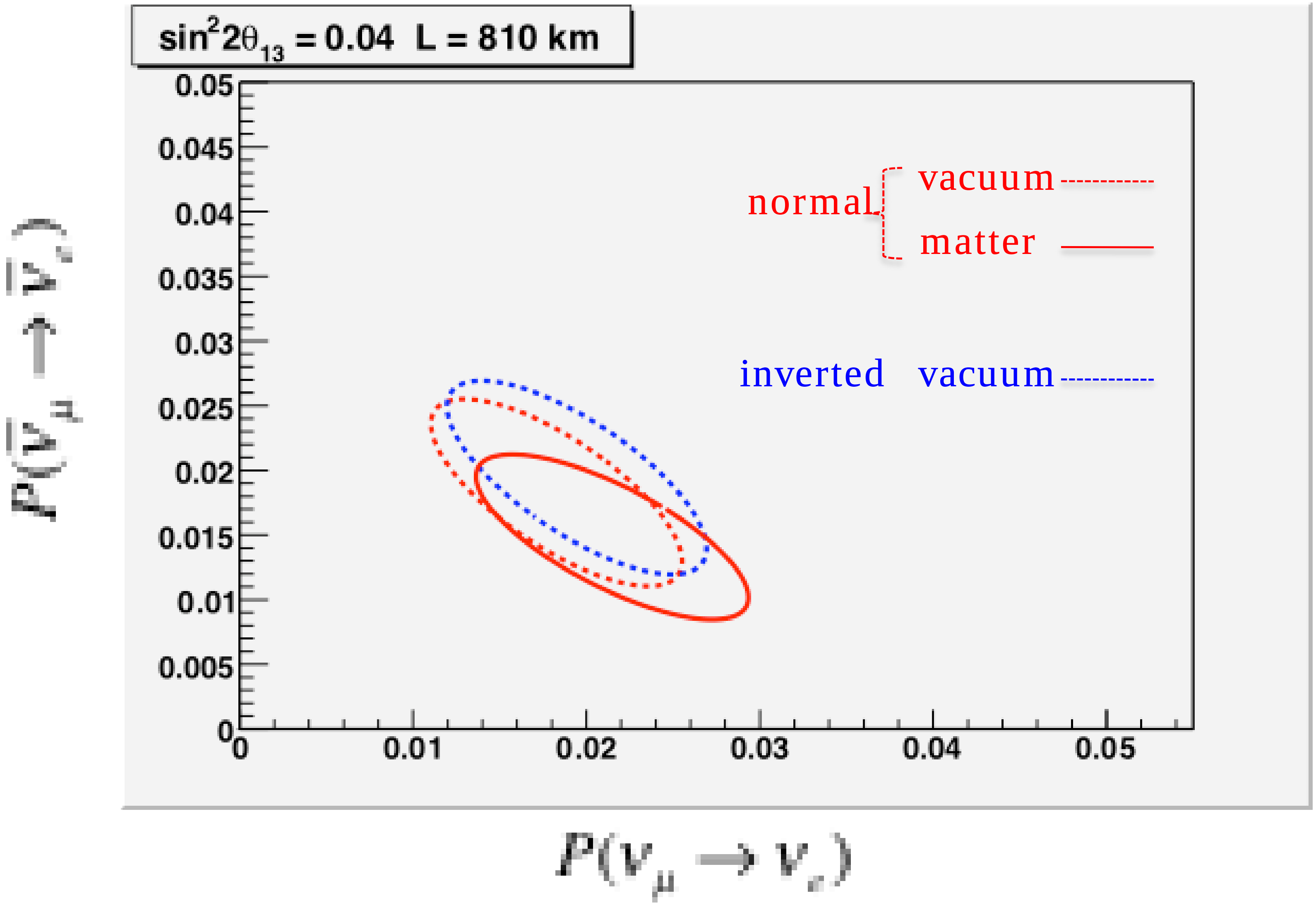
Neutrino vs. anti-neutrino bi-probability plots



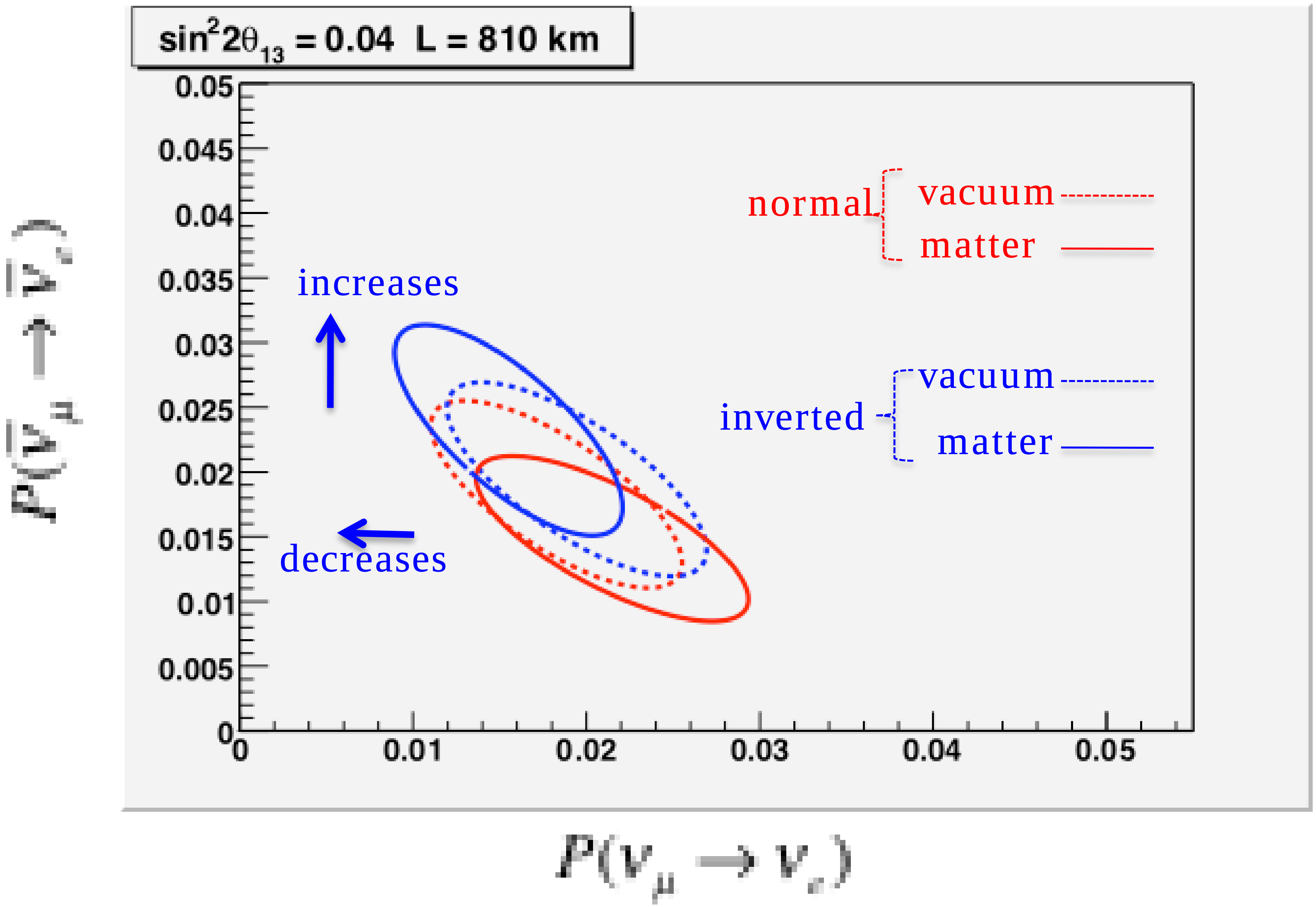
Include matter effects



Plot for the inverted mass hierarchy $\Delta m^2_{32}(inverted) = -\left|\Delta m^2_{32}\right|(normal)$

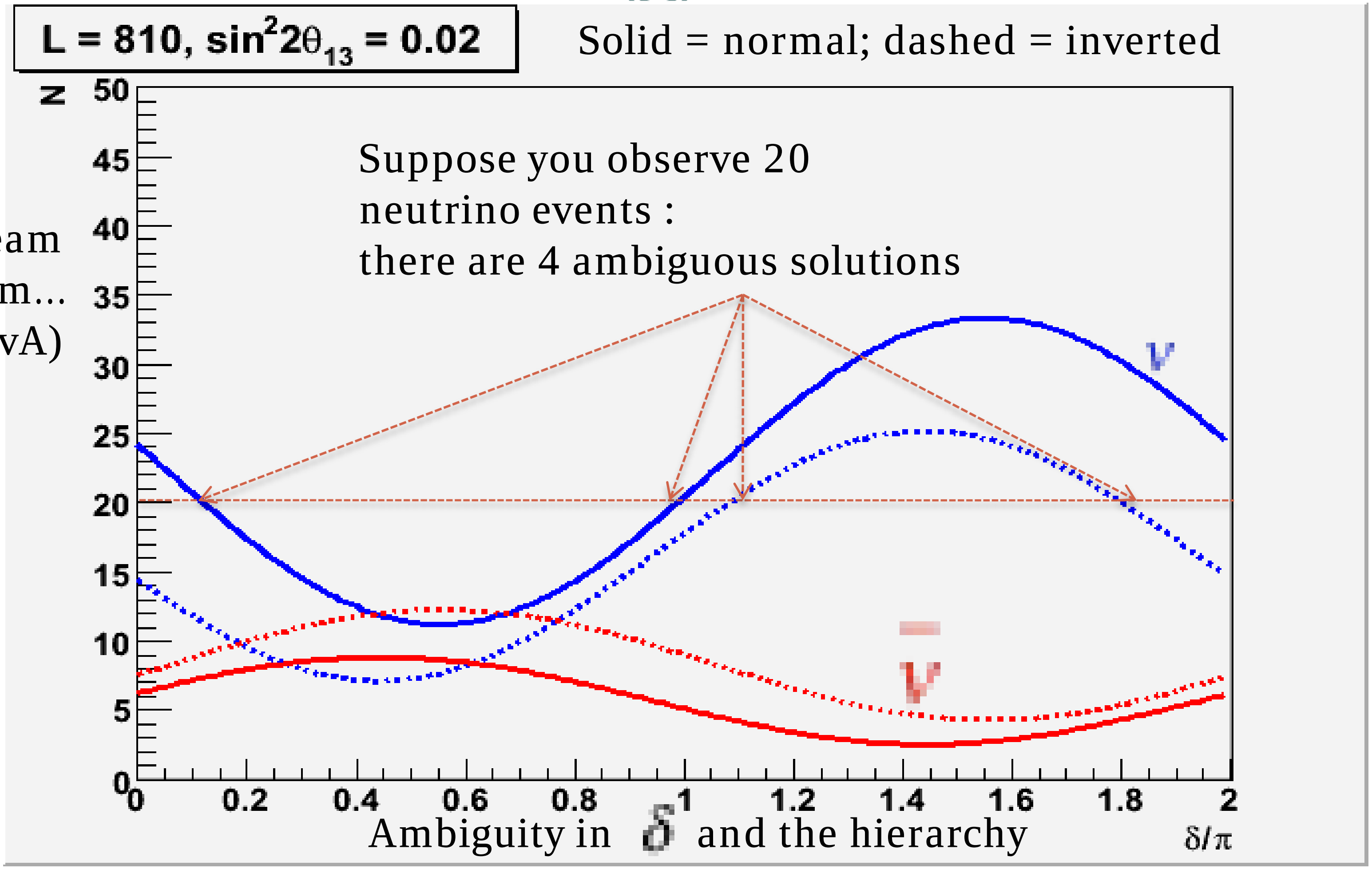


Overlapping probabilities ➔ ambiguities

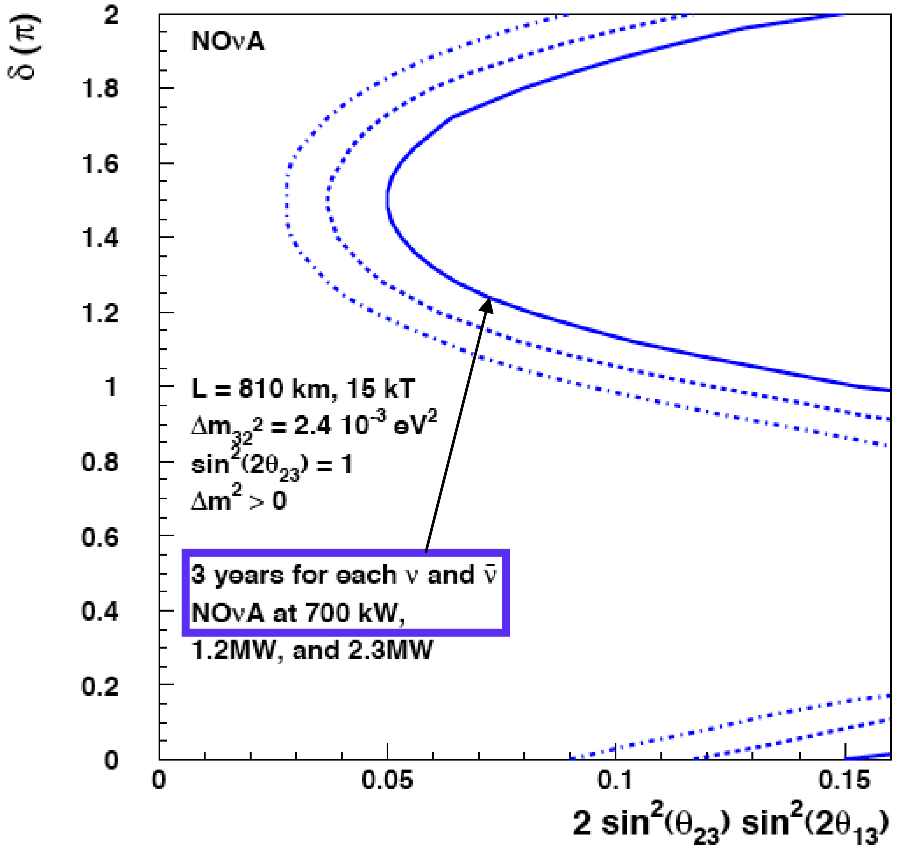


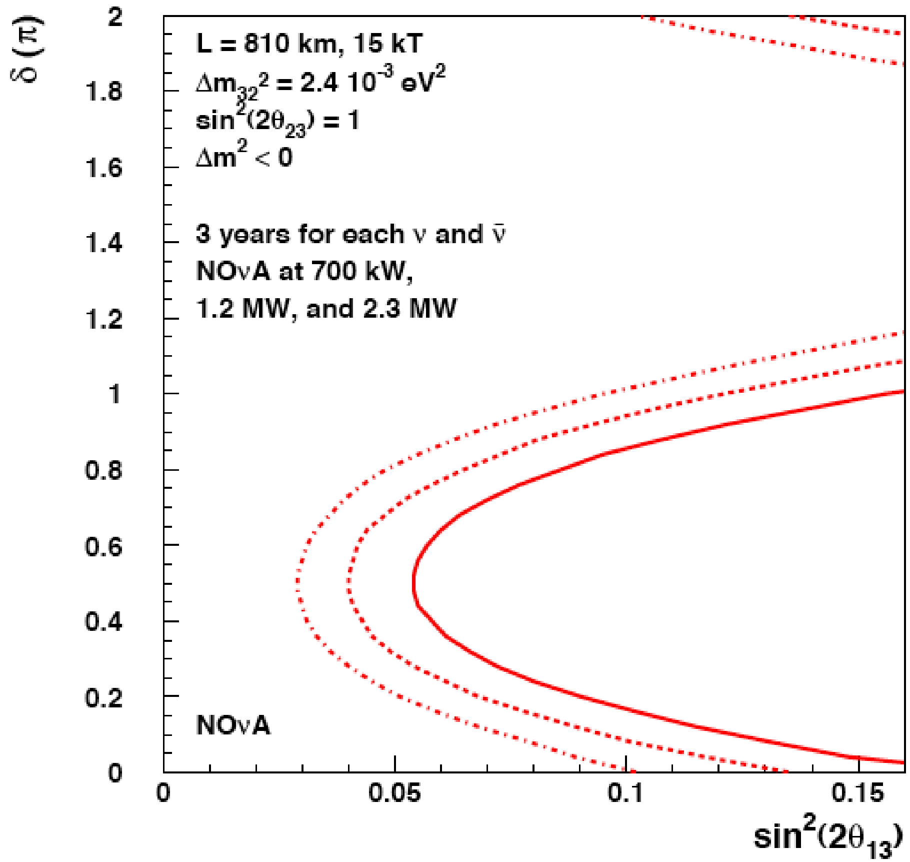
Probabilities ➔ Event rate
Calculate Event Numbers!

Get a beam Spectrum… (i.e. NOvA)



NOνA Sensitivity to the Mass Hierarchy

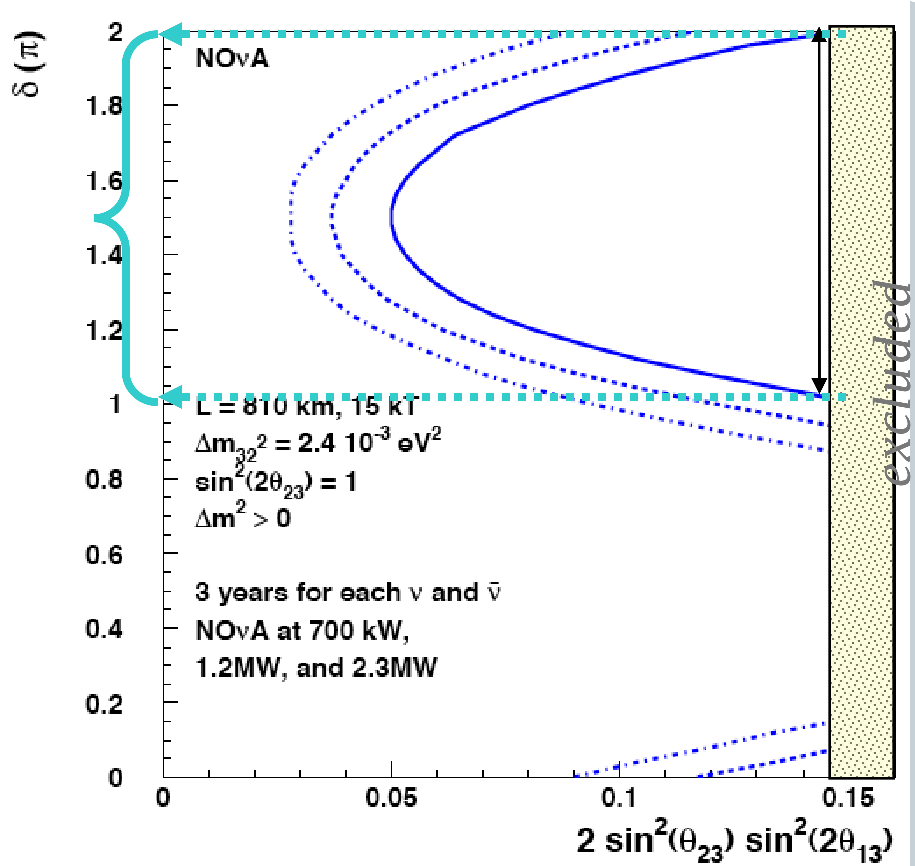


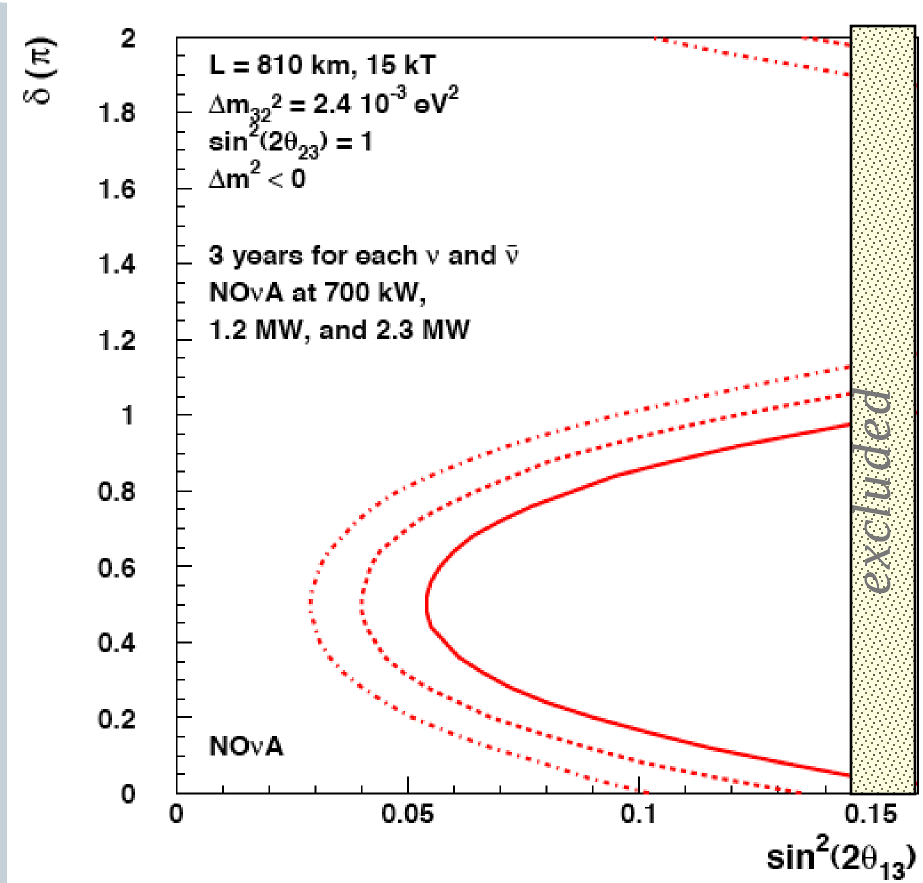


Interpreting

NOνA Sensitivity to the Mass Hierarchy

95% CL

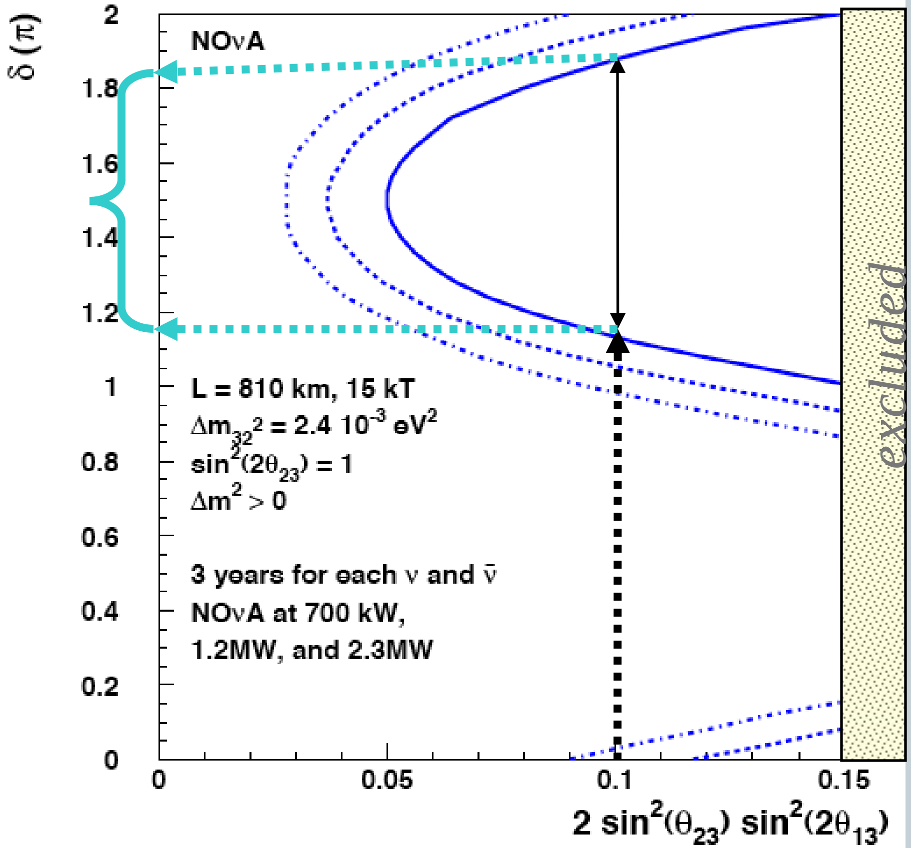


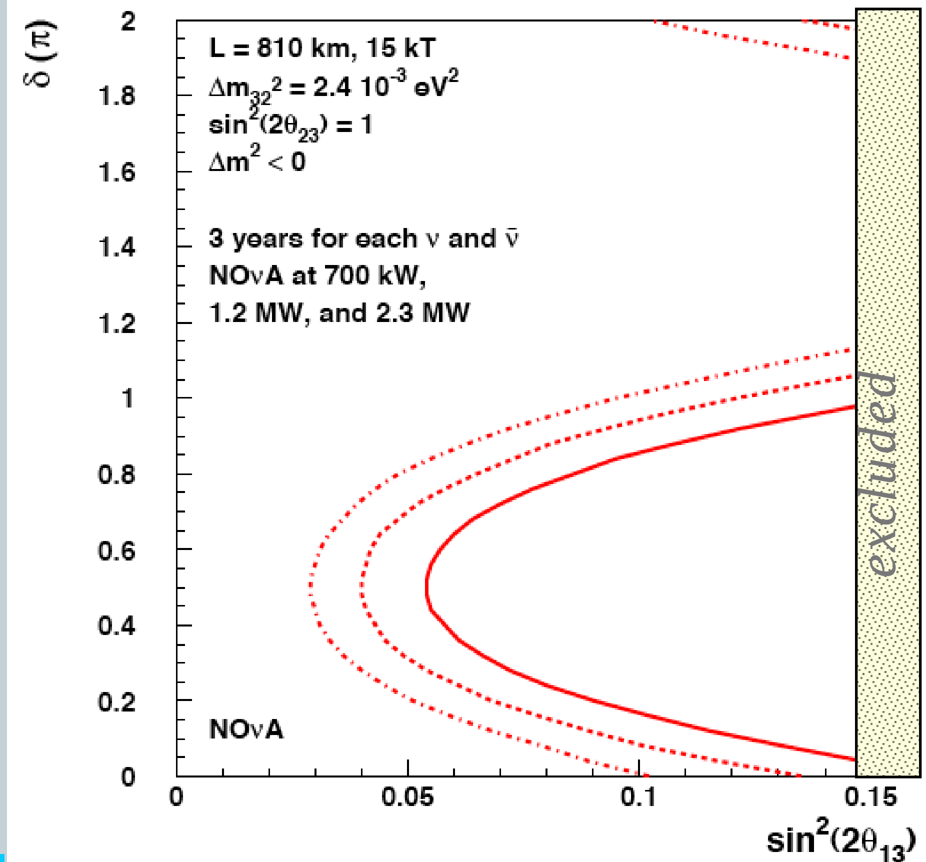


If $\sin^2 2\theta_{13} = 0.15$, for 50% of the possible values of δ_{CP} the mass hierarchy can be determined at 95%CL

Interpreting
NO{ A Sensitivity to the Mass Hierarchy

95% CL



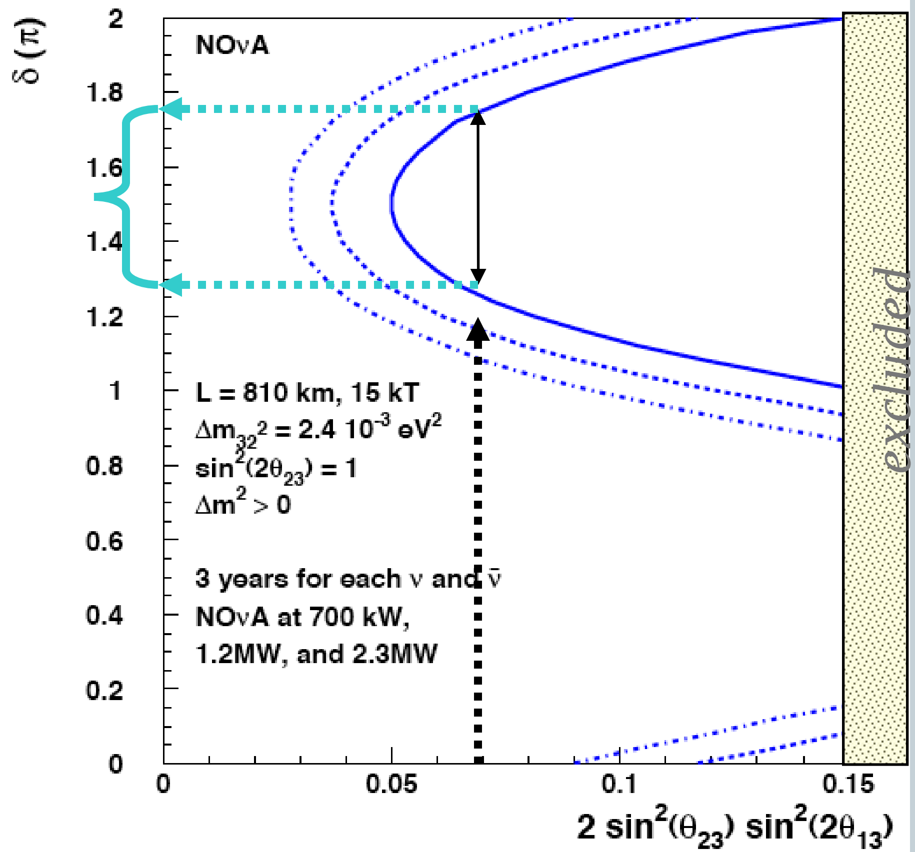


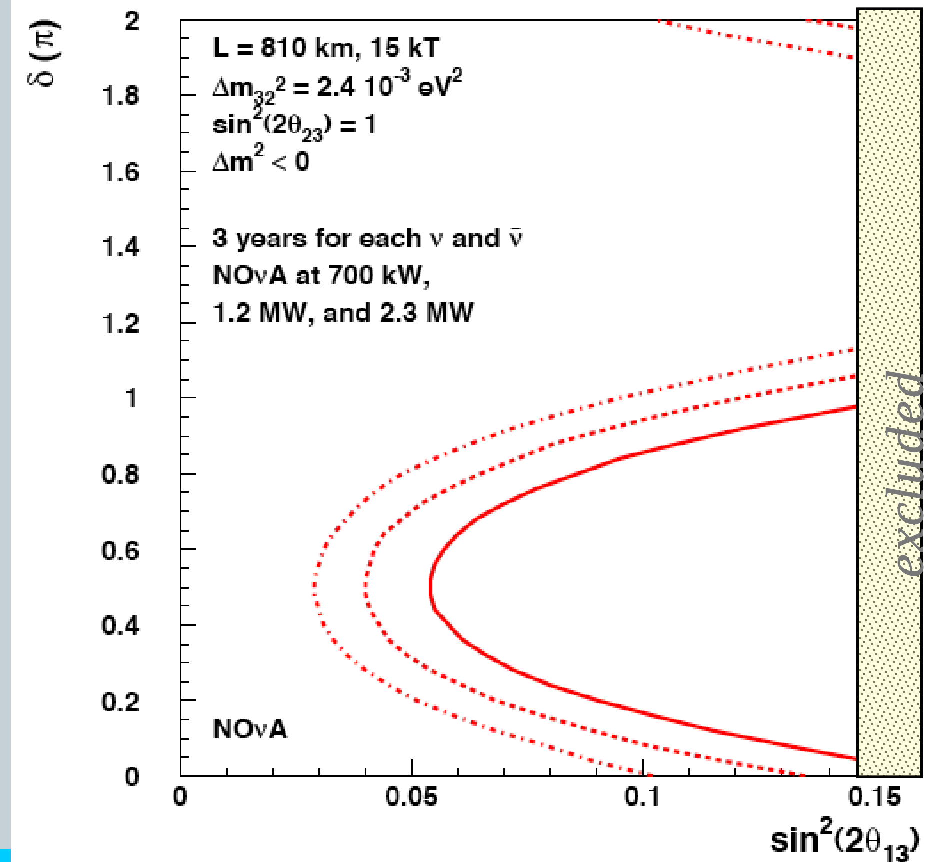
If $\sin^2 2\theta_{13} = 0.10$, for 36% of the possible values of δ_{CP} the mass hierarchy can be determined at 95%CL

Interpreting

NO{A Sensitivity to the Mass Hierarchy

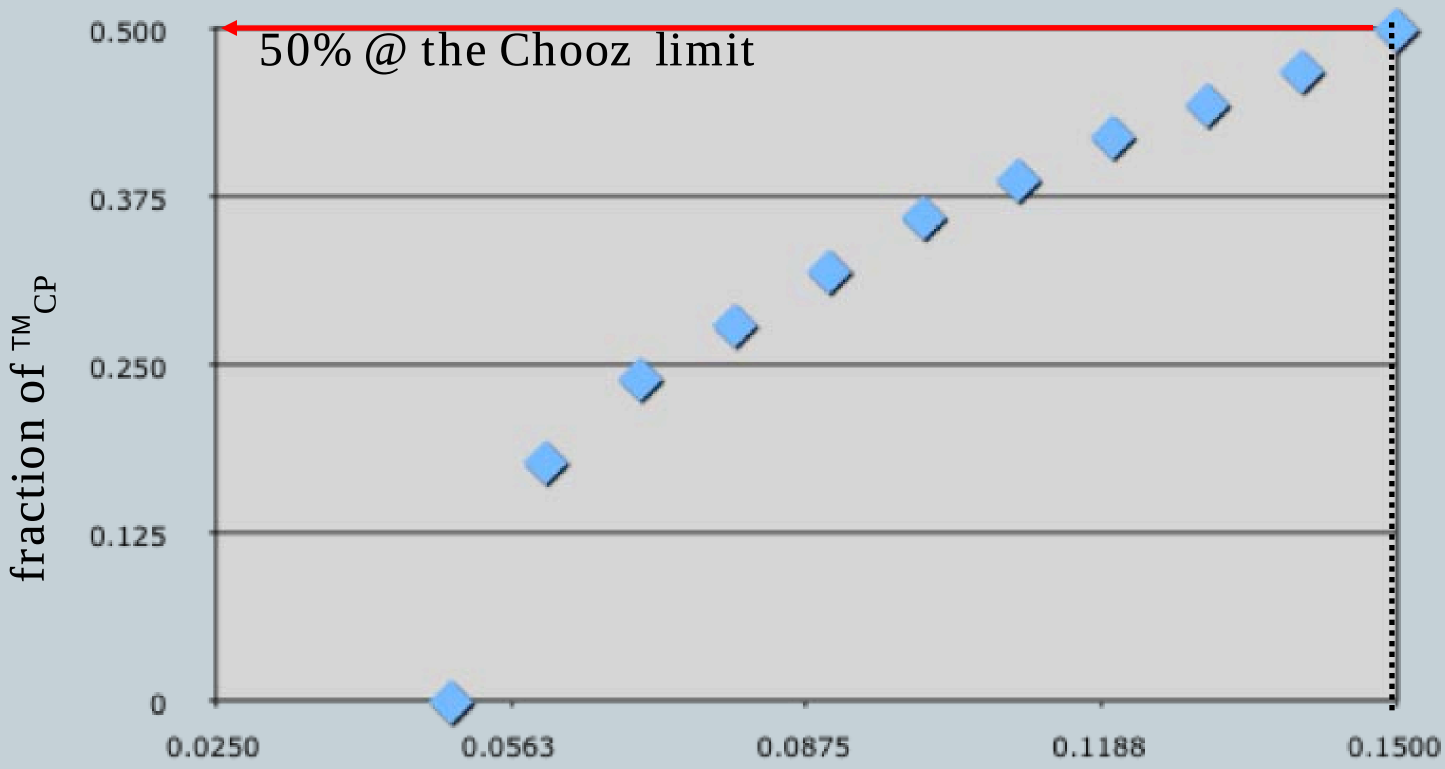
95% CL





If $\sin^2 2\theta_{13} = 0.07$, for 24% of the possible values of δ_{CP} the mass hierarchy can be determined at 95%CL

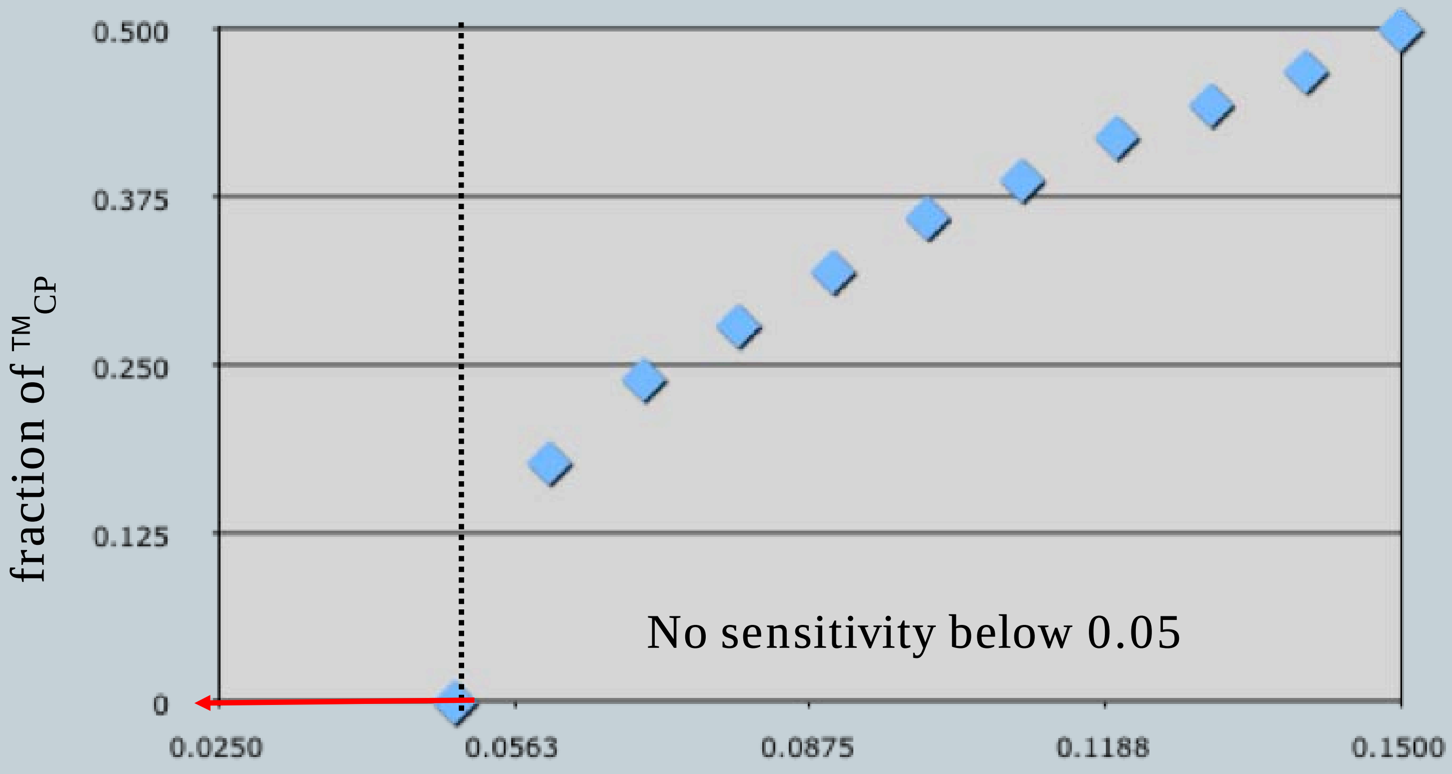
NOνA 95% CL sensitivity to the Mass Hierarchy



700kW for 6 years

$\sin^2 2\theta_{13}$

NO{A 95% CL sensitivity to the Mass Hierarchy



700kW for 6 years

sin²2(13

Take away - 1

- Reactor disappearance
  - A positive result from Double Chooz will indicate a "good" value for θ_{13}
  - Limit results from Reno and Daya Bay (several years from now) will indicate that $\sin^2 2\theta_{13}$ is not larger than ~0.01
- T2K appearance
  - Prompt results from T2K will begin to shed light on the θ_{13} question and help guide the way for future long baseline experiments needing to use a non-zero θ_{13} (mass hierarchy and CP violation)

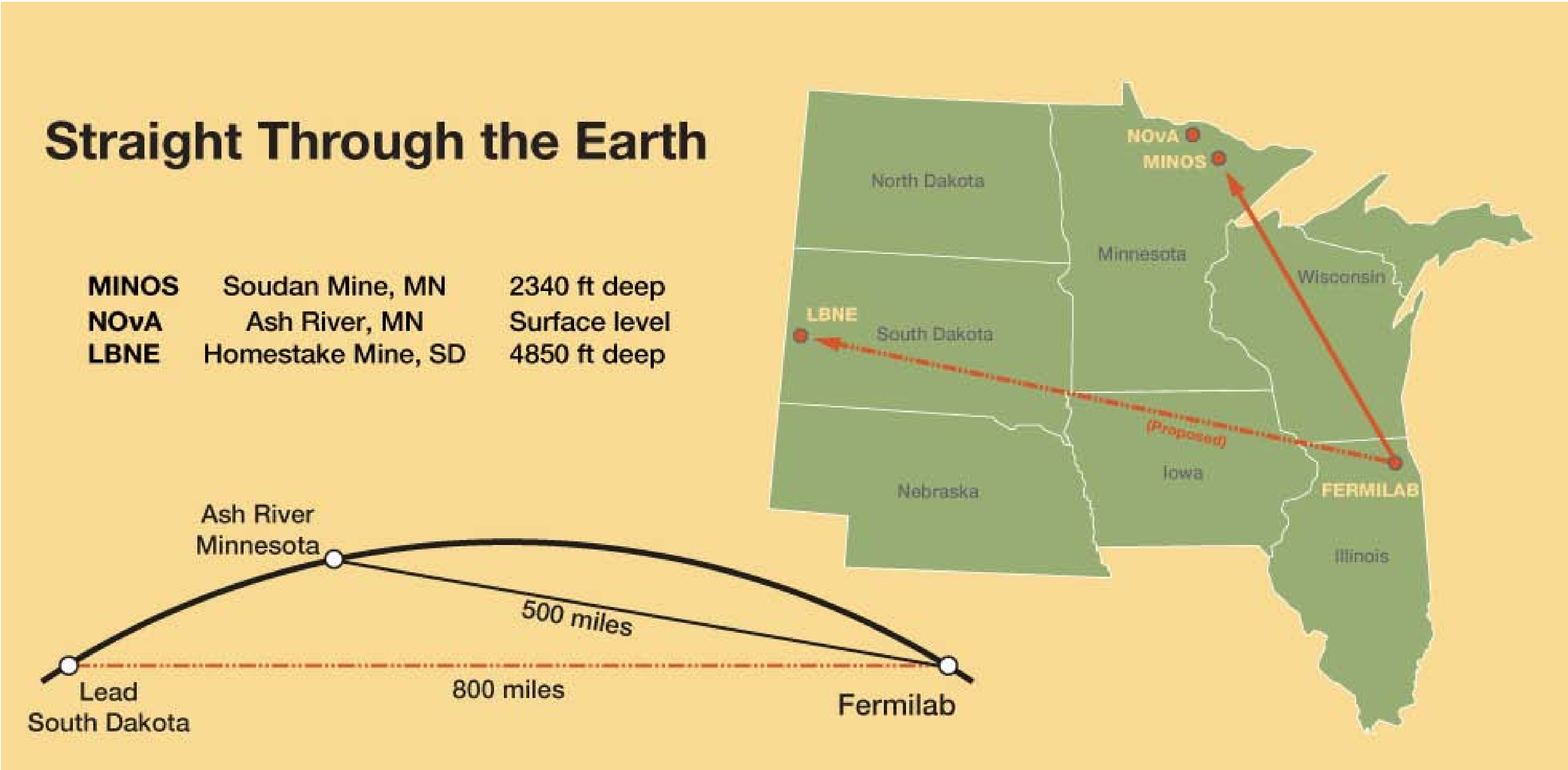
Take-away -2

- NOvA has a baseline of 810 km, which is long enough to exhibit matter effects in the $\nu_\mu \rightarrow \nu_e$ appearance probability
- However, for half the possible values of δ the effect is not large enough to resolve the ambiguities which arise among θ_{13}, δ and the hierarchy
- Nor, for values of $\sin^2 2\theta_{13} < 0.05$ can the ambiguity be resolved
  - Though $\sin^2 2\theta_{13}$ can be observed for values to approaching ~0.01

Resolving the mass hierarchy

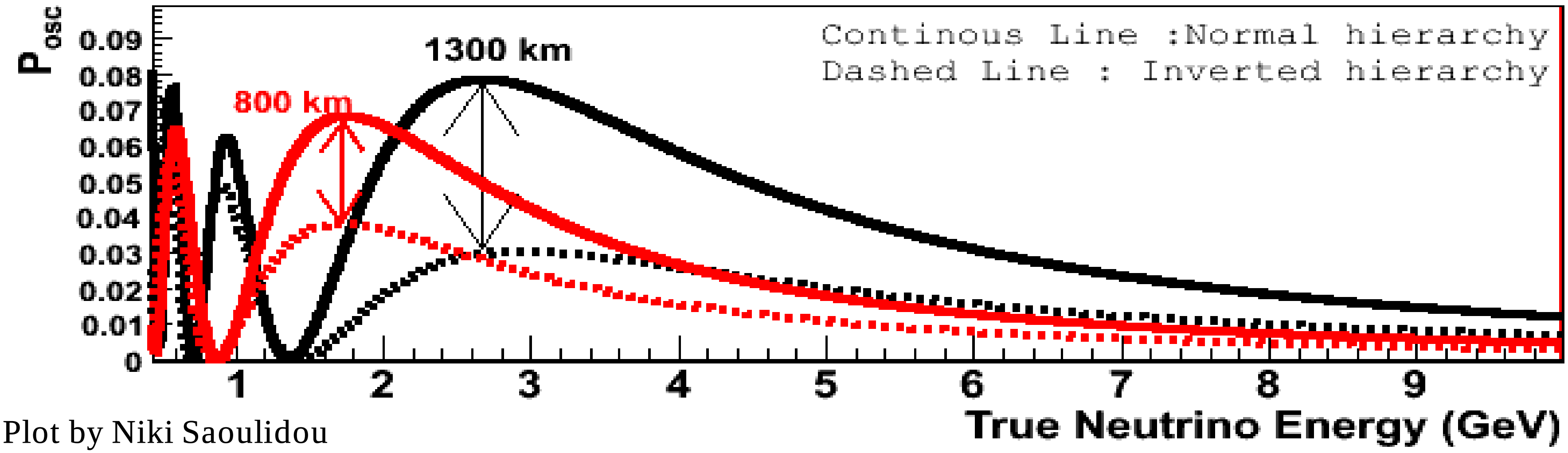
THE EXPERIMENT BASELINE

A longer baseline



What happens at the longer baseline?

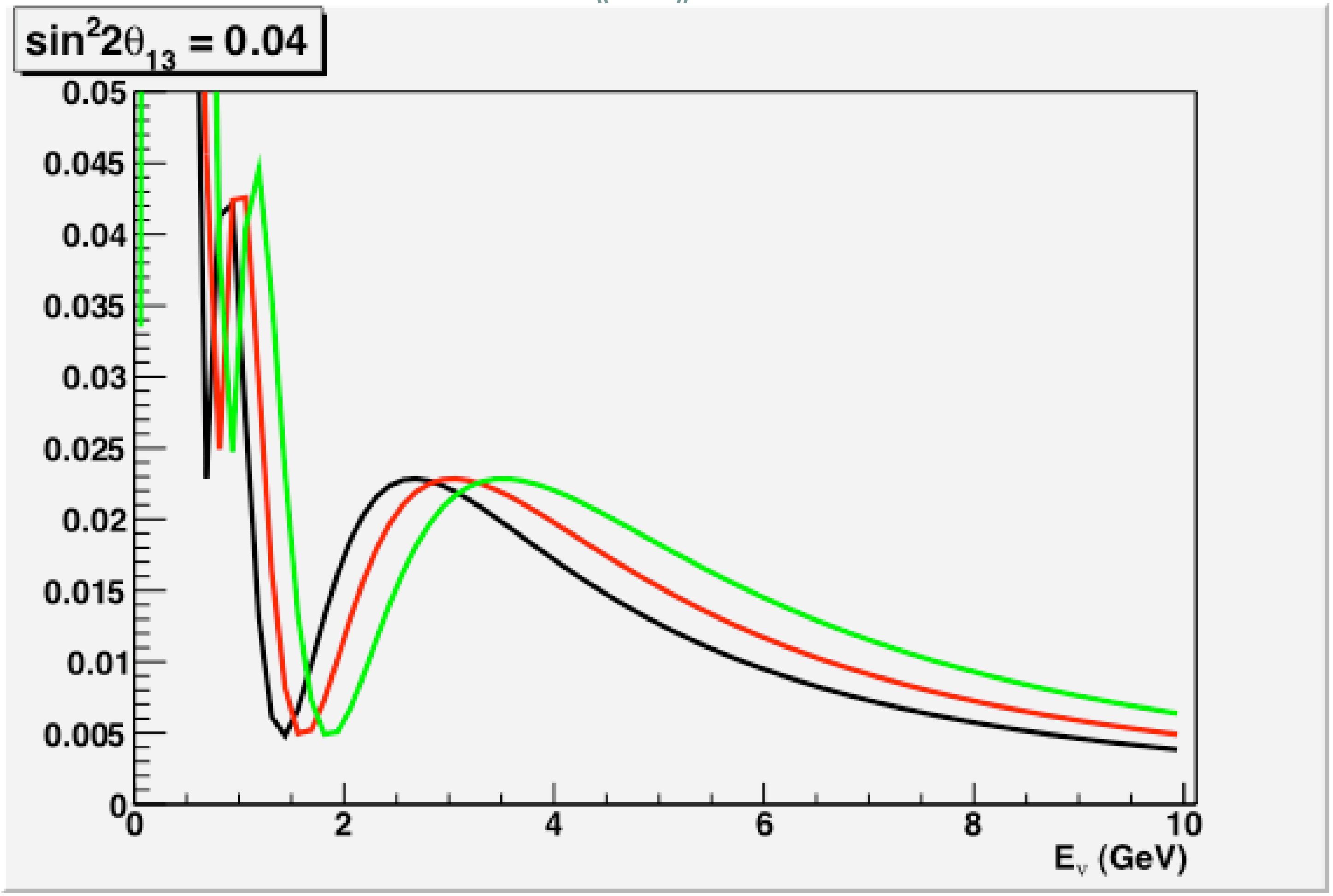
$P(\nu_{\mu} \rightarrow \nu_{e})$



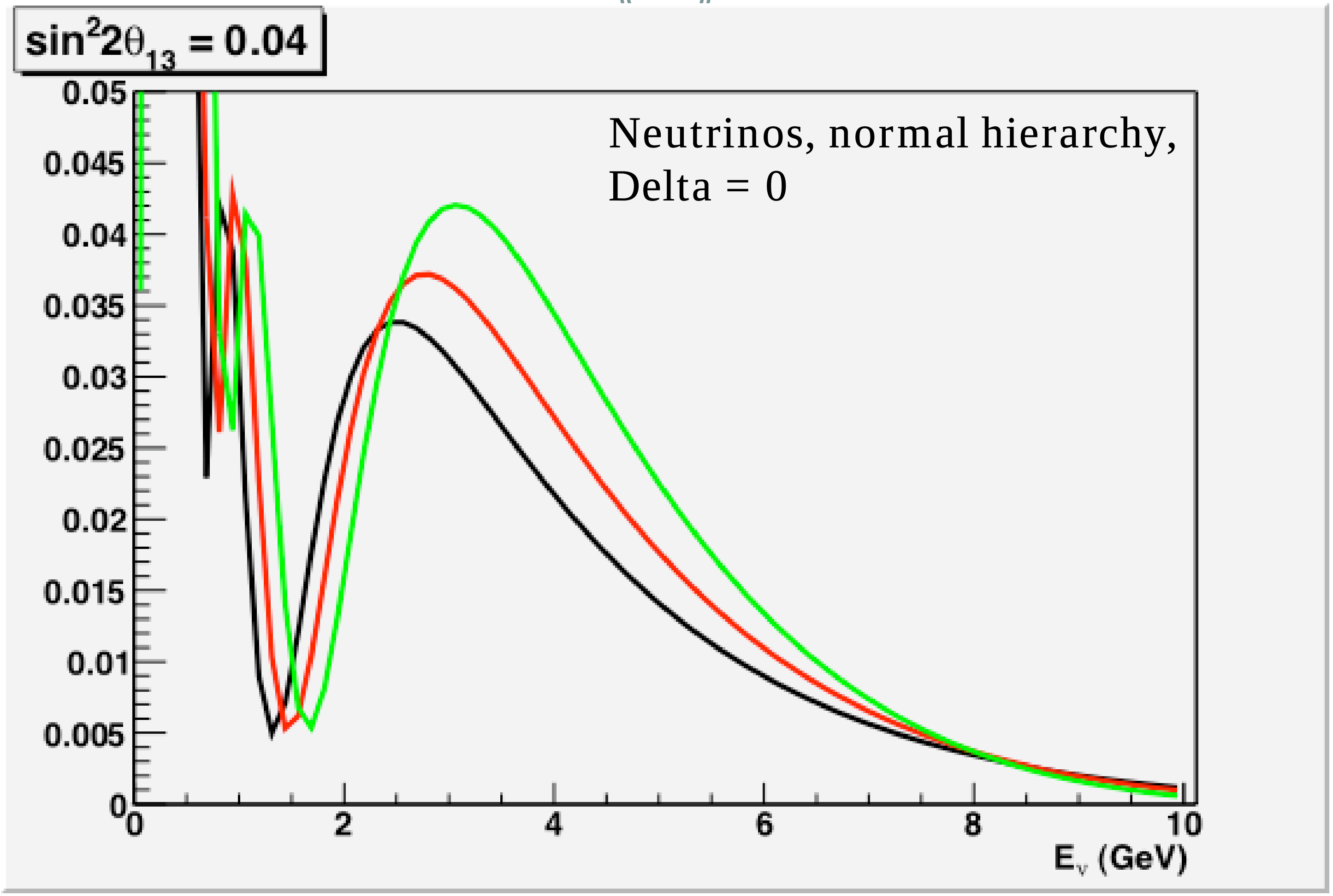
Plot by Niki Saoulidou

- Oscillation maxima are moved to higher energy
- Matter effects are significantly larger

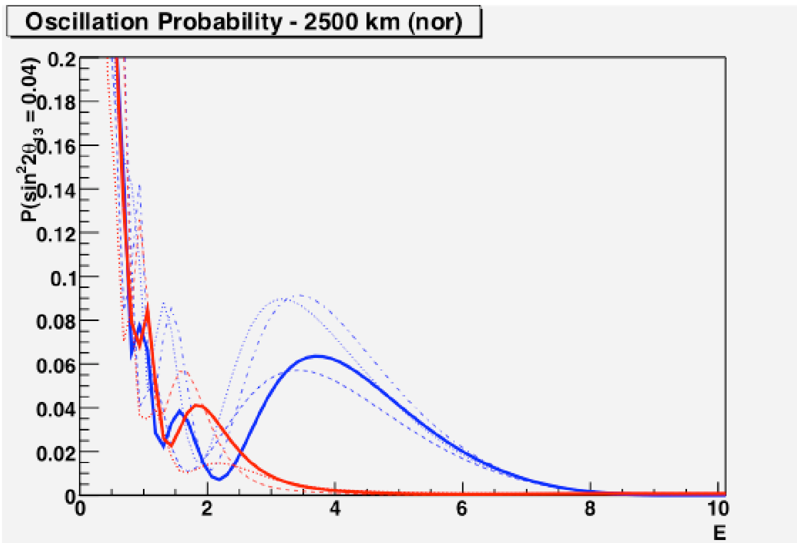
1300,1400,1700 km probabilities (vacuum)

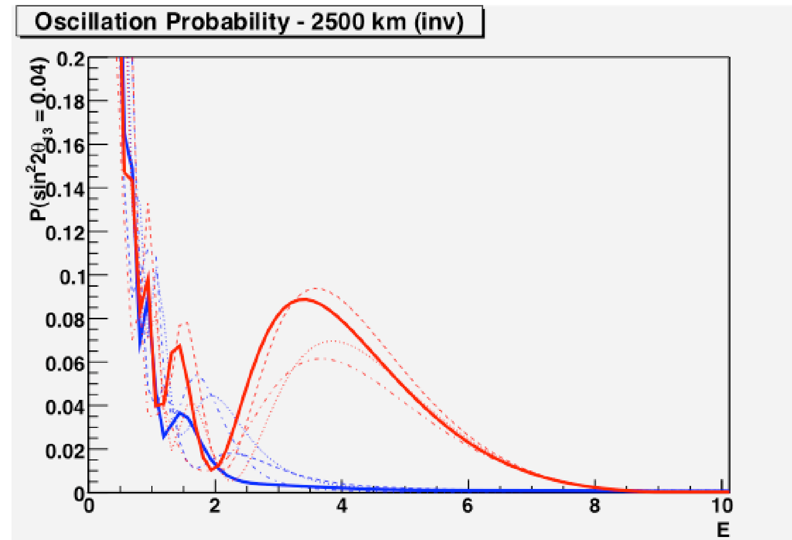


1300,1400,1700 km including matter affect



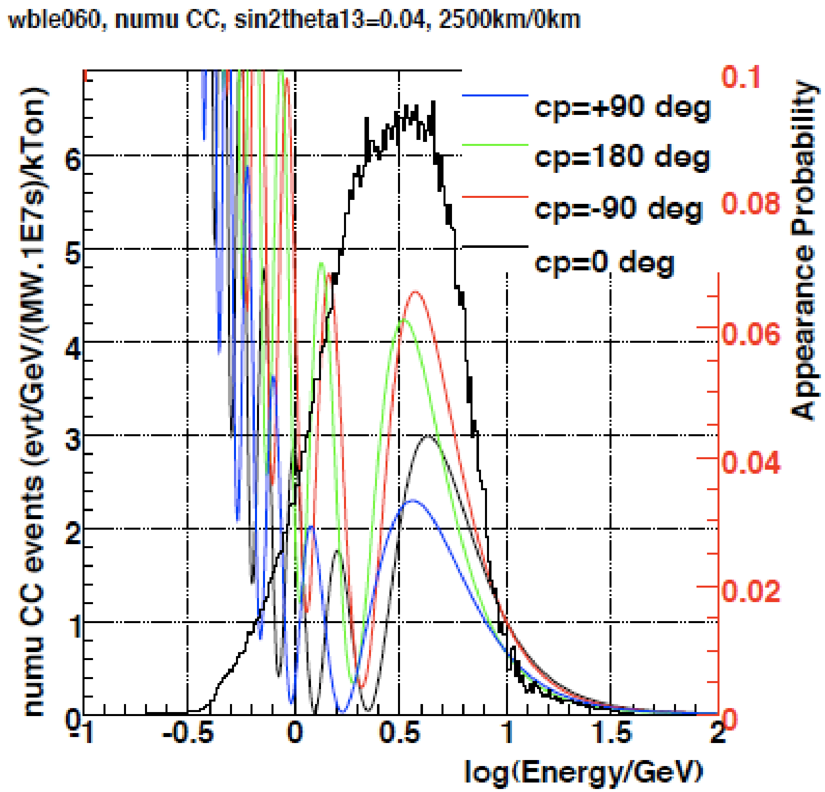
Dramatic matter and δ effects at 2500 km

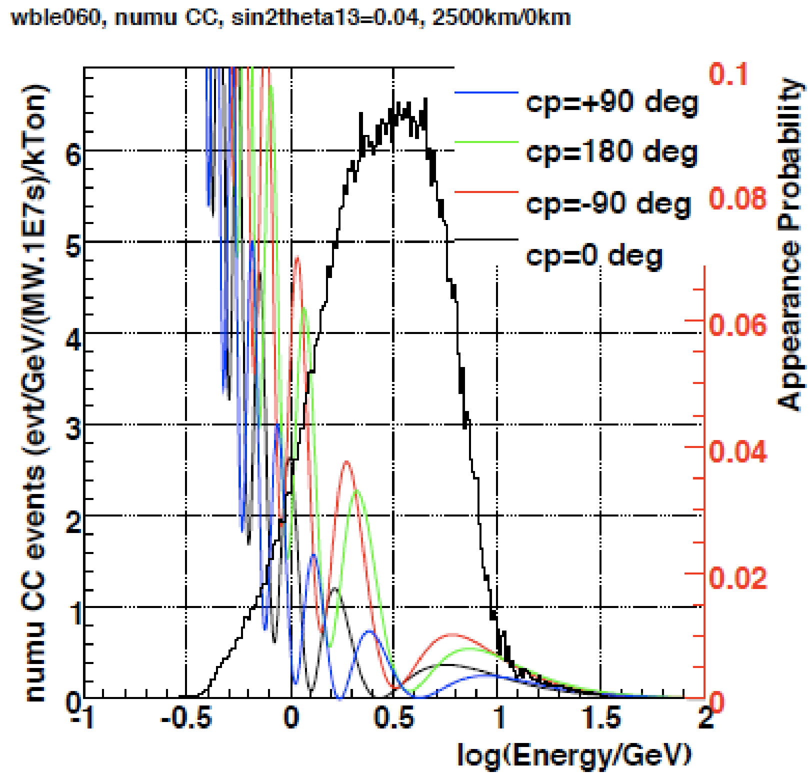




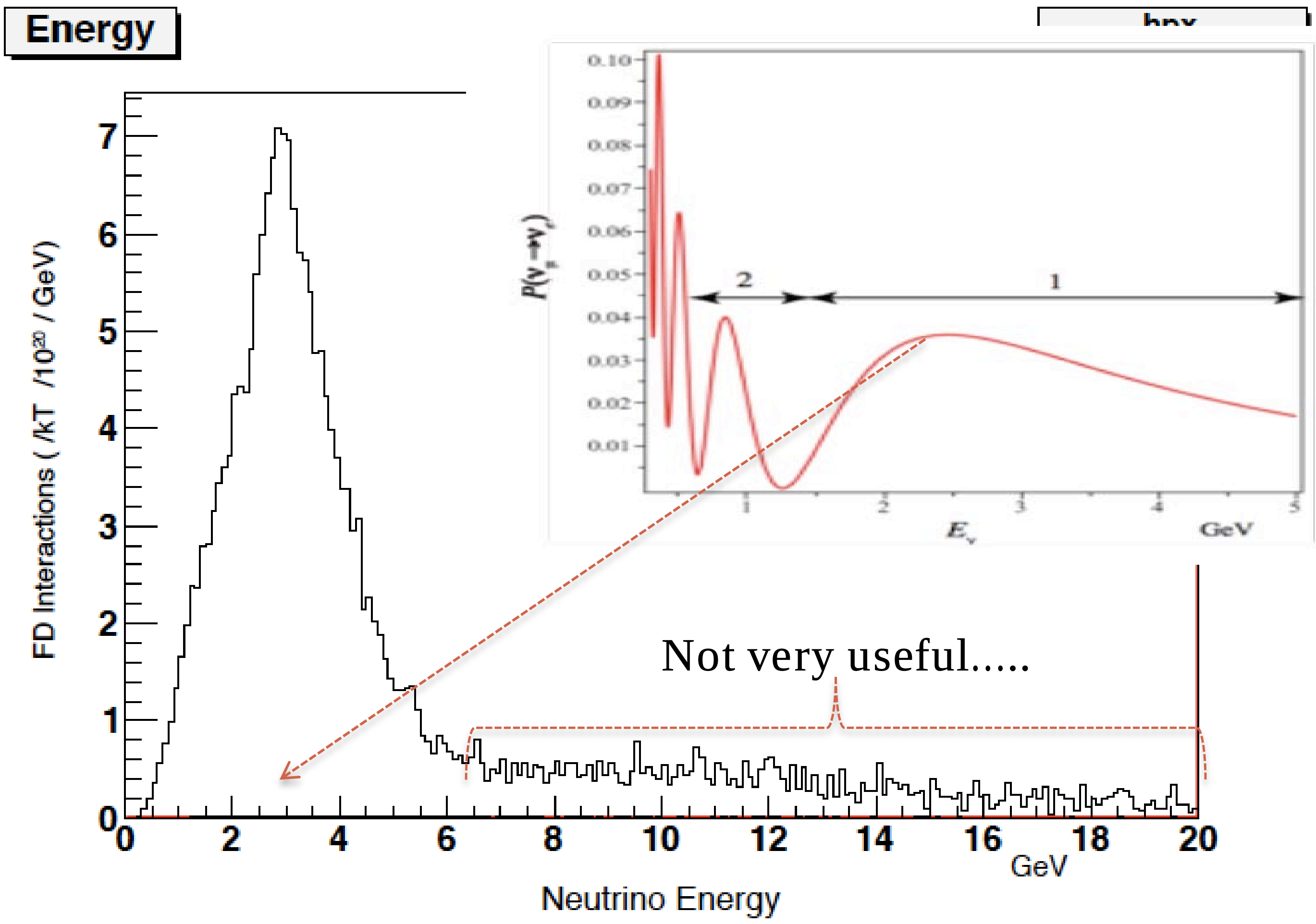
$$\delta : solid \rightarrow 0, dashed \rightarrow \frac{\pi}{2}, \pi, \frac{3\pi}{2}$$

Wide Band Beam covering multiple nodes

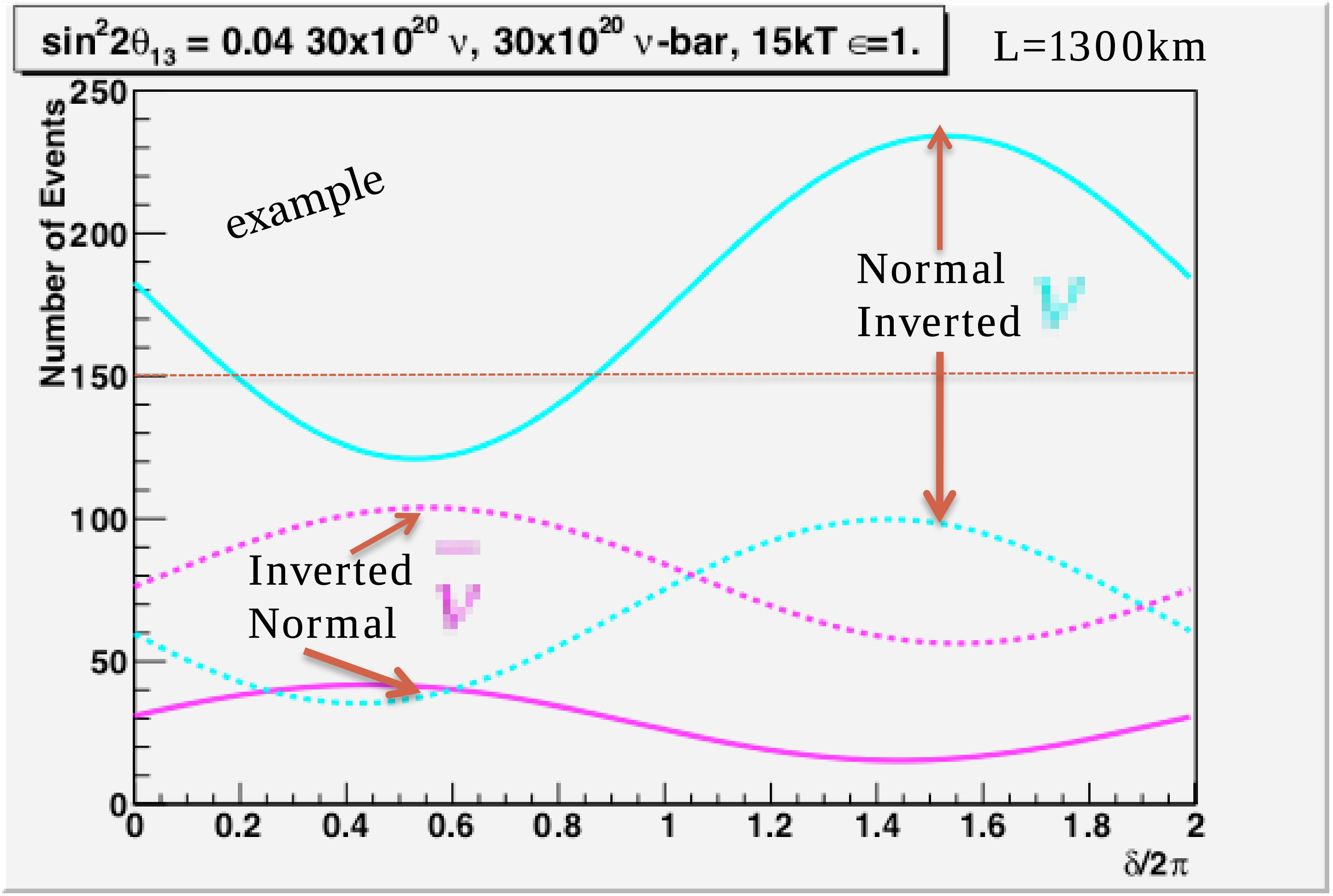




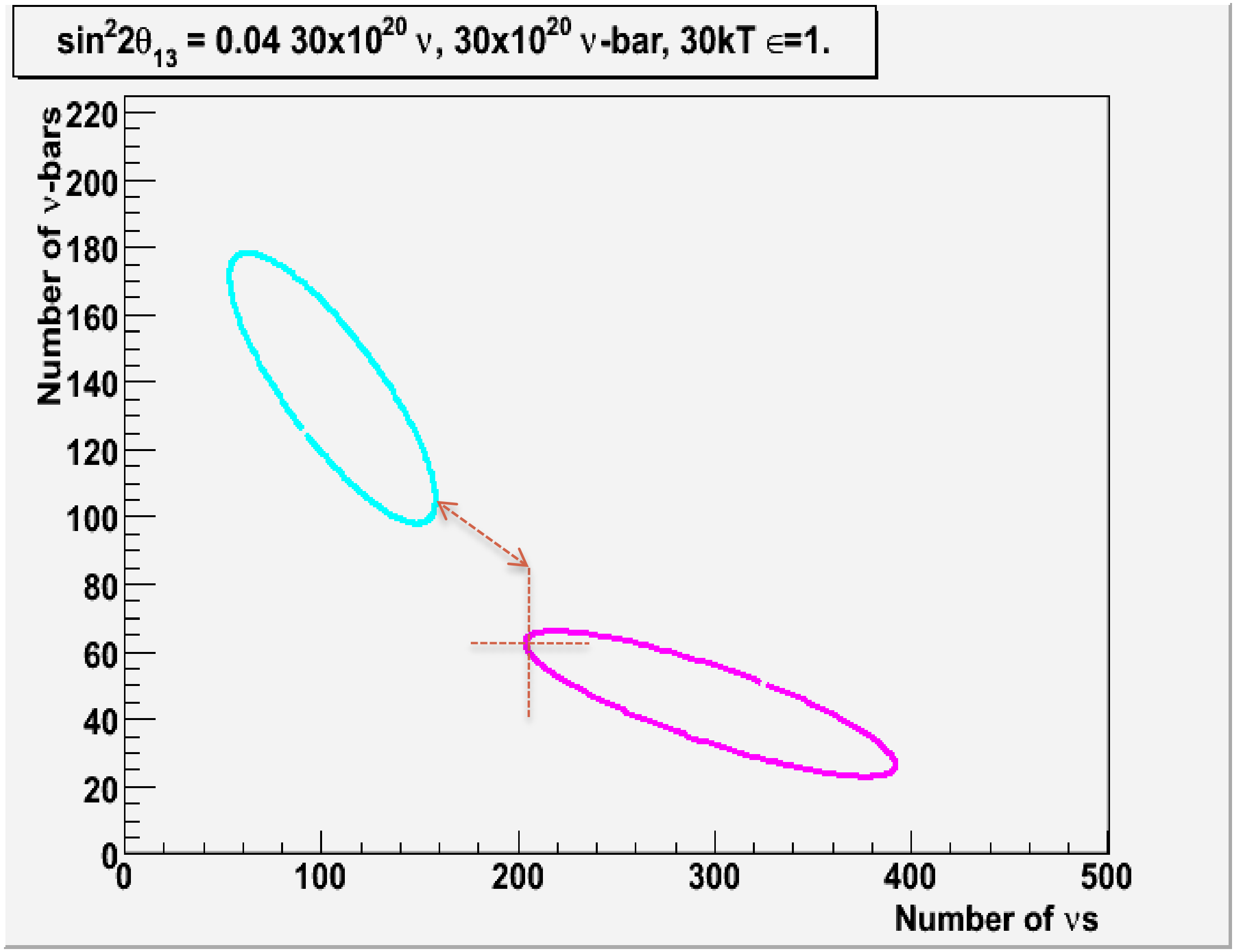
Beam Spectra and Probability



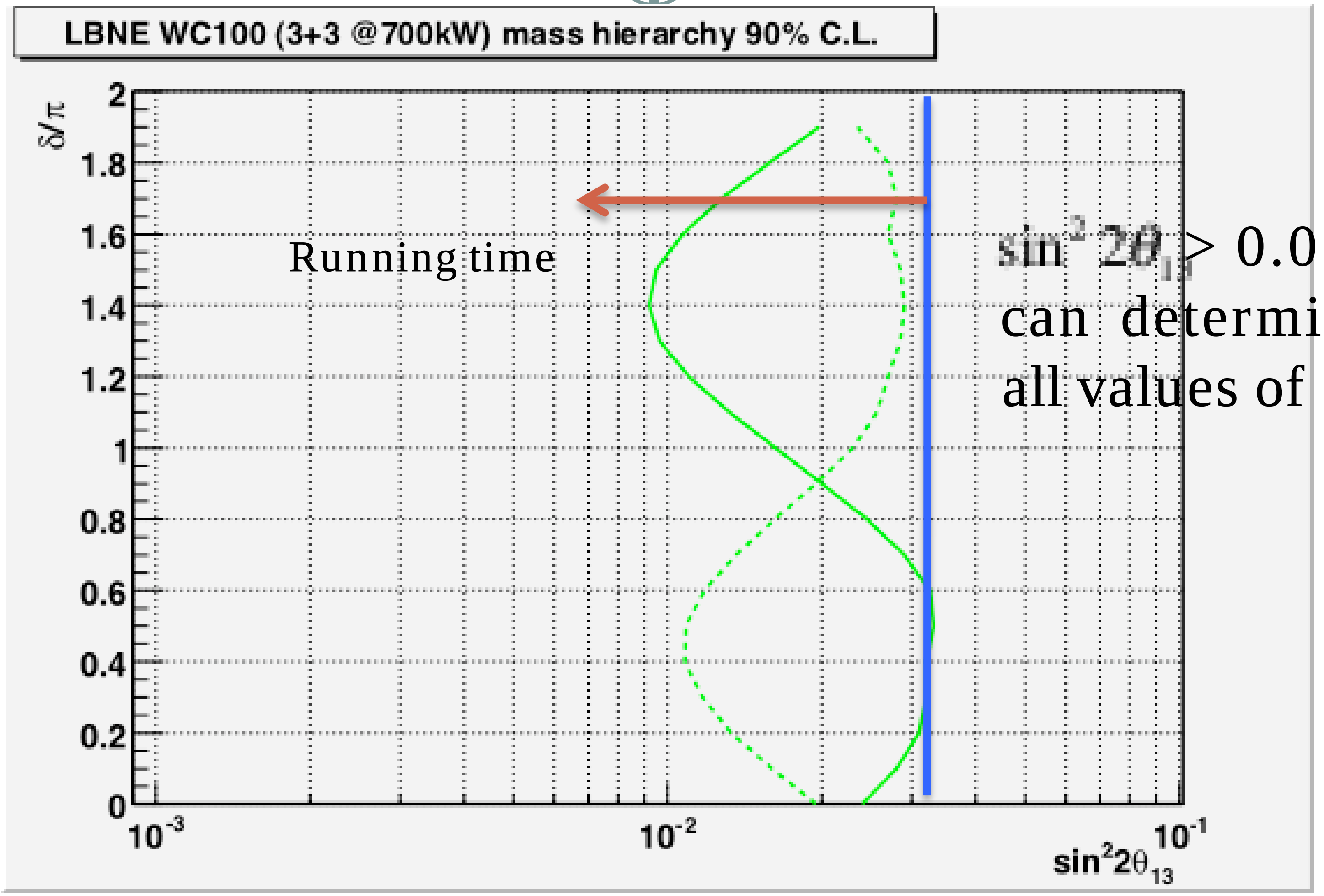
Reducing Ambiguities



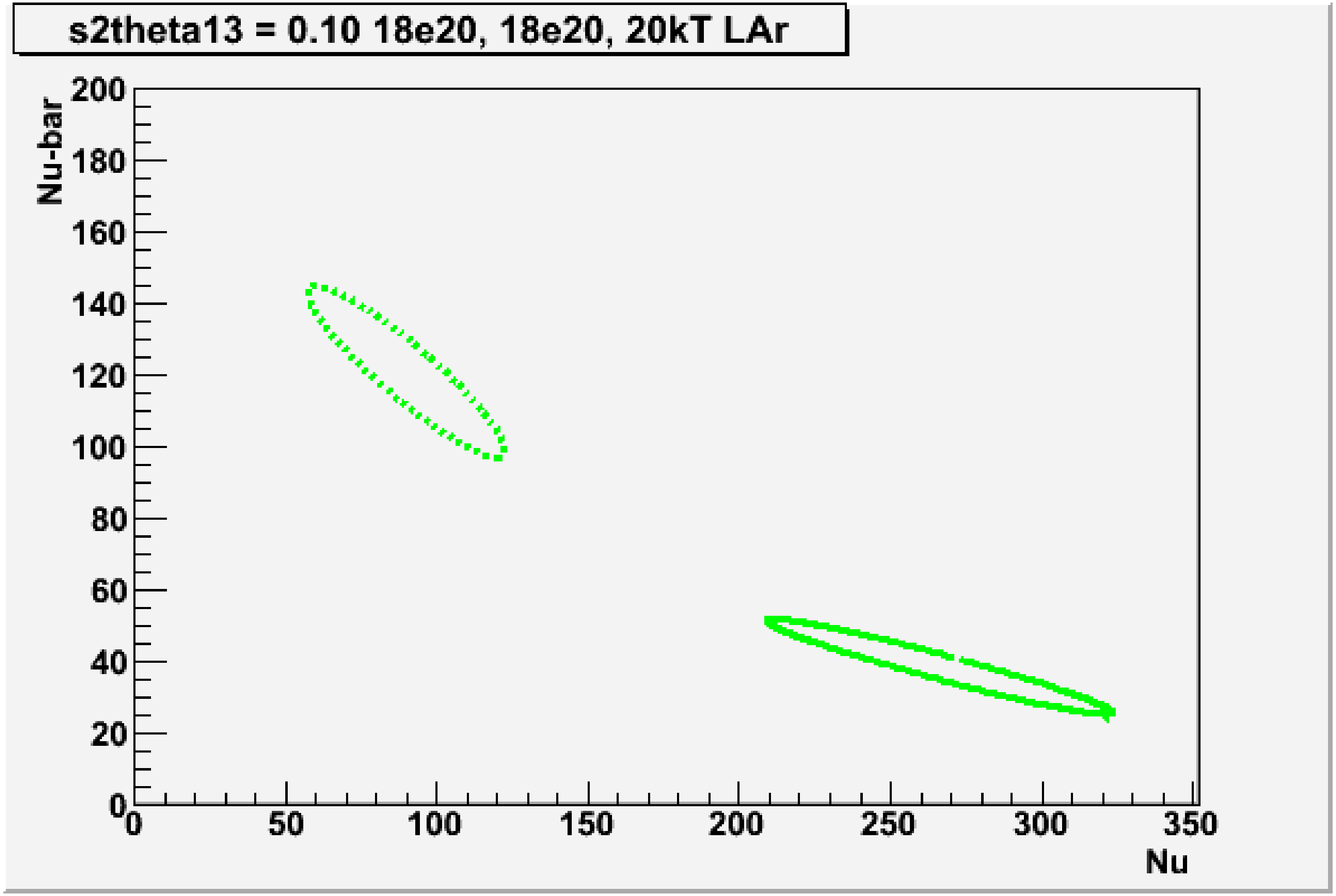
Resolving the mass hierarchy



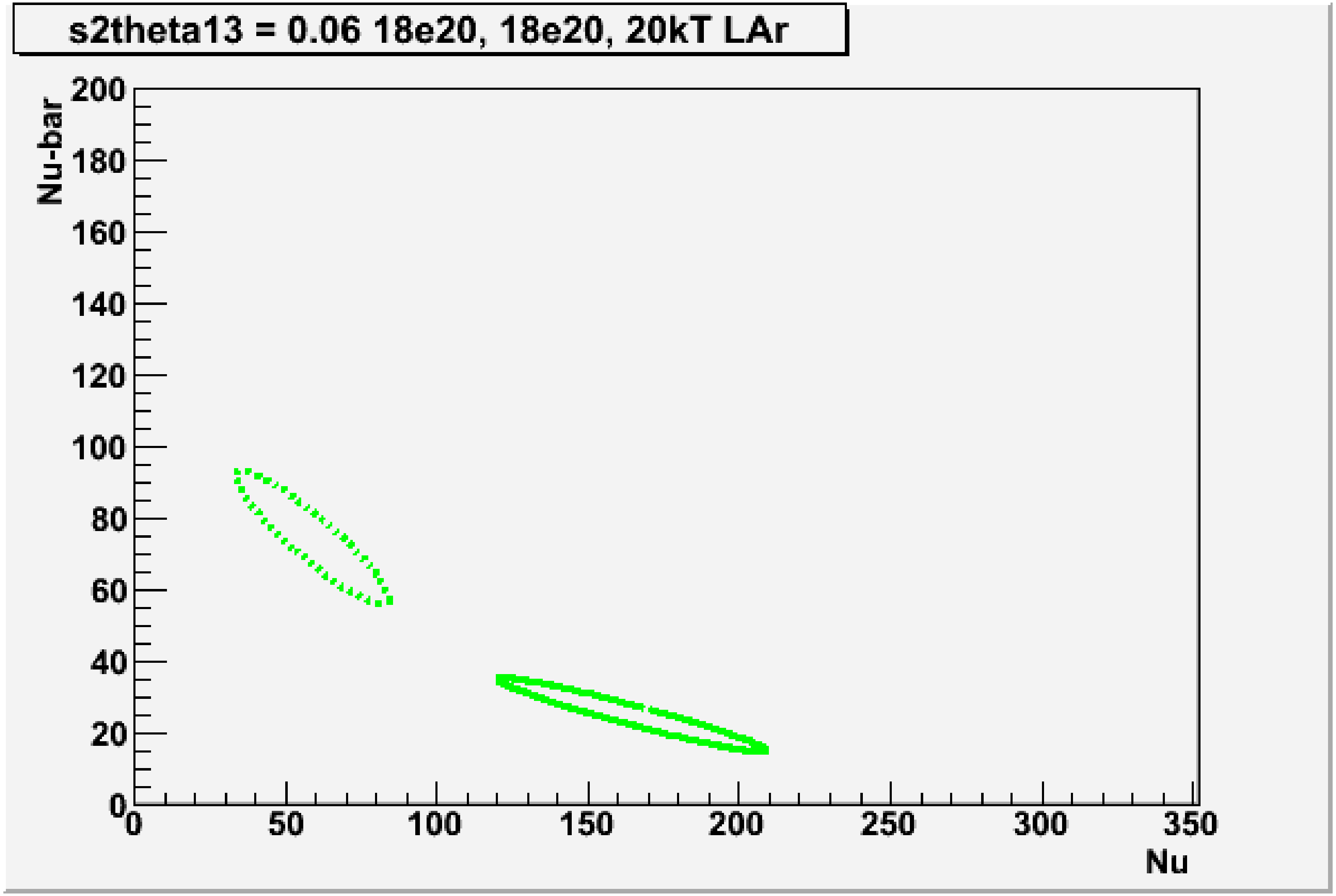
Mass hierarchy at 1300 km baseline

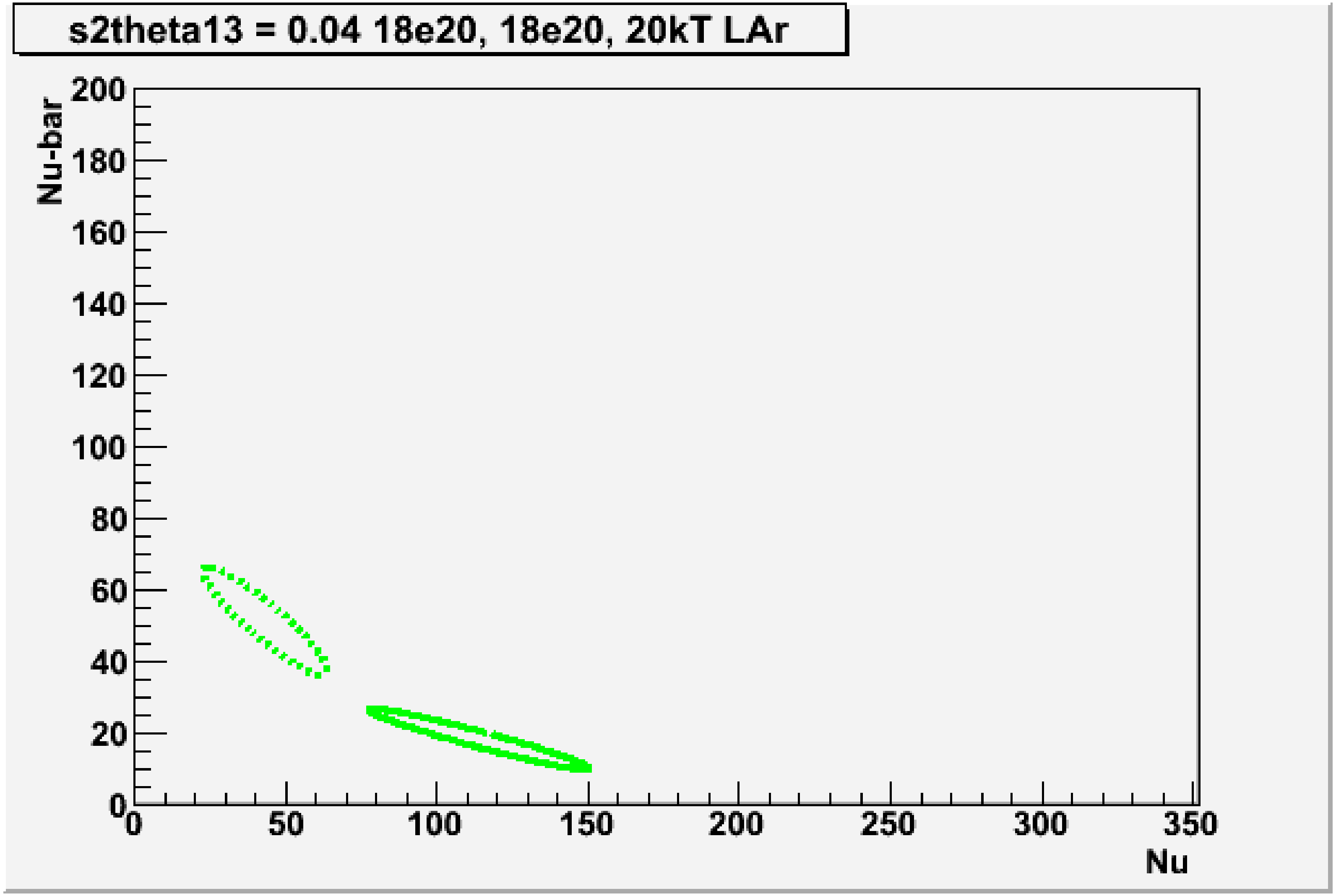


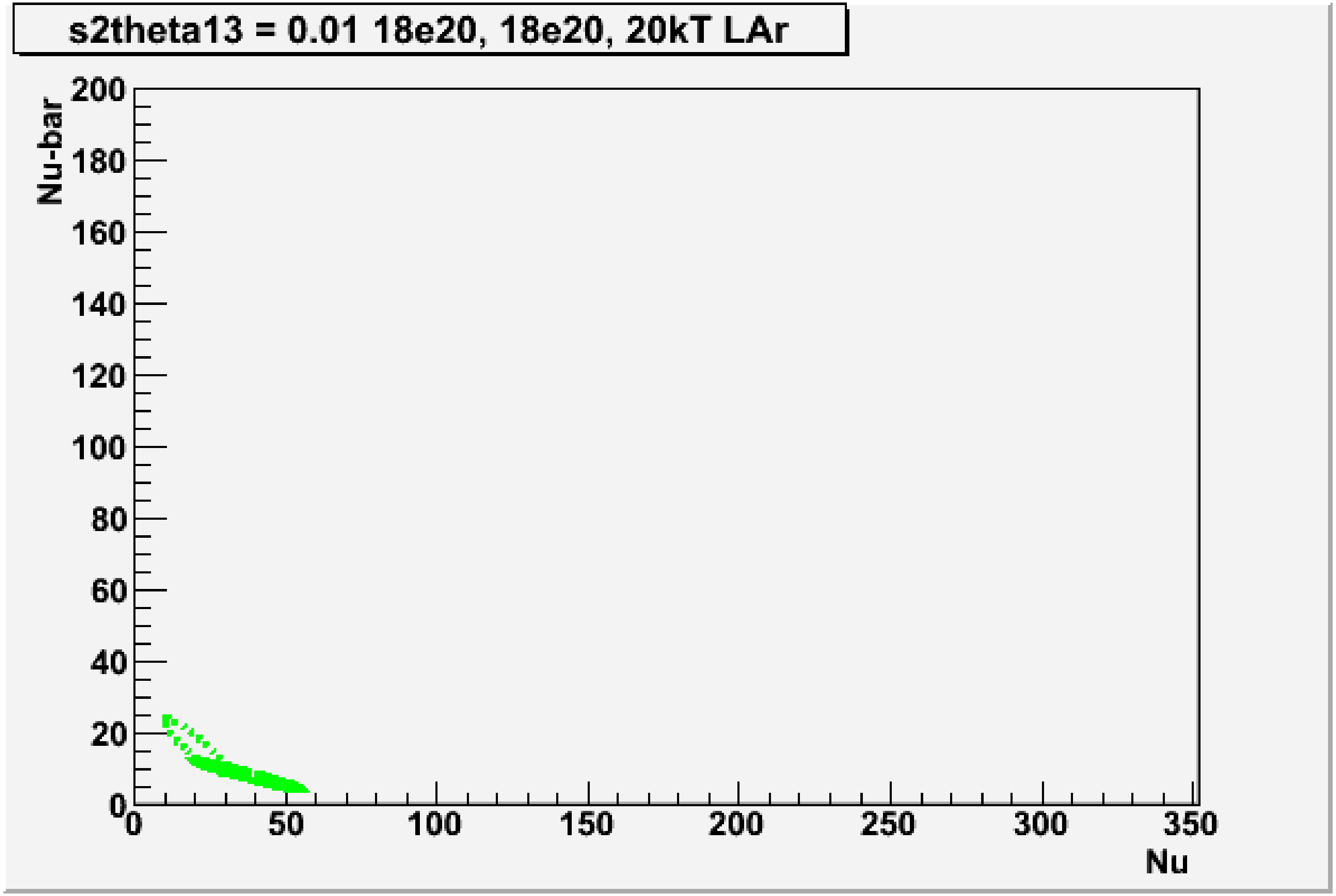
$\sin^2 2\theta_{13} > 0.03$ can determine for all values of δ



s2theta13 = 0.10 18e20, 18e20, 20kT LAr
Nu-bar
200
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
Nu

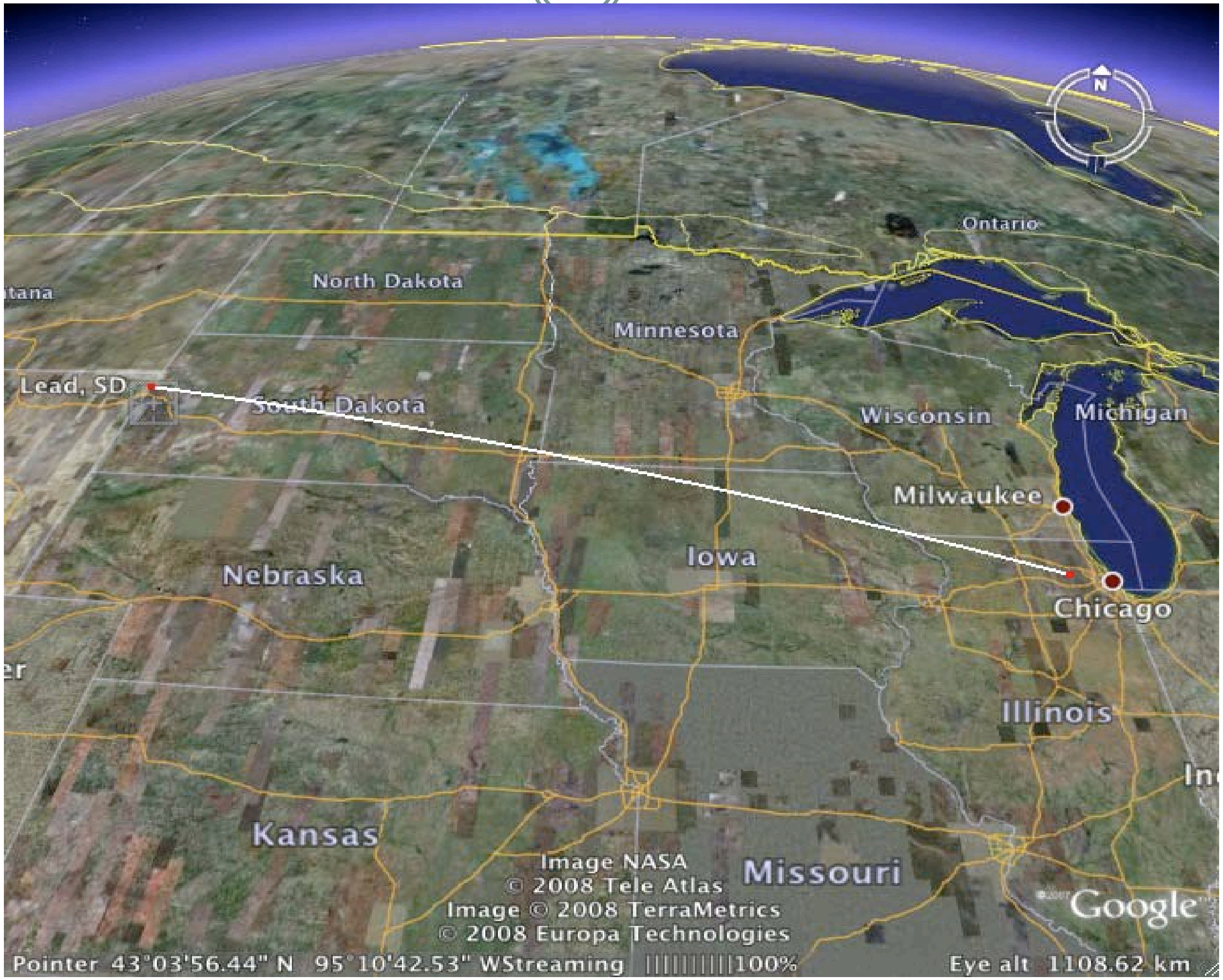

s2theta13 = 0.06 18e20, 18e20, 20kT LAr
Nu-bar
200
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
Nu


s2theta13 = 0.04 18e20, 18e20, 20kT LAr
Nu-bar
200
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350
Nu

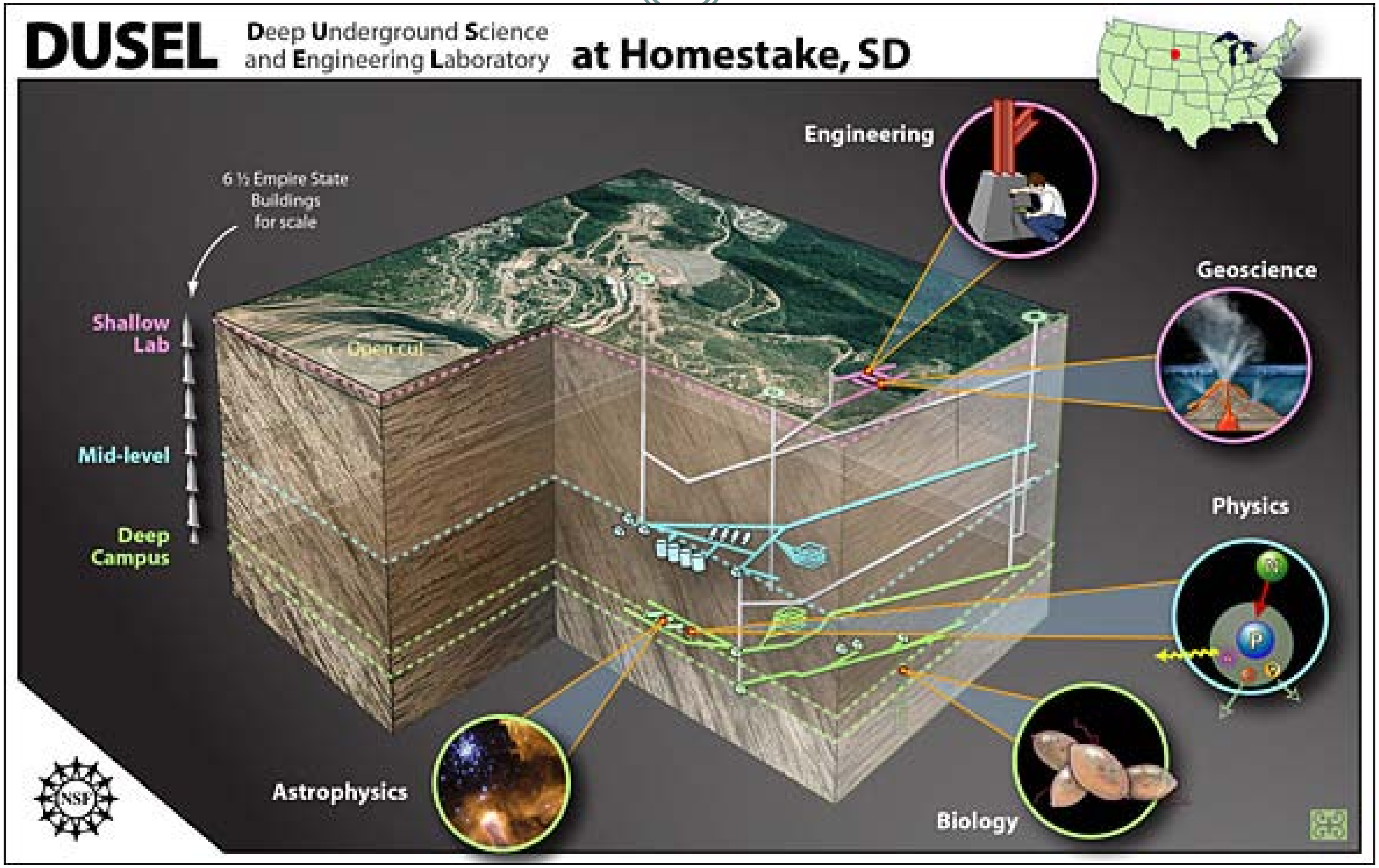


s2theta13 = 0.01 18e20, 18e20, 20kT LAr
Nu-bar
Nu
0
20
40
60
80
100
120
140
160
180
200
50
100
150
200
250
300
350

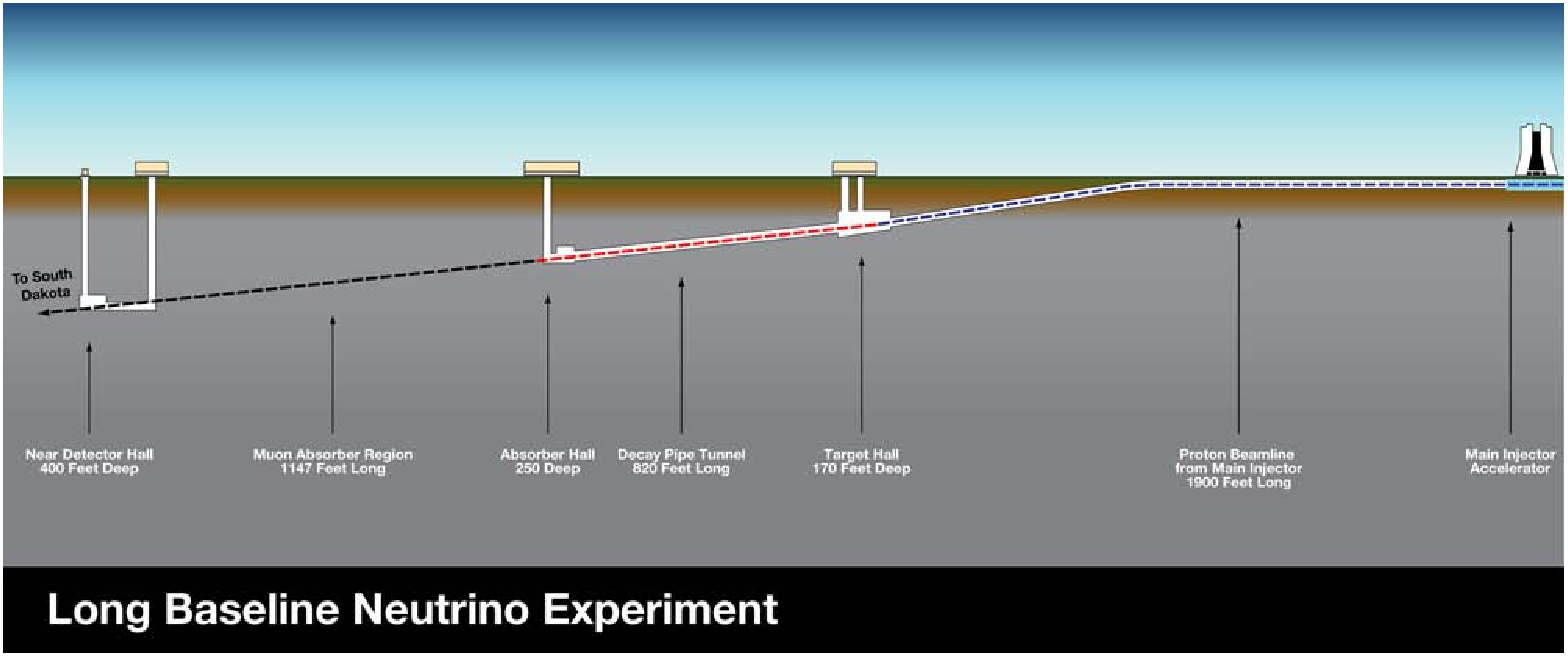
Long Baseline Neutrino Experiment



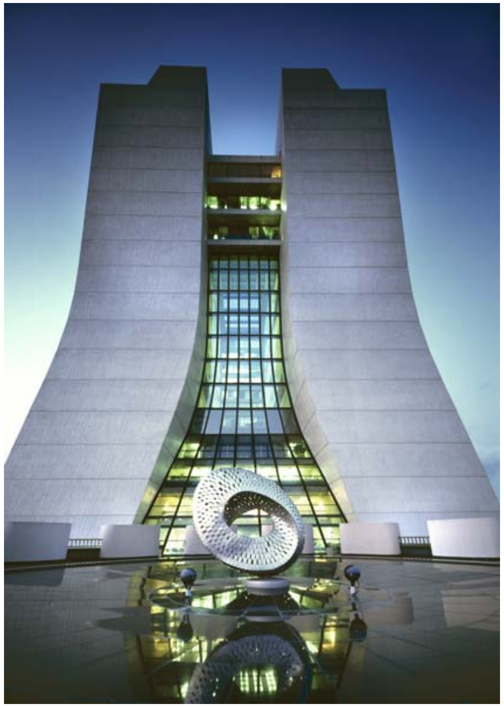
A deep underground laboratory

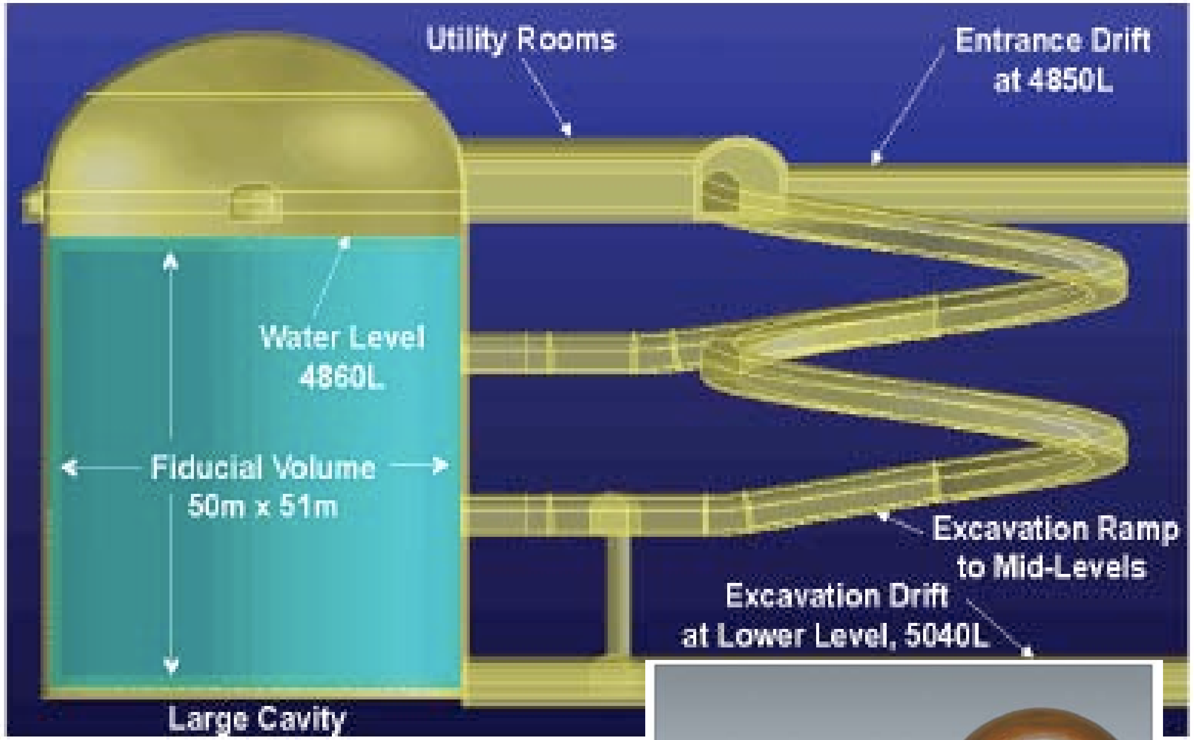


A new neutrino beam at Fermilab

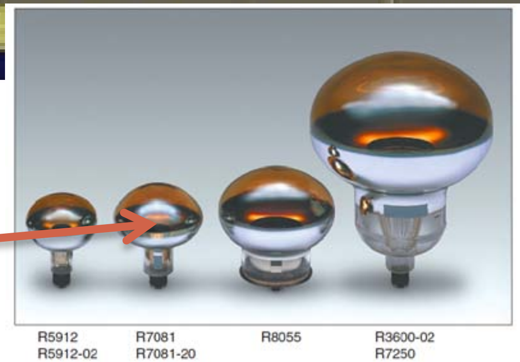


Very Large Detectors





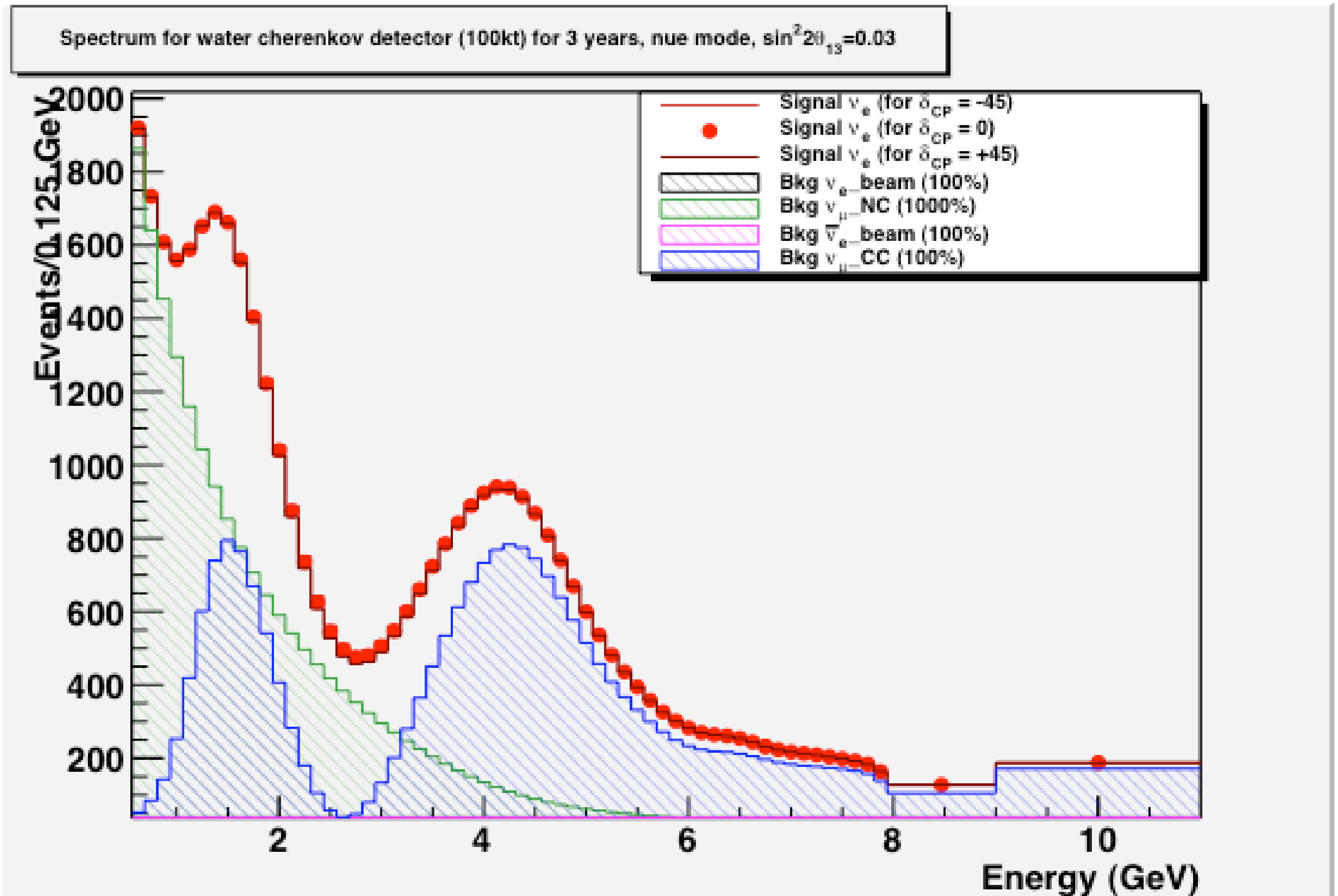
50,000 PMTs



Why so large?

- Significance of a signal : $\sigma \sim N_{signal} / \sqrt{N_{background}}$
- Two Detector Dependent factors :
  - Signal efficiency : $N_{signal}^{observed} = N_{signal}^{produced} \times efficiency$
  - Rejection on non-intrinsic backgrounds depends on detector resolutions

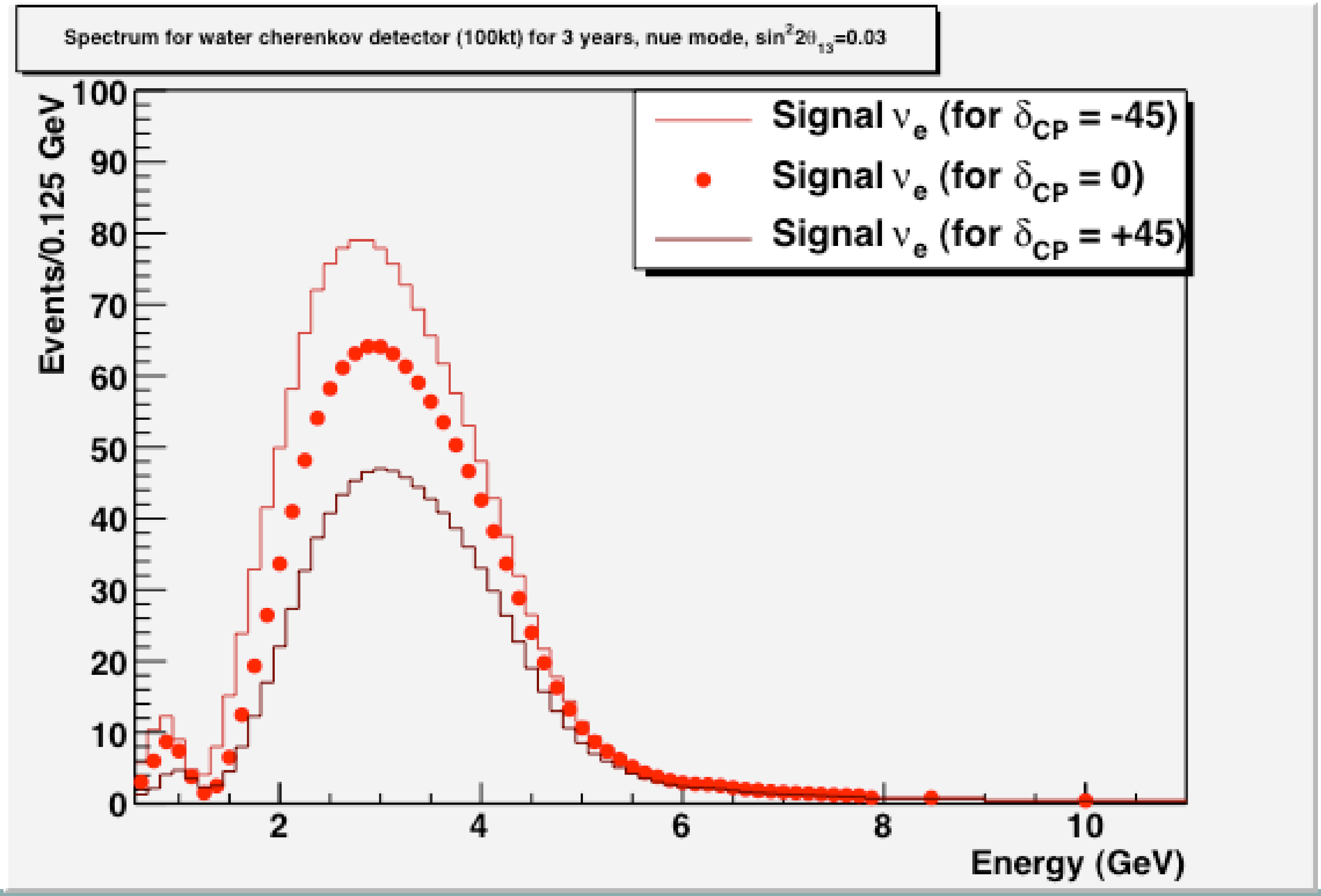
What events occur in a detector of this size?



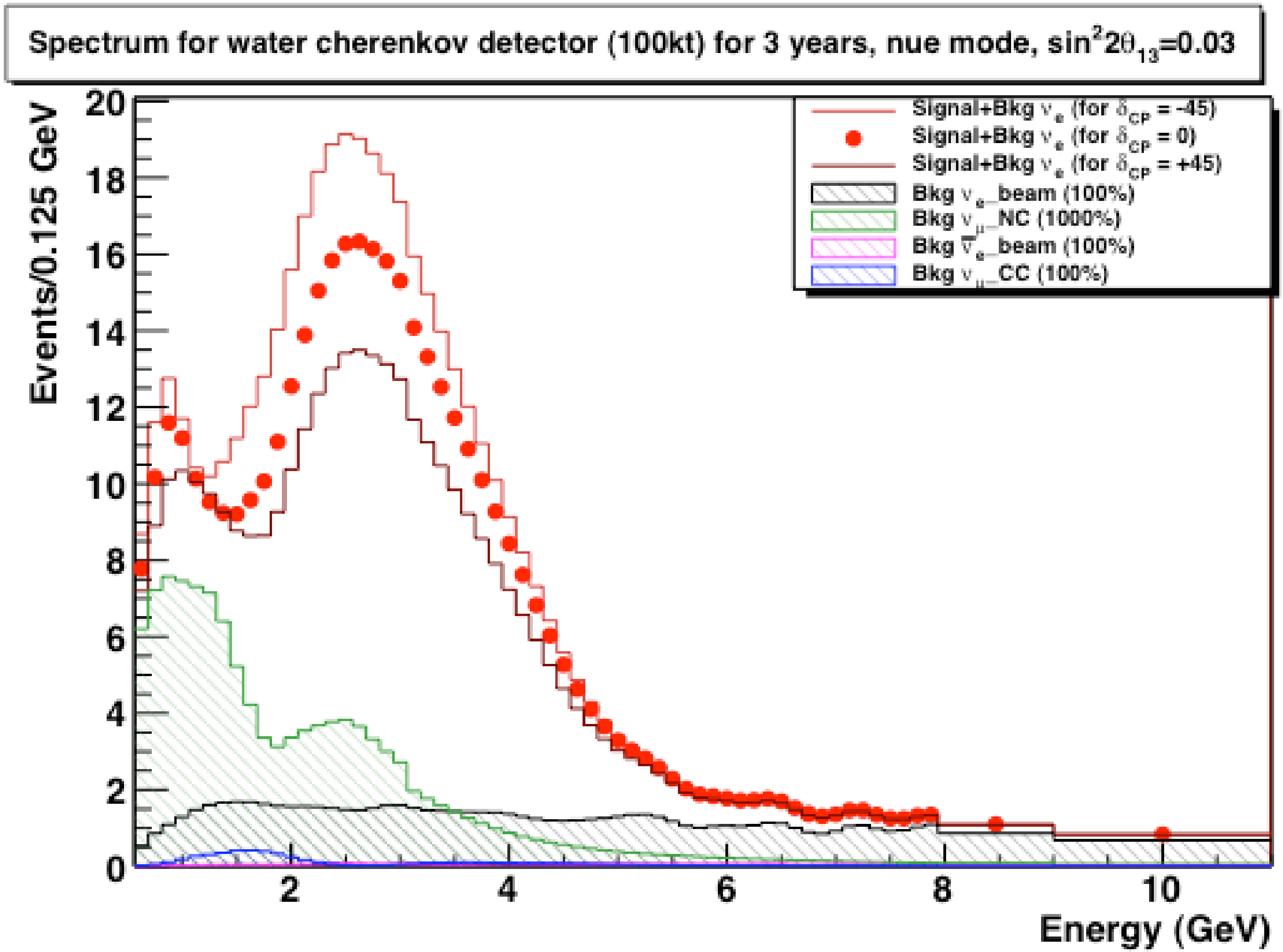
Events that could look like a ν_e

Event spectra by Roxanne Guenette, Yale U.
LBNE LB Physics Working Group

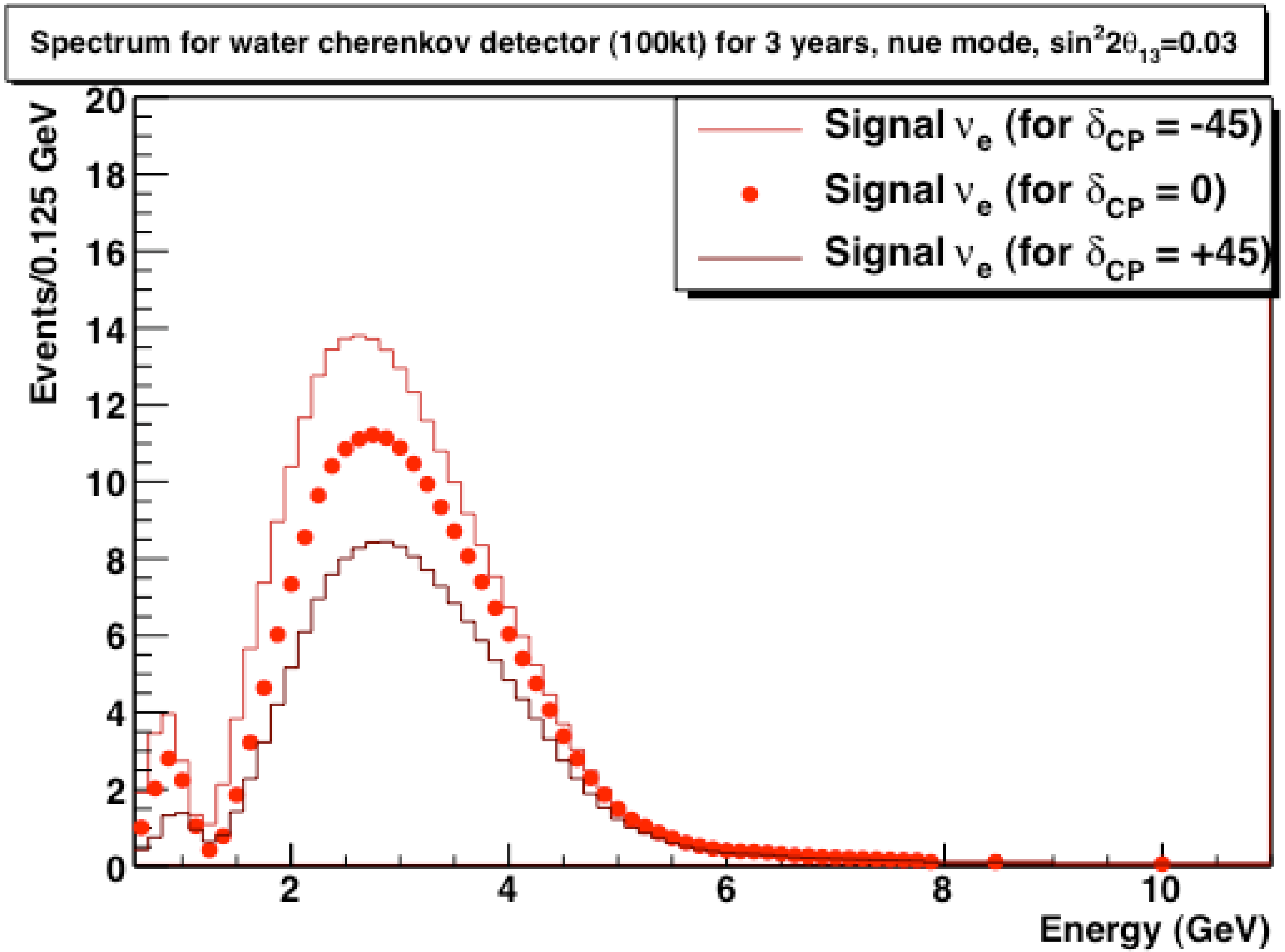
Real appearance signal



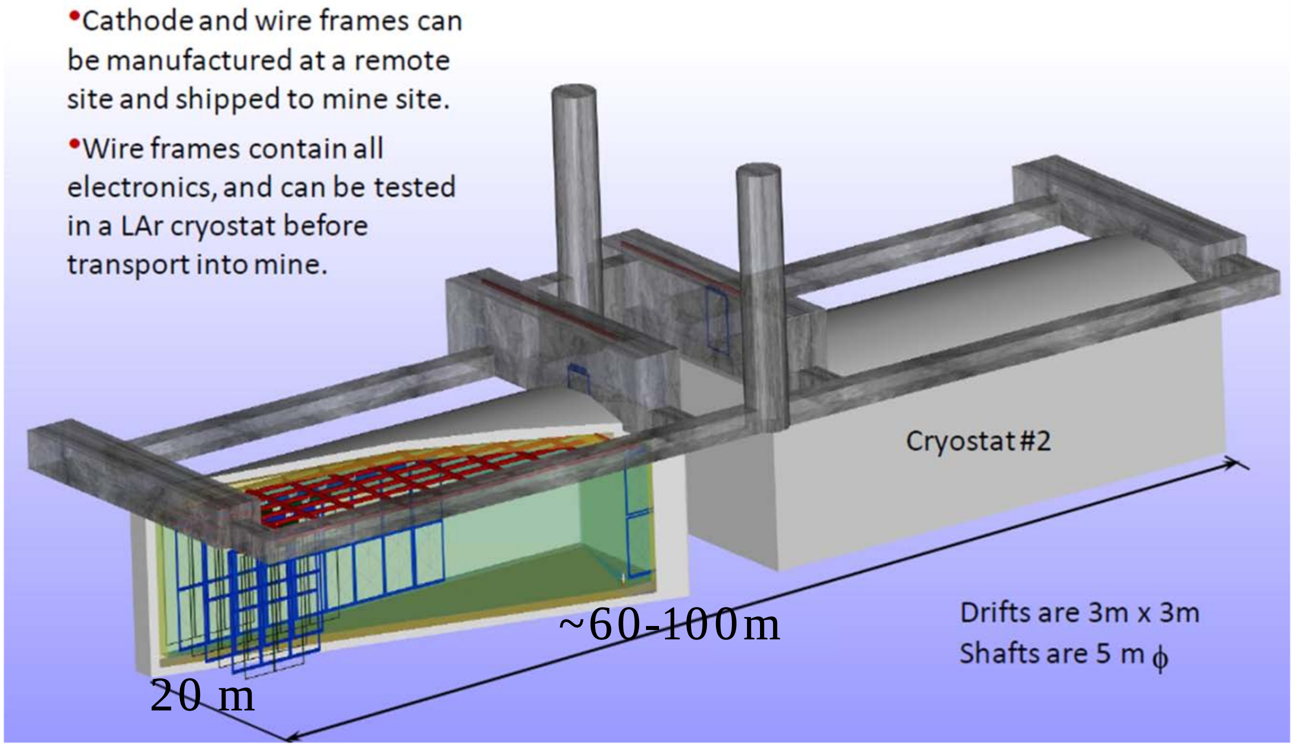
Observed Signal and Background events



Background Subtraction → small stats

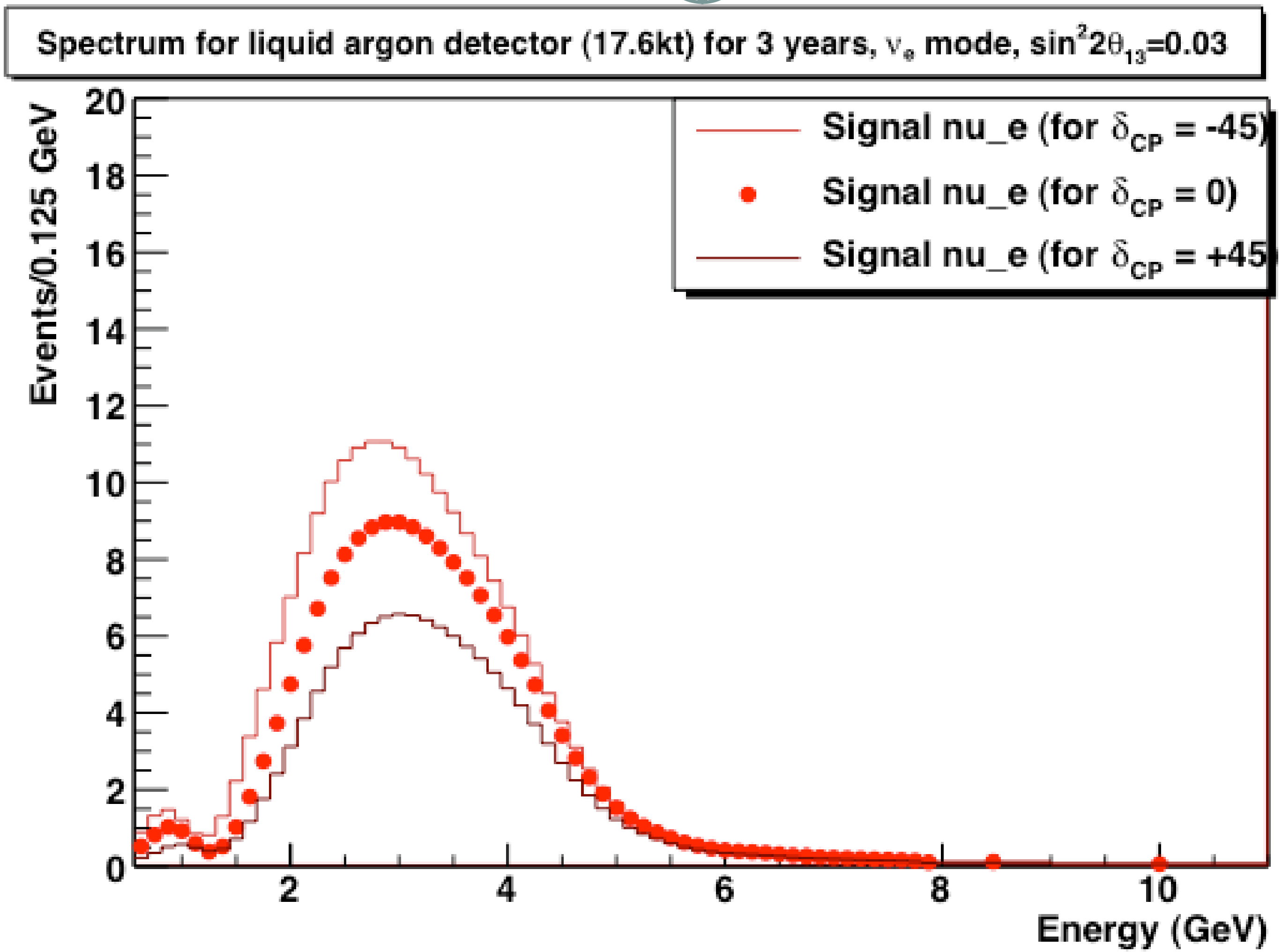


Can we improve efficiency?

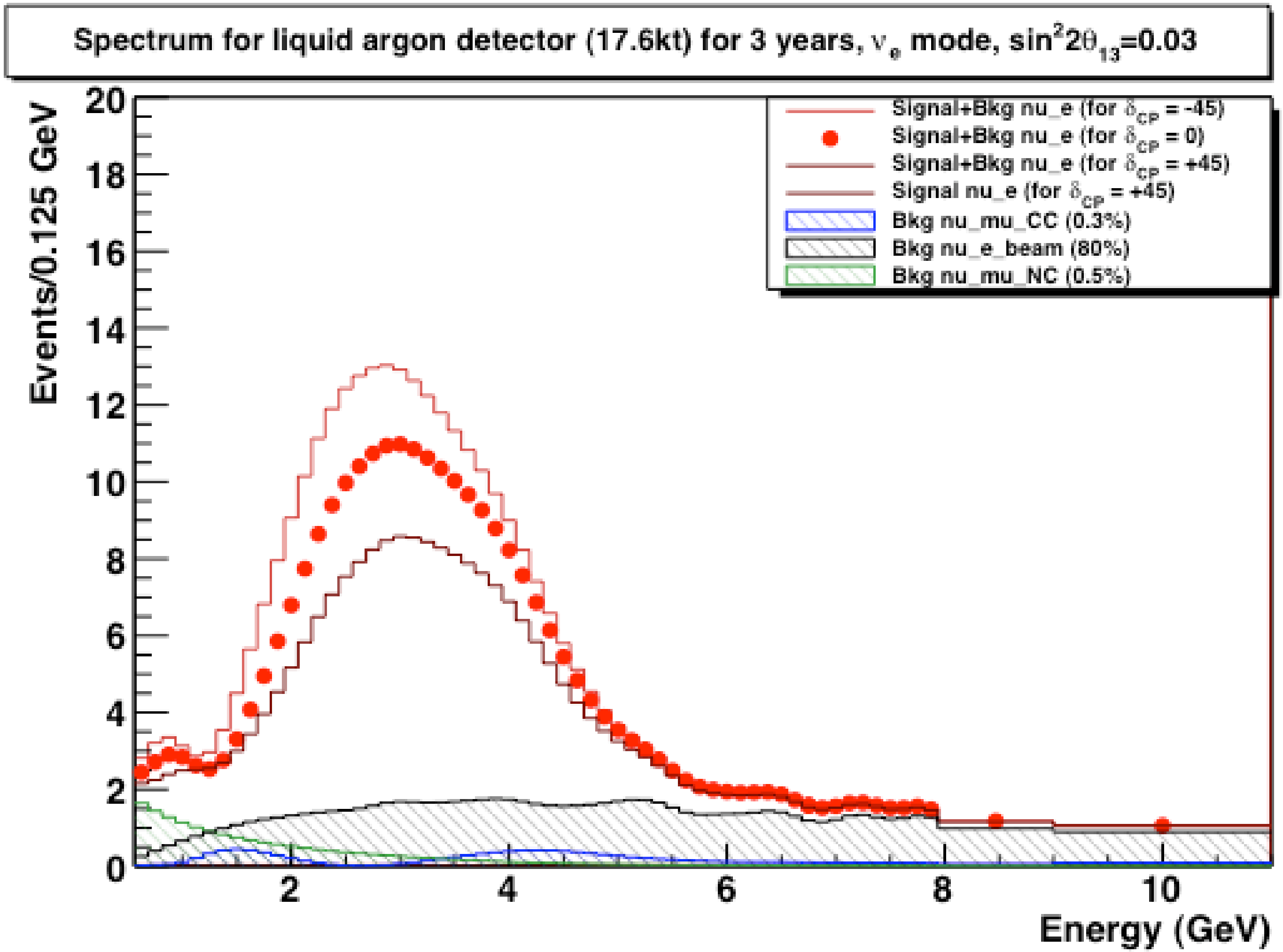


Liquid Argon Time Projection Chamber may offer 5-6 times the detection efficiency of a Water Cerenkov detector, allowing for a significantly smaller detector

“Equivalent” # of signal events



Efficiency is high and background is small



What’s the best approach?

- Need to evaluate pro’s and con’s
- Performance
- Cost, risk, time to build
- Other physics potential
- ....
- Community wide evaluation underway

A quick lesson in “Project Speak”

- New Department of Energy Project’s must pass through a “Critical Decision” process : CDs
- CD-0
  - Approval to think (and do conceptual design)
- CD-1
  - What can you do, and for how much $$? When could you do it?
- CD-2
  - How much does it *really* cost and how long will it *really* take?
- CD-3
  - What are you really going to build and are you really ready to build it?
- CD-4
  - Does it work? Did we get what we paid for?

LBNE Milestones/Timeline

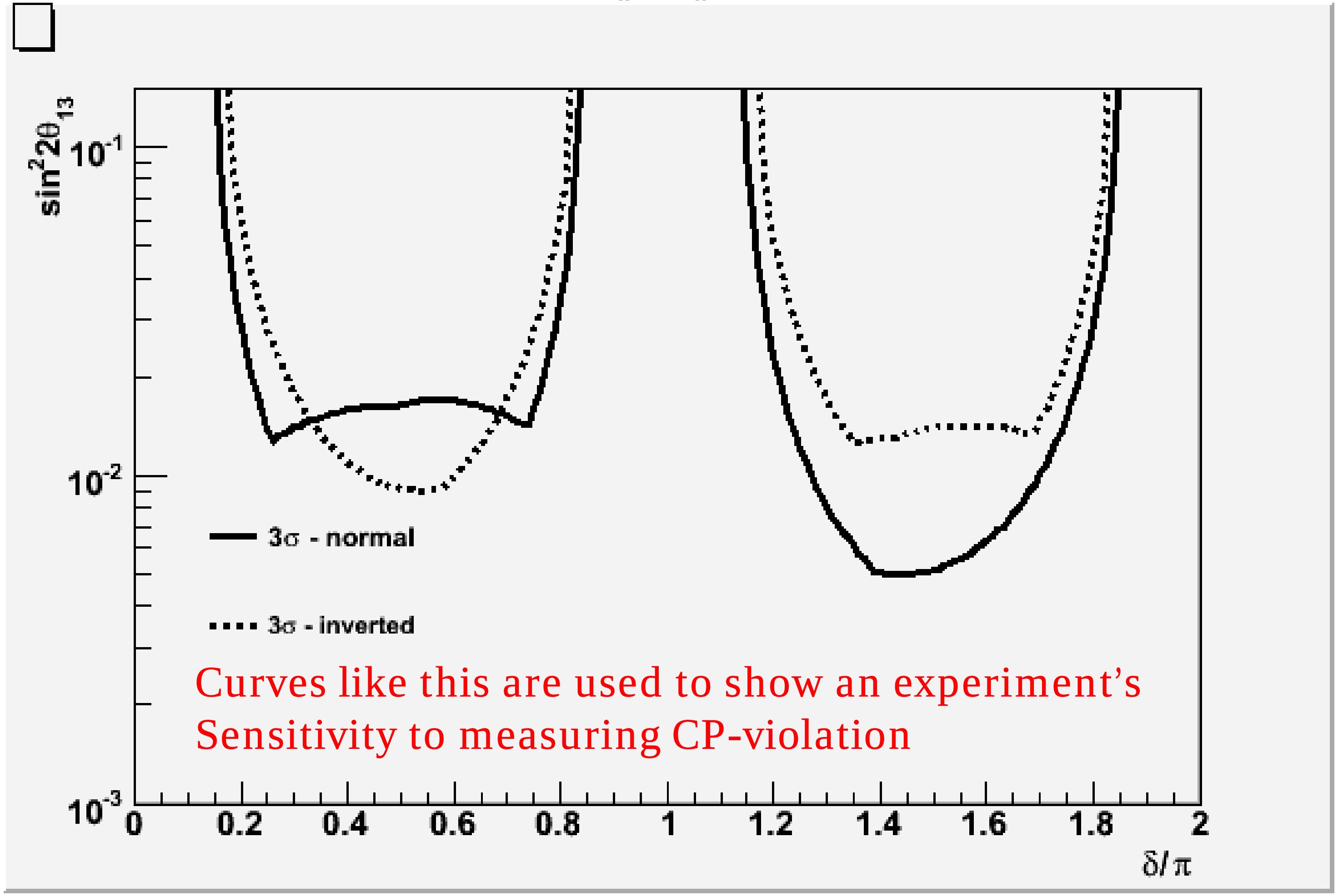
- Department of Energy CD-0
  - January 2010
- CD-1 Review and Approval
  - January-May 2011
- CD-2 (Cost and Schedule Baseline)
  - 2013
- CD-3 : Start Construction!
  - 2015
- CD-4 : Start Operations !
  - 2020-2021 (if all goes well)

What's the big gain?

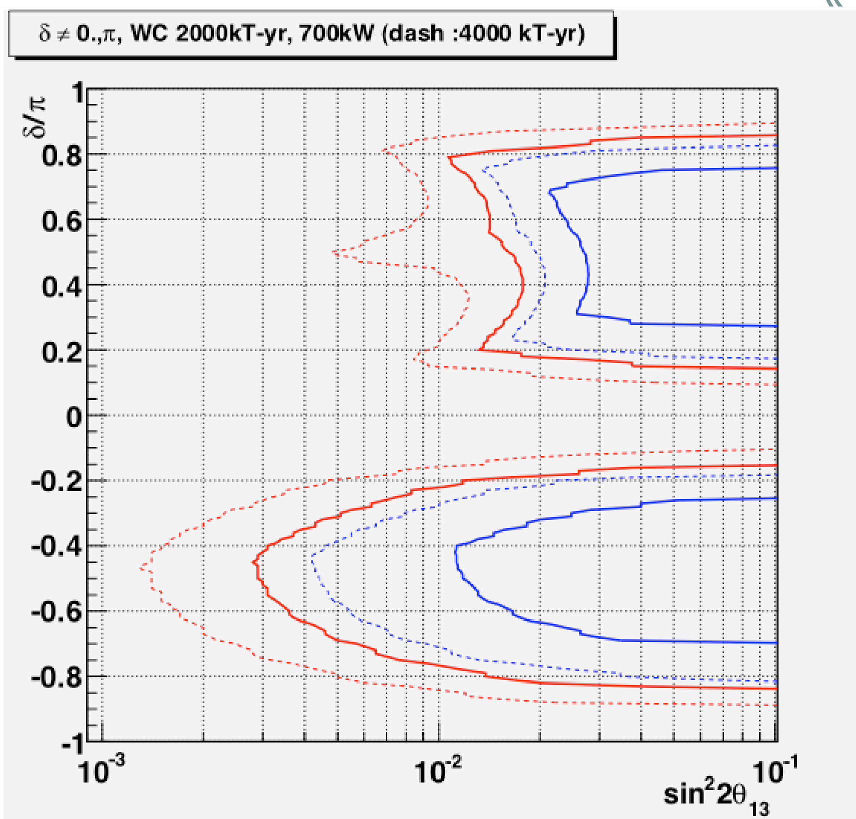
SENSITIVITY TO CP-VIOLATION

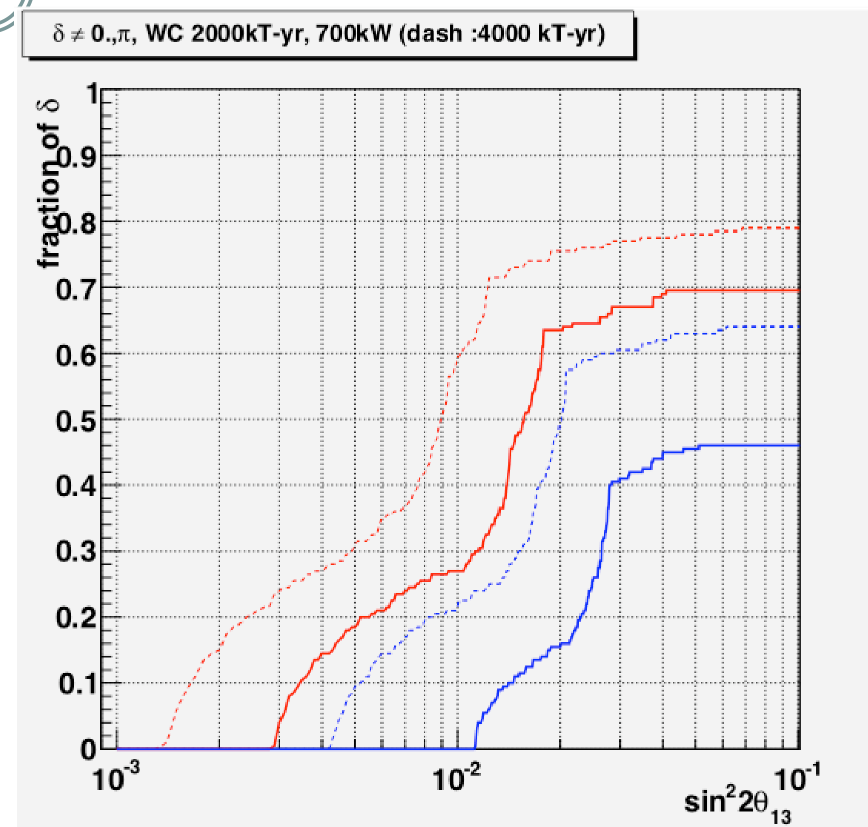
MEASURING PARAMETERS

Sensitivity to $\delta \neq 0, \pi \rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



LBNE Sensitivity to δ_{CP}



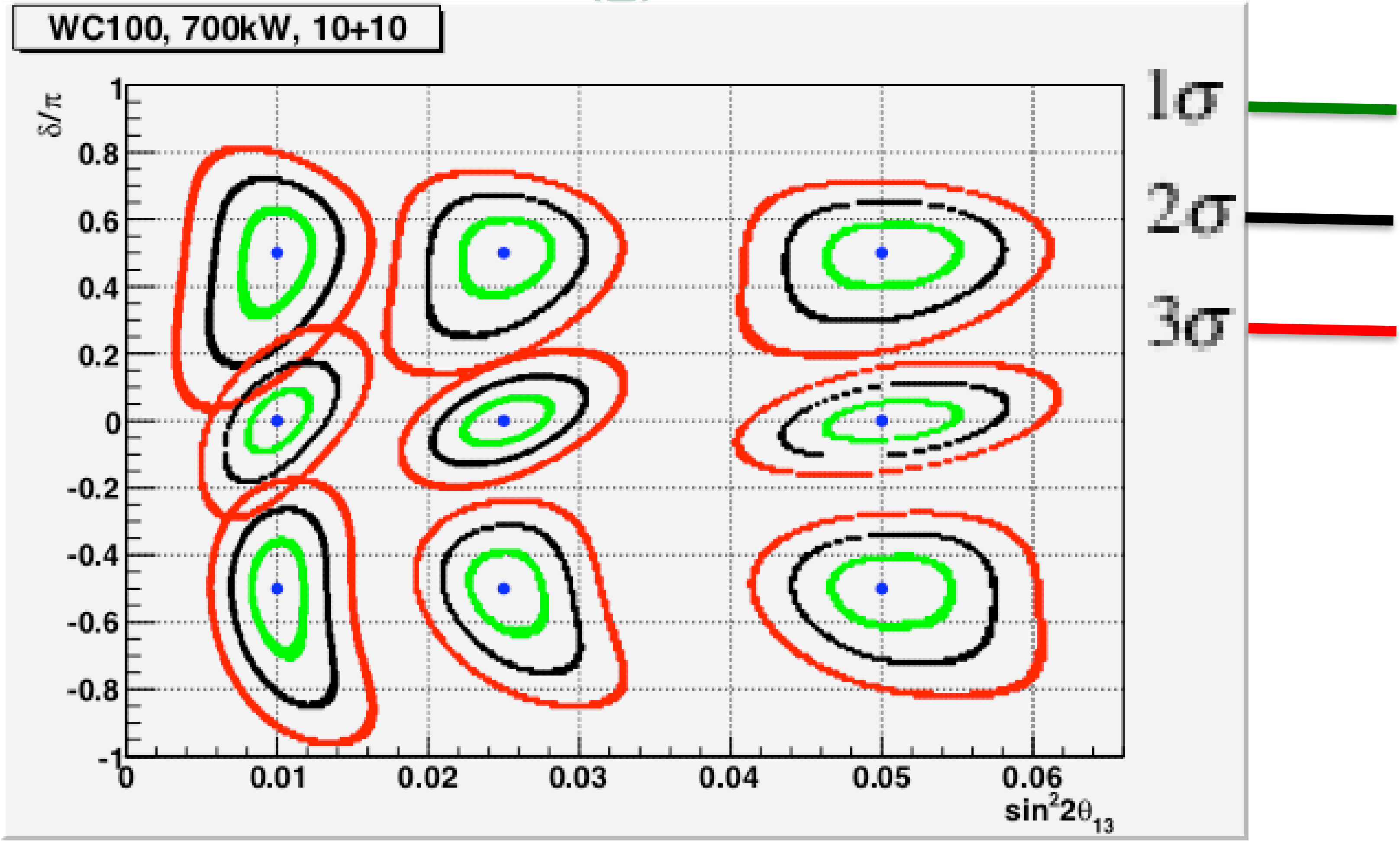


3σ (red)

5σ (blue)

200 kT WC for 10 (or 20) years of Beam exposure

Measuring Parameters (including $\delta = 0$)

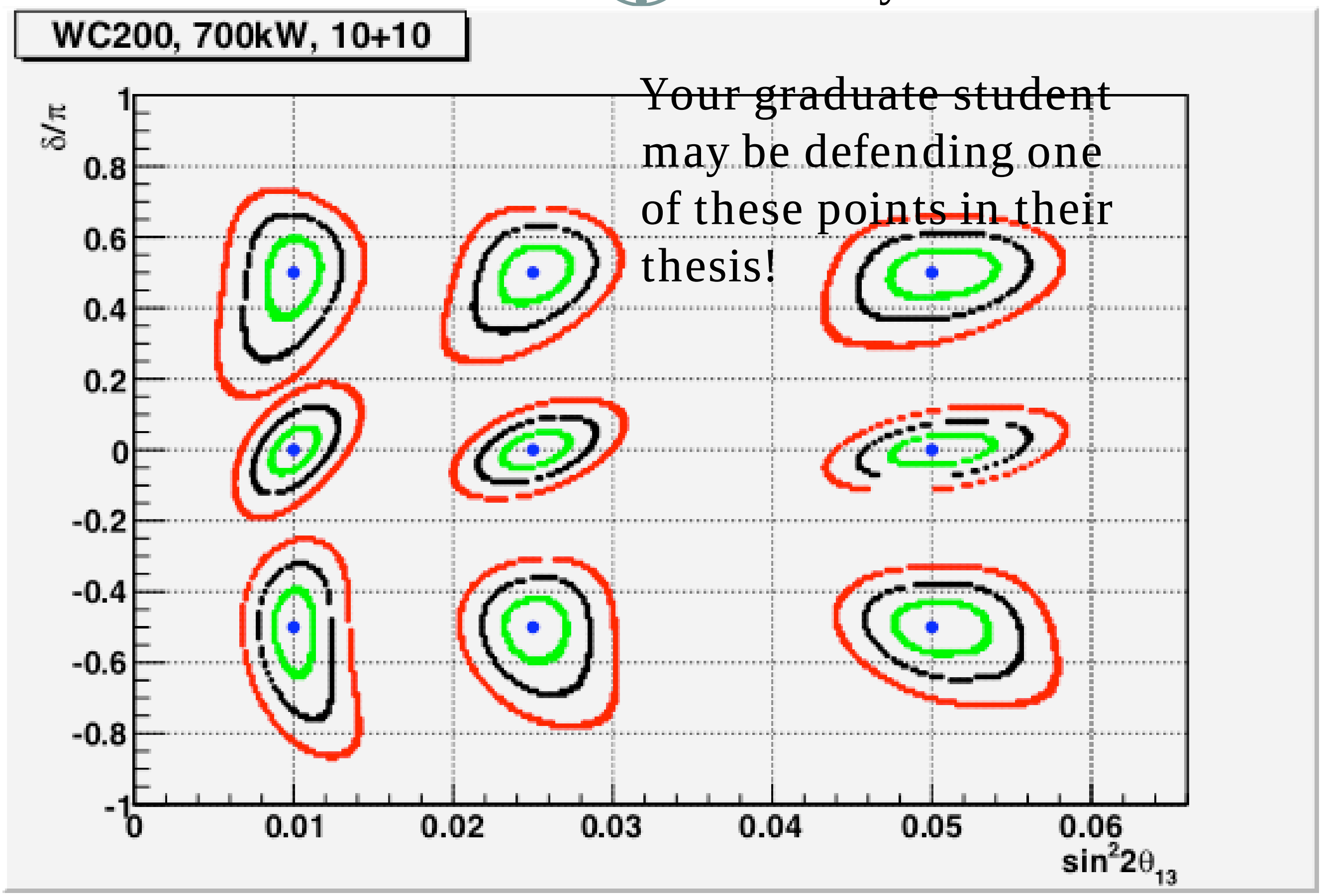


At 0.01, we can just barely distinguish δ at its maximum and minimum

Doubling Exposure

Where will you be in 2040?

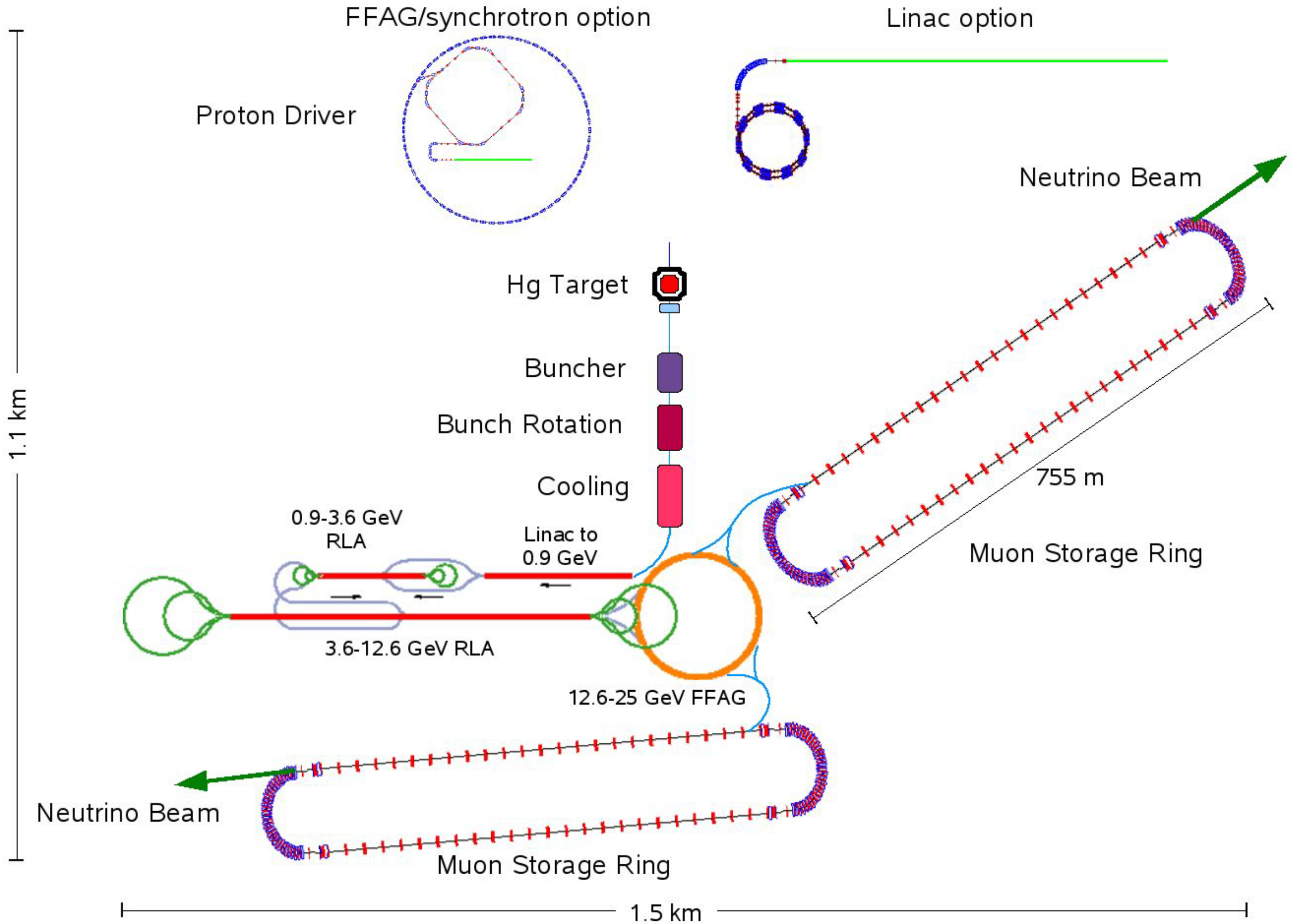
Your graduate student may be defending one of these points in their thesis!



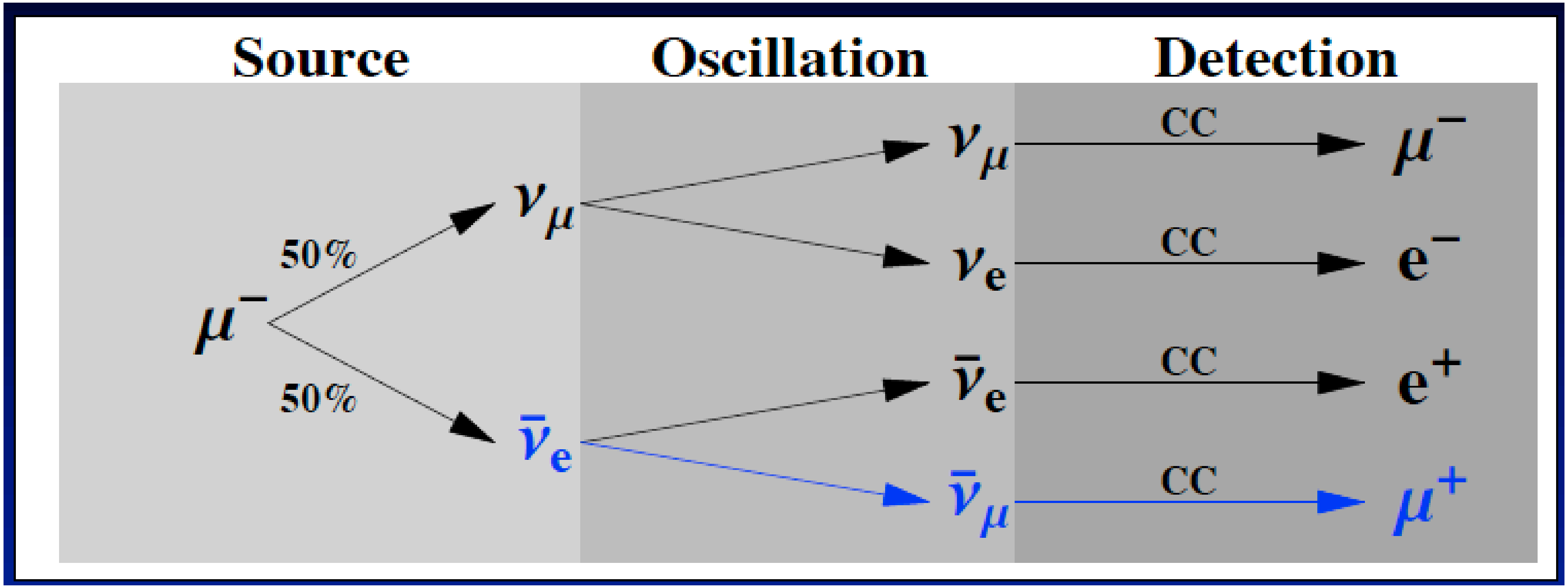
Some tough questions

- What if we don't know how big θ_{13} is?
- What if we think it's ($\sin^2 2\theta_{13}$)~0.01 ?
- Are conventional beams the only route to this physics?

Neutrino Factory



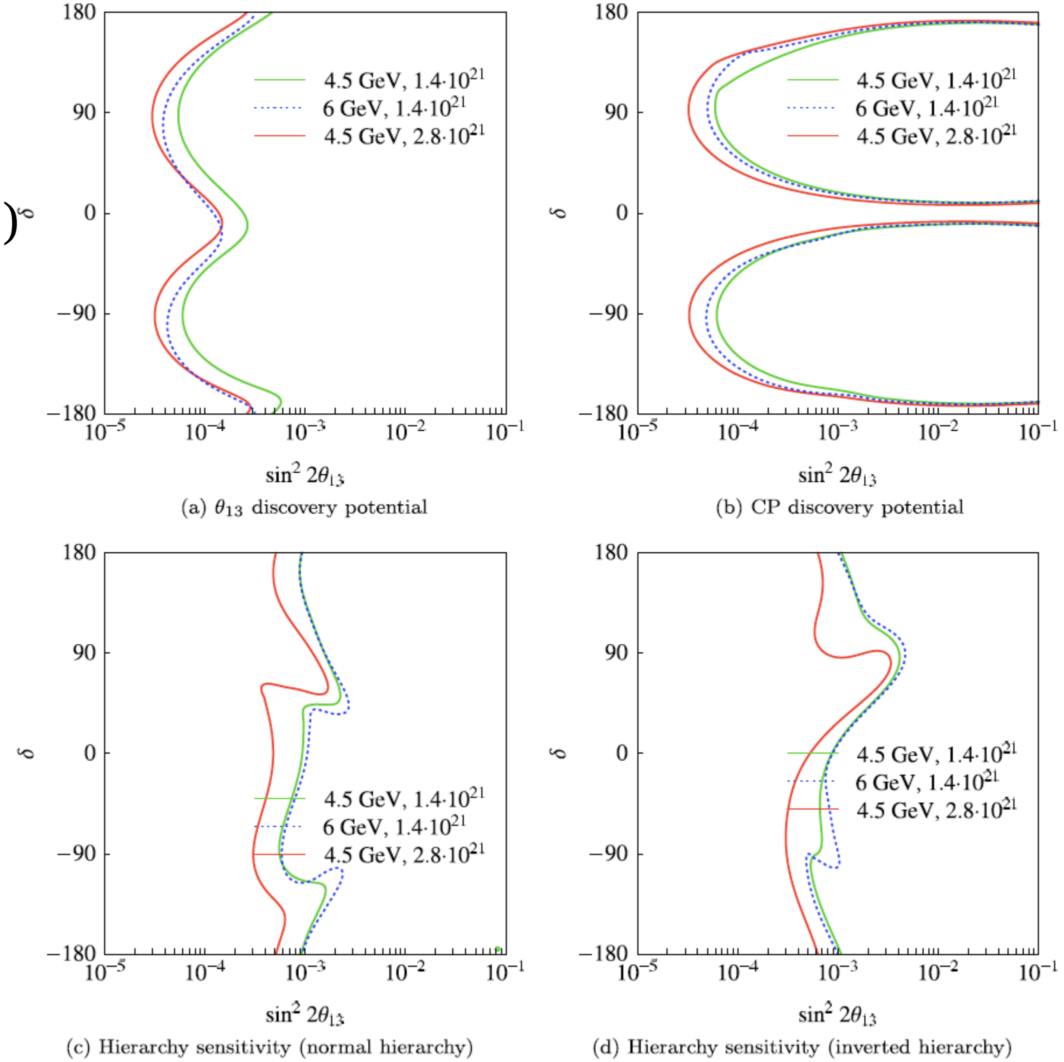
Unique signature



Need to be able to tell + from –
➔magnetized detector :
MINOS like ?
Magnetize NOvA?
Magnetize LAr ?

Potential sensitivity to very small θ_{13}

Martinez, et.al.
Phys.Rev. D.
81,073010(2010)



(a) θ_{13} discovery potential

(b) CP discovery potential

(c) Hierarchy sensitivity (normal hierarchy)

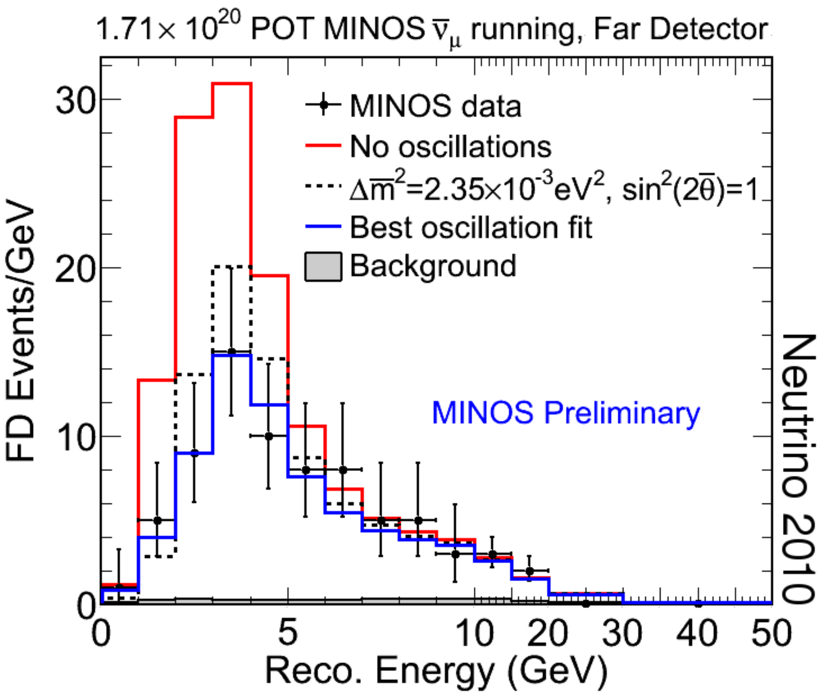
(d) Hierarchy sensitivity (inverted hierarchy)

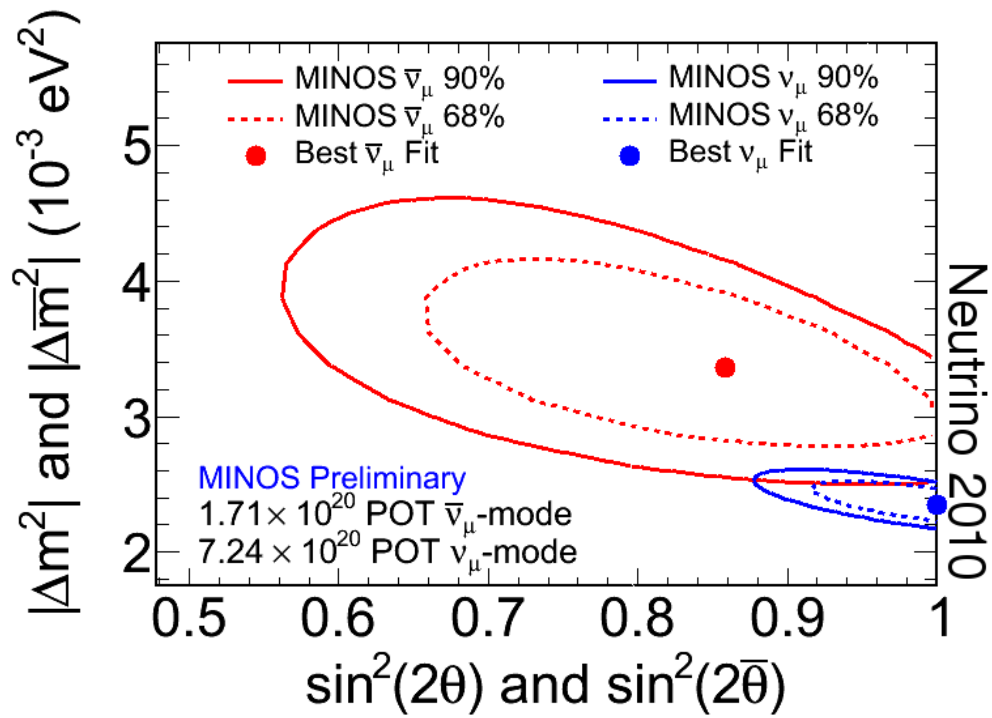
Consideration of a low energy neutrino factory

New Results to Keep an Eye On

Neutrino 2010 (http://www-numi.fnal.gov/PublicInfo/; SSI talk by M. Sanchez)

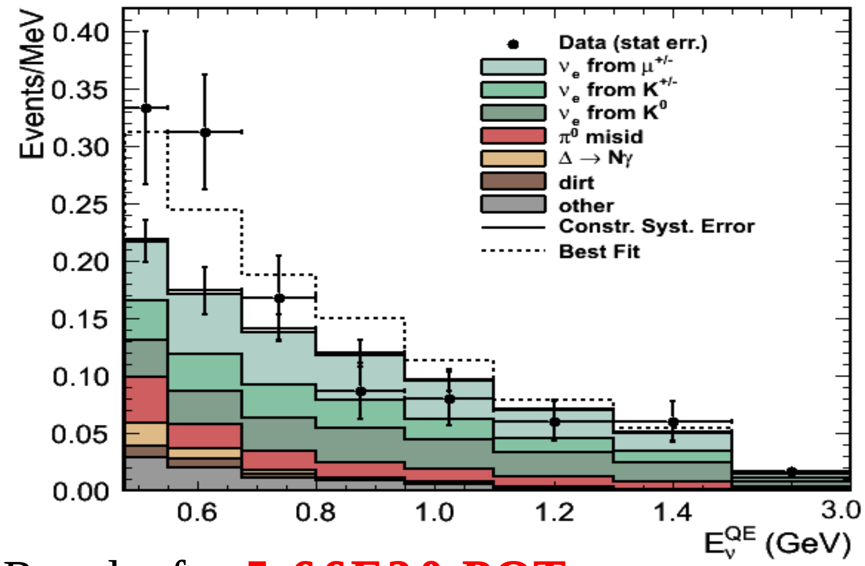
MINOS Anti-neutrinos

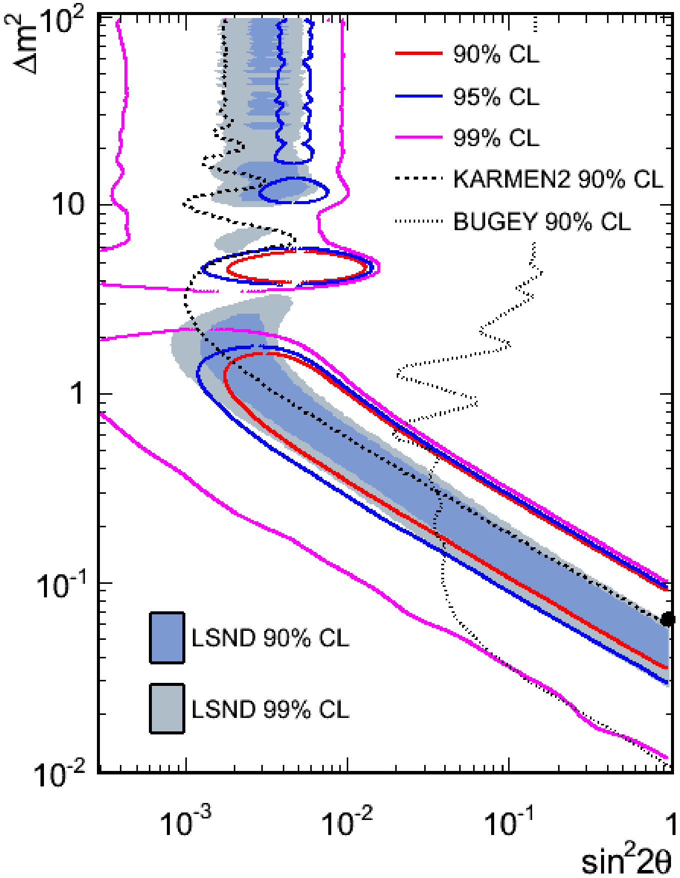




New Results to Keep an Eye On

Neutrino 2010 (R. Vandewater; SSI talk by Eric Zimmerman)
MiniBooNE Anti-neutrinos





Results for **5.66E20 POT**

- Best Fit Point
  $(\Delta m^2, \sin^2 2\theta)$ =
  (0.064 eV^2, 0.96)
  χ^2/NDF= 16.4/12.6
  $P(\chi^2)$= 20.5%

Take-away

- The third mixing angle θ_{13} has not yet been measured and it is known to be small
- Results are expected from both reactor and accelerator experiments (T2K and NOvA) within ?(few) years
- A non-zero value of θ_{13} is required to determine the neutrino mass hierarchy and observe the CP phase δ using $\nu_\mu \rightarrow \nu_e$ oscillations
- A long baseline experiment (>>L~1000) with massive and/or highly efficient detectors and a conventional neutrino beam offers an opportunity to determine the mass hierarchy and measure δ provided $\sin^2 2\theta_{13}$ ~0.01 or larger

This is a tricky number......


Thank you!