Long Baseline Neutrino Physics: From Fermilab to Kamioka

Fritz DeJongh

Fermilab

March 18, 2002

- Motivation and goals
- Beamline design
- Walk-thru of results
- Plans

Motivation and Goals

JHF-Kamioka: $L = 295$ km

- Phase 1: 0.75 MW protons, 22.5 kton fiducial detector (Super-K)
- Phase 2: $\times 5$ proton power, $\times 20$ fiducial mass (Hyper-K)

Fermilab-Kamioka: $L = 9300$ km

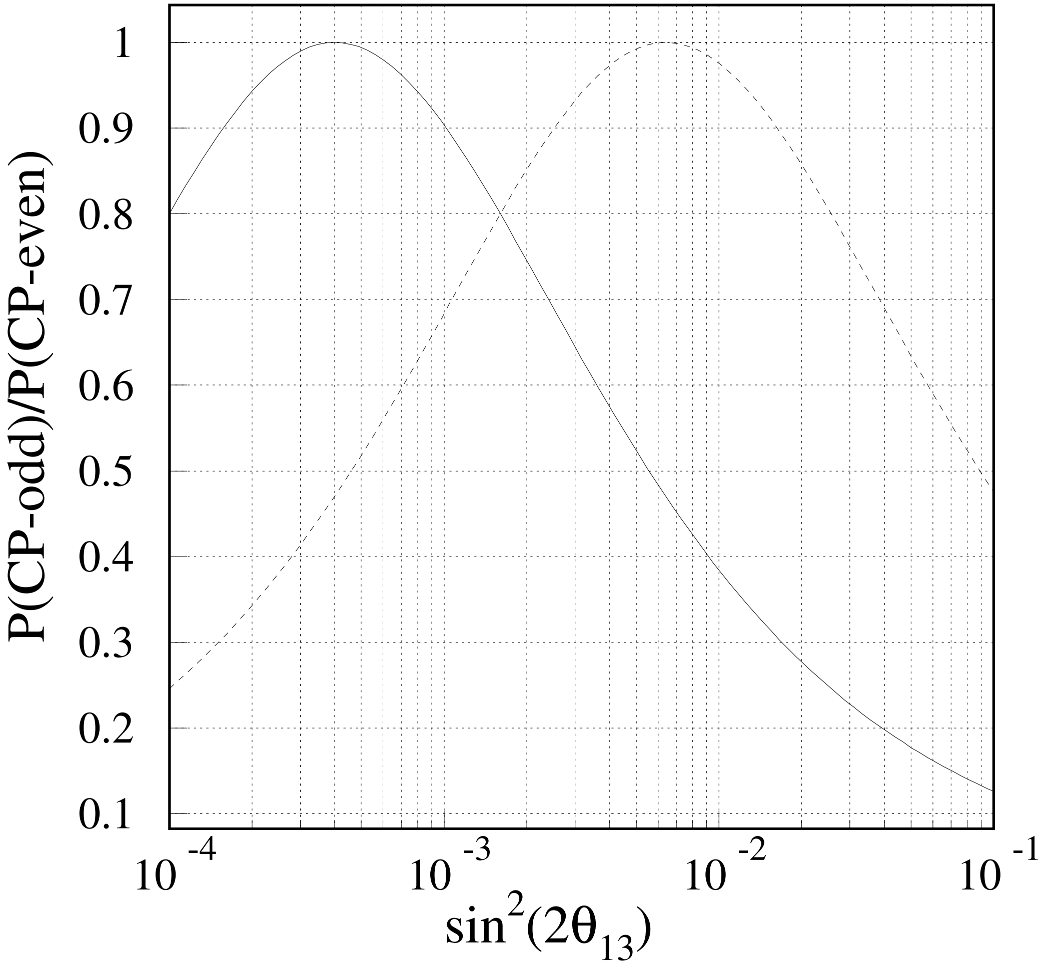
- How can you observe a signal with such a long baseline?
  Matter effect $\Rightarrow$ $\times 20$ amplification in S (over max in vacuum)
  $\times 20$ improvement in S/N
- How does it complement the JHF beam?
  – May have best sensitivity to very small ν_e appearance.
  – Matter effects resolve hierarchy: Normal or inverted
  – Matter-amplified signal is mainly CP-conserving atmospheric component
  $\Rightarrow$ Use to separate CP-violating component seen with JHF beam

Can we make a strong case for Phase 2 before $\sin^2(2\theta_{13})$ is known?

Yes, if sensitive to maximal CP violation for a wide range of parameters.

Goal: 3σ sensitivity to maximal CP violation for $\sin^2(2\theta_{13}) > 10^{-3}$.

CP Asymmetry at the peak of the atmospheric oscillation

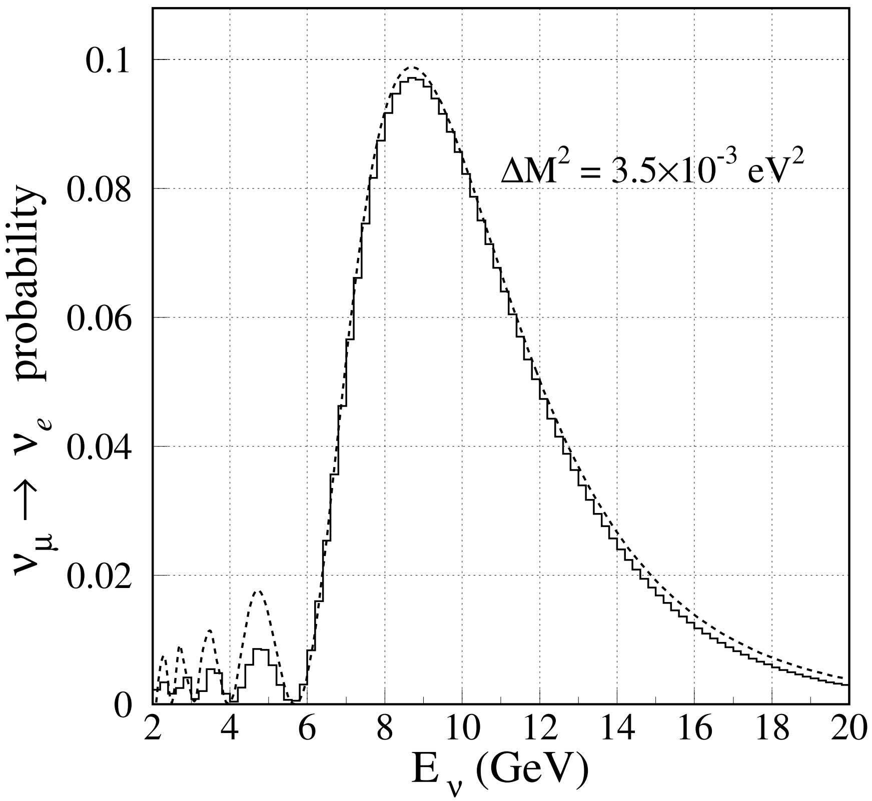


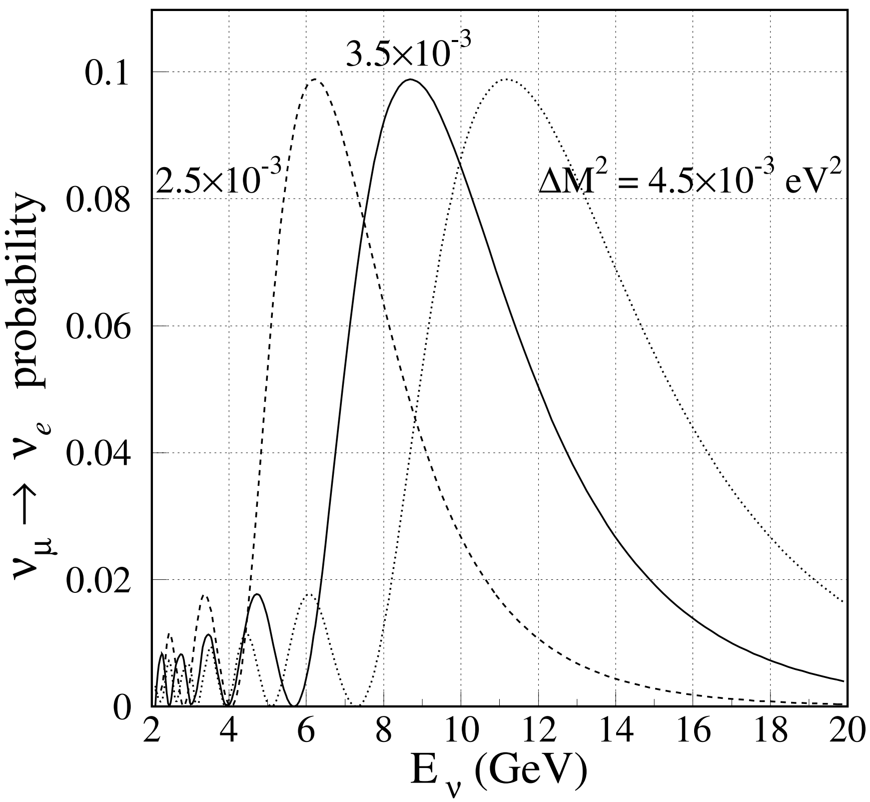
- Matter effects not included
- Solid line is for default parameters:

$\sin^2(2\theta_{13})$	variable
ΔM^2	3.5×10^{-3} eV^2
Δm^2	5.0×10^{-5} eV^2
$\sin^2(2\theta_{23})$	1.0
$\sin^2(2\theta_{12})$	0.8
δ	$\pi/2$

- Dashed line has $\Delta m^2 = 2 \times 10^{-4}$ eV^2

Leading oscillations: $\bullet L = 9300$ km, $\bullet \sin^2(2\theta_{13}) = 0.01$





Solid: Numerical calculation.
Dashed: Analytical approximation, with constant density.

Dependence on ΔM^2

Beamline design

We start from the following observations:

1. Large matter effects occur at a particular resonant energy.
2. Most backgrounds "feed-down" from E_ν to lower E_{vis}.

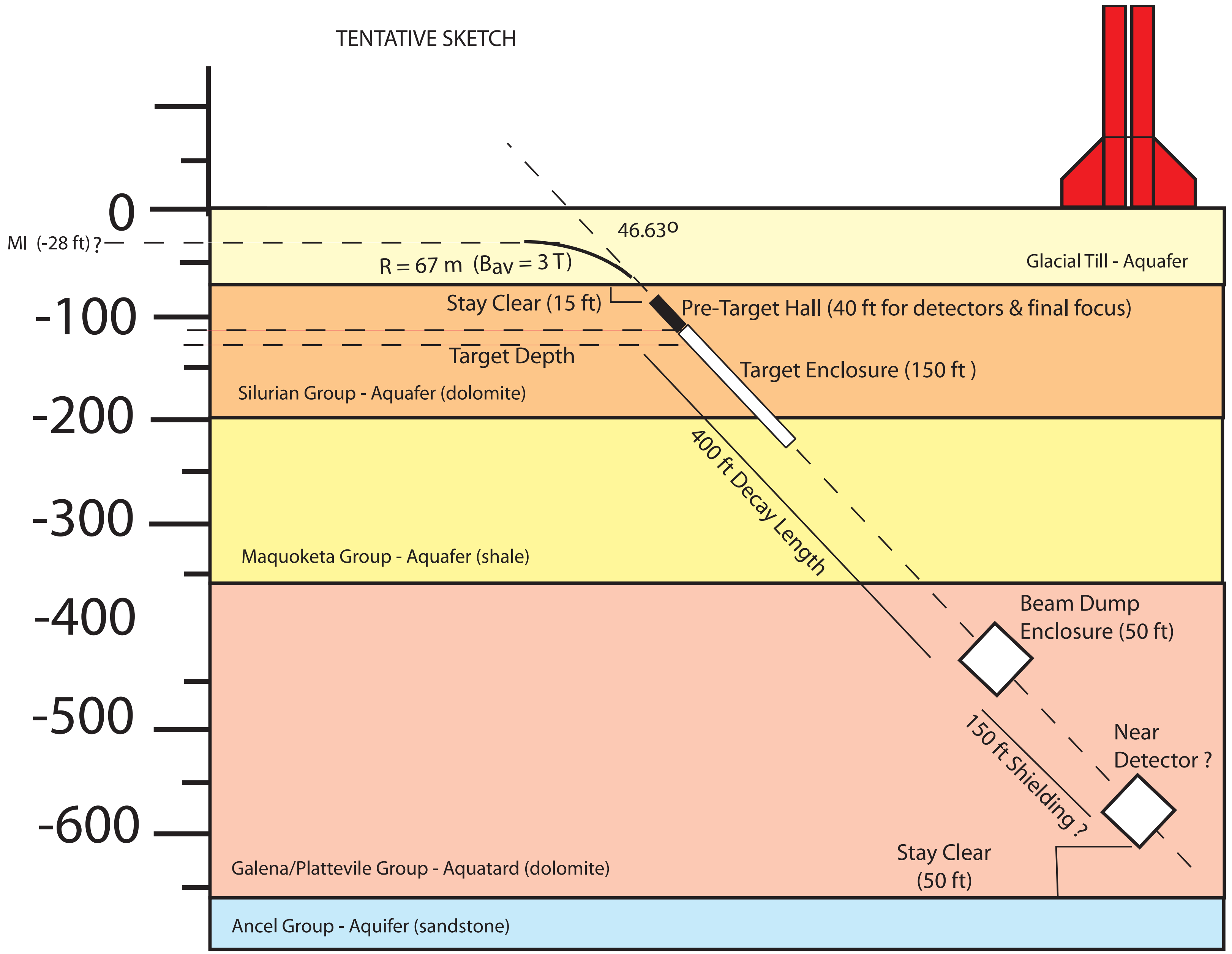
These lead to the following design principles:

1. Tune the spectrum to the resonant energy of the matter effect.
2. Aim for a "sawtooth" spectrum shape, with sharp cut-off at high E.

We start with the NuMI design and make the following modifications:

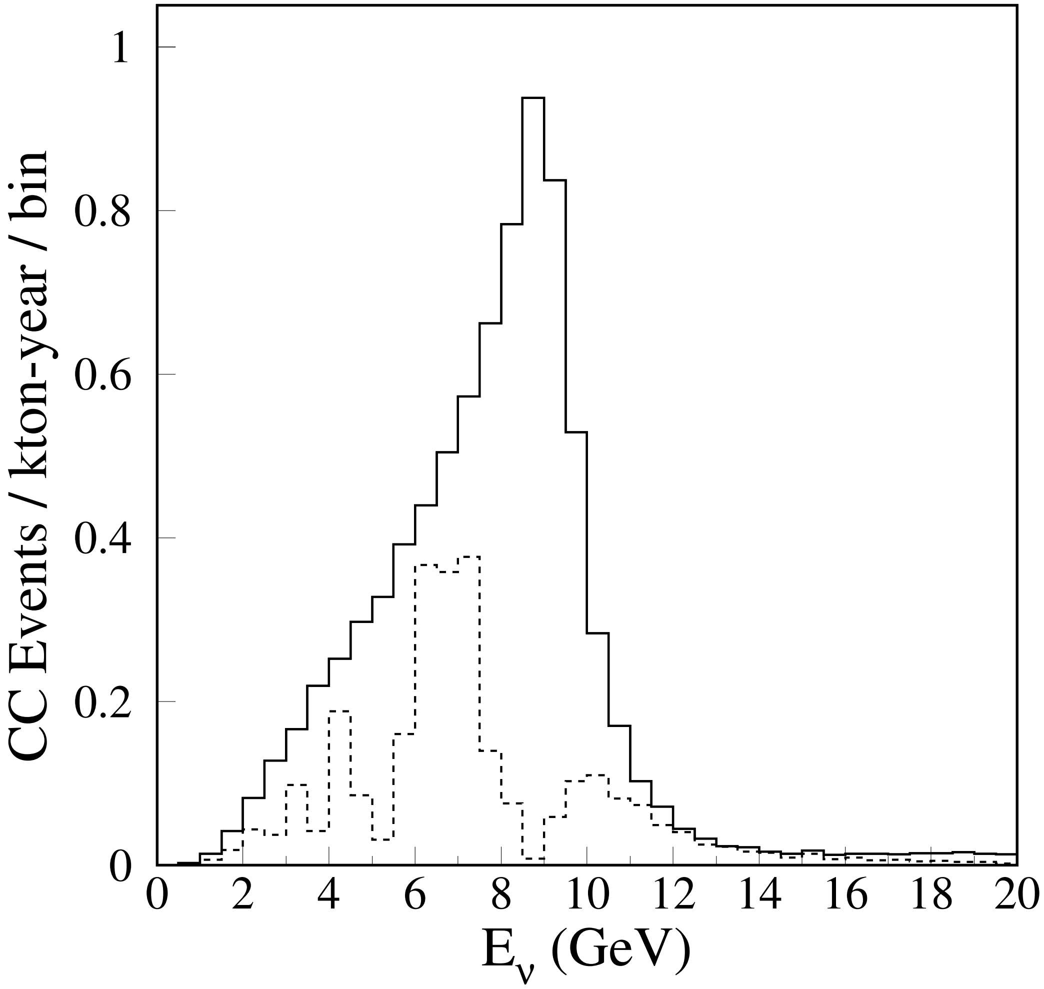
1. 2 MW of proton power at 60 GeV (assumes linac proton driver)
2. Target/horn configuration producing peak in spectrum at 10 GeV.
3. Dipole bend after 2nd horn: $0.5°$ for 20 GeV pions.

Steve Geer has started work on the layout (nextpage).



TENTATIVE SKETCH
0
-100
-200
-300
-400
-500
-600
MI (-28 ft) ?
46.63°
R = 67 m (Bav = 3 T)
Glacial Till - Aquafer
Stay Clear (15 ft)
Pre-Target Hall (40 ft for detectors & final focus)
Target Depth
Target Enclosure (150 ft)
Silurian Group - Aquafer (dolomite)
400 ft Decay Length
Maquoketa Group - Aquafer (shale)
Beam Dump
Enclosure (50 ft)
Near
Detector ?
150 ft Shielding ?
Stay Clear
(50 ft)
Galena/Plattevile Group - Aquatard (dolomite)
Ancel Group - Aquifer (sandstone)

Results from pbeam simulation

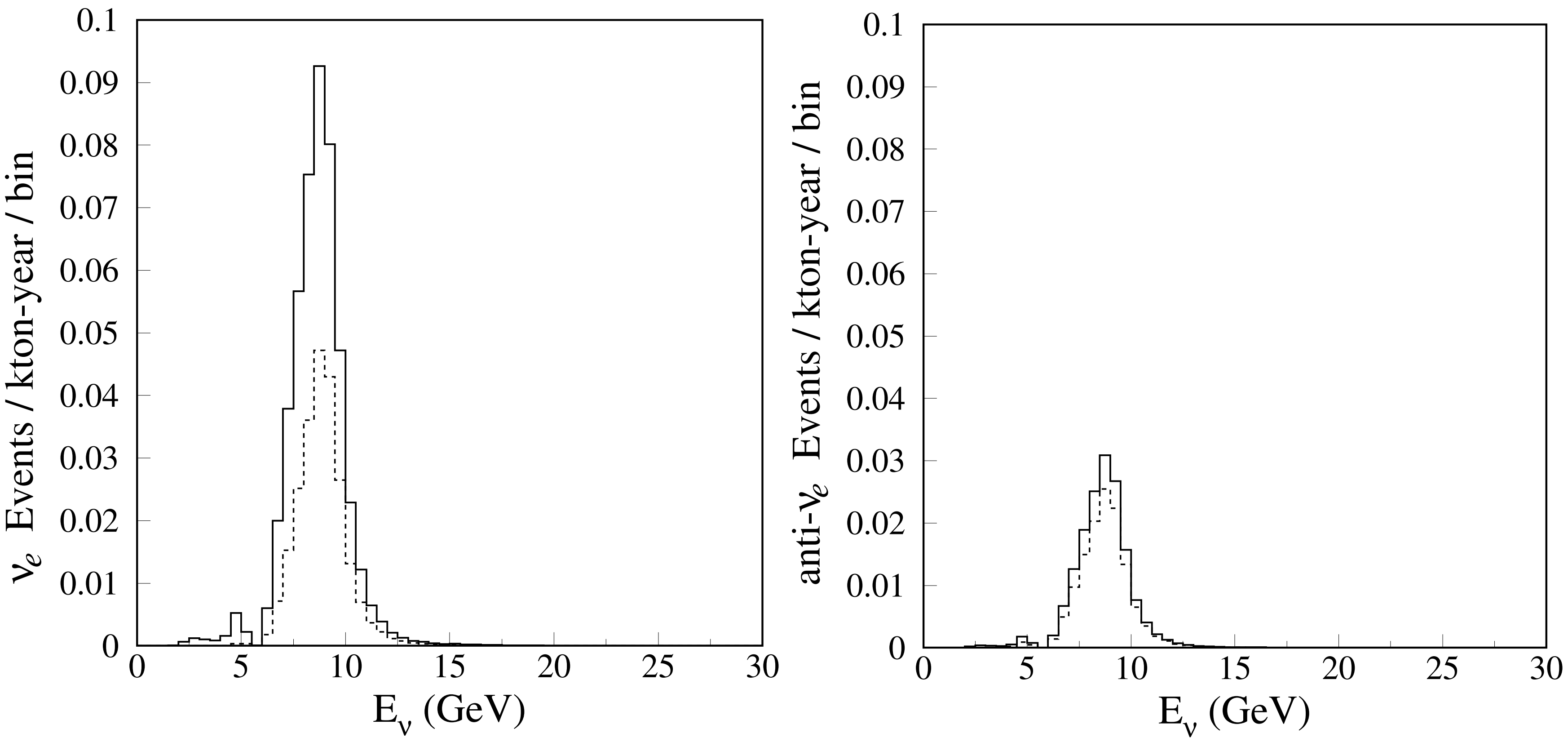


Solid line: ν_μ CC interactions assuming no oscillations.
Dashed line: With oscillations
2nd disappearance max occurs at peak!

The following factors are included:

- Scale up by 1.25 to agree with Geant results.
- Efficiency of tunnel is 37% relative to NuMI.

Signal selection: Find one EM ring with energy E

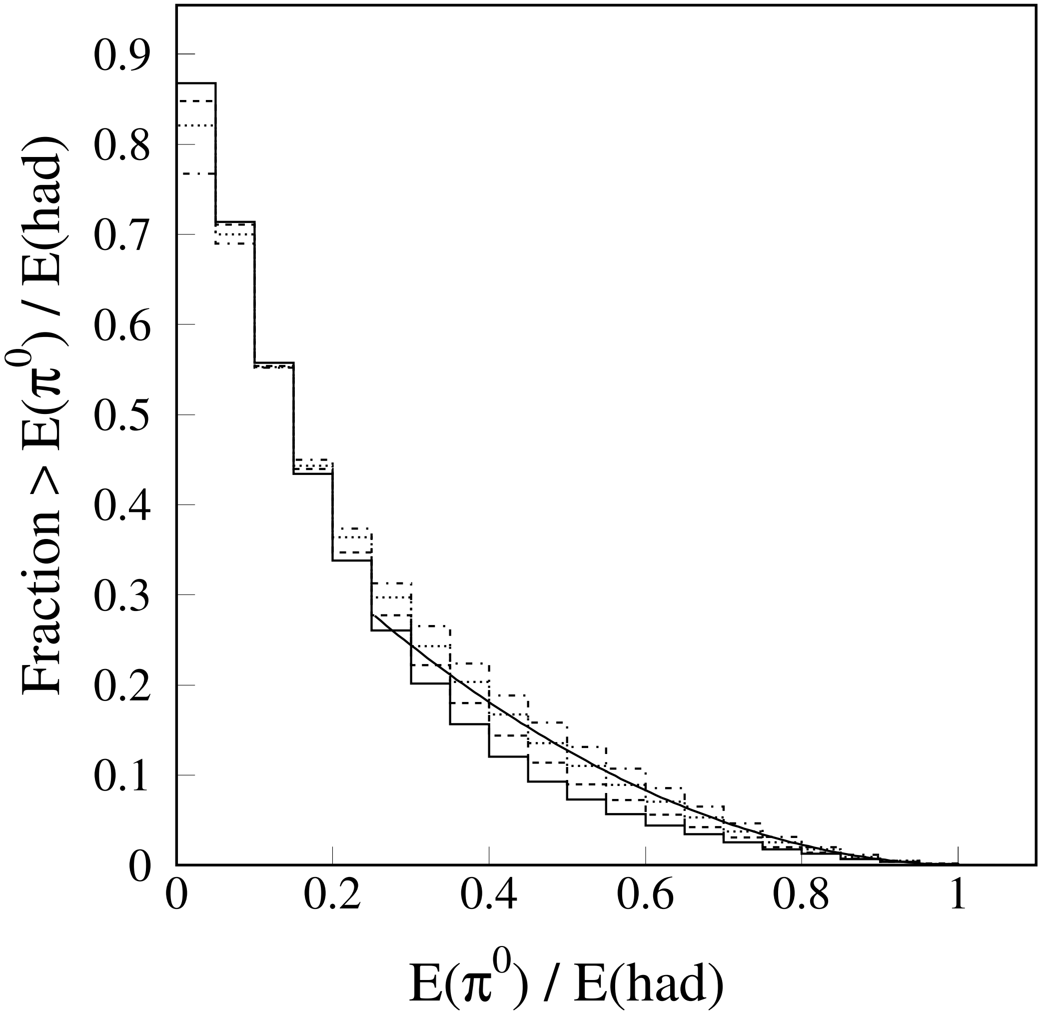


Solid: ν_e CC events.
Dash: $E > 4.5$ GeV, $E/E_{\rm vis} > 0.45$

Solid: $\bar{\nu}_e$ CC events.
Dash: $E > 3.3$ GeV, $E/E_{\rm vis} > 0.33$

After cuts, $\bar{\nu}_e$ rate = 55% of ν_e rate

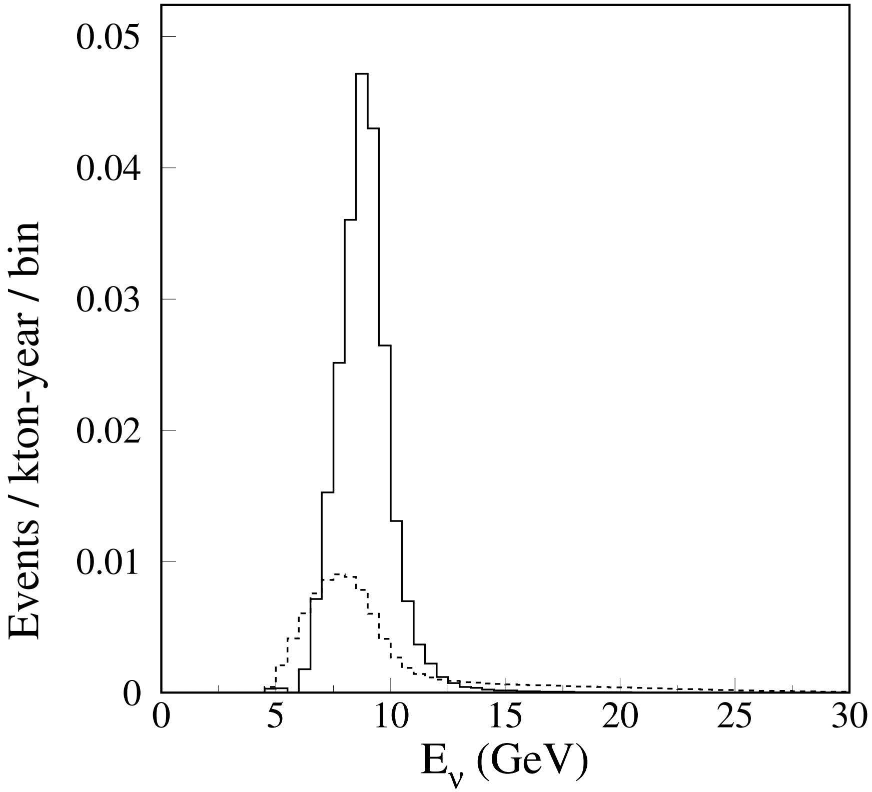
Neutral-current background

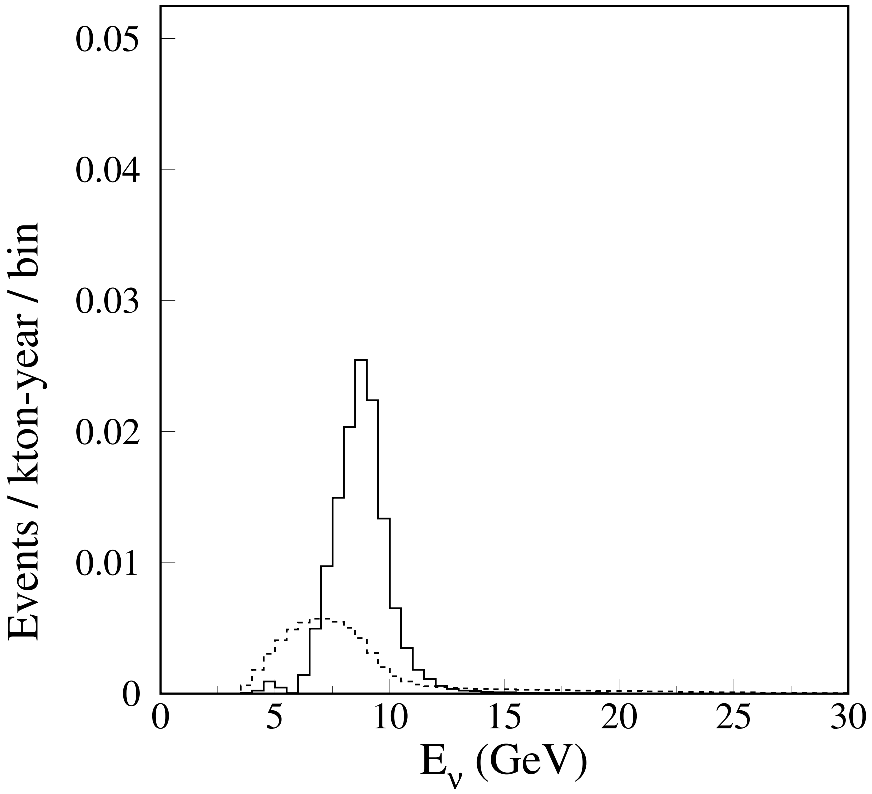


NC events with π^0 fragmentation are the major background

$\sigma_{NC} = 0.4\ \sigma_{CC}$
Parametrize y distribution
Parametrize fragmentation
$\Rightarrow$ Convolute spectrum into NC background

Comparison of S and NC for $\sin^2(2\theta_{13}) = 0.01$ (leading)





Solid line: ν_e events
Dashed line: NC background

Solid line: $\bar{\nu}_e$ events
Dashed line: NC background

Neutrino direction information has not yet been used.

Other backgrounds

- ν_μ CC events. Reject events with a muon.
  Miss muon in high-y events.
  However, most ν_μ have disappeared.
  $\Rightarrow$ Assume negligeable.
- ν_τ CC events.
  Cross-section is 8% compared to ν_μ.
  $BR(\tau \to e\nu\bar{\nu}) = 18\%$.
  Missing energy $\Rightarrow$ Feeds down.
  Assume negligeable.
- Intrinsic ν_e
  Signal region is narrow part of spectrum.
  Dipole bend helps reduce source from neutral kaons.
  $\Rightarrow$ Should be very small.

Summary of signal and background rates

Normalized to $\sin^2(2\theta_{13}) = 0.01$ and leading terms only.

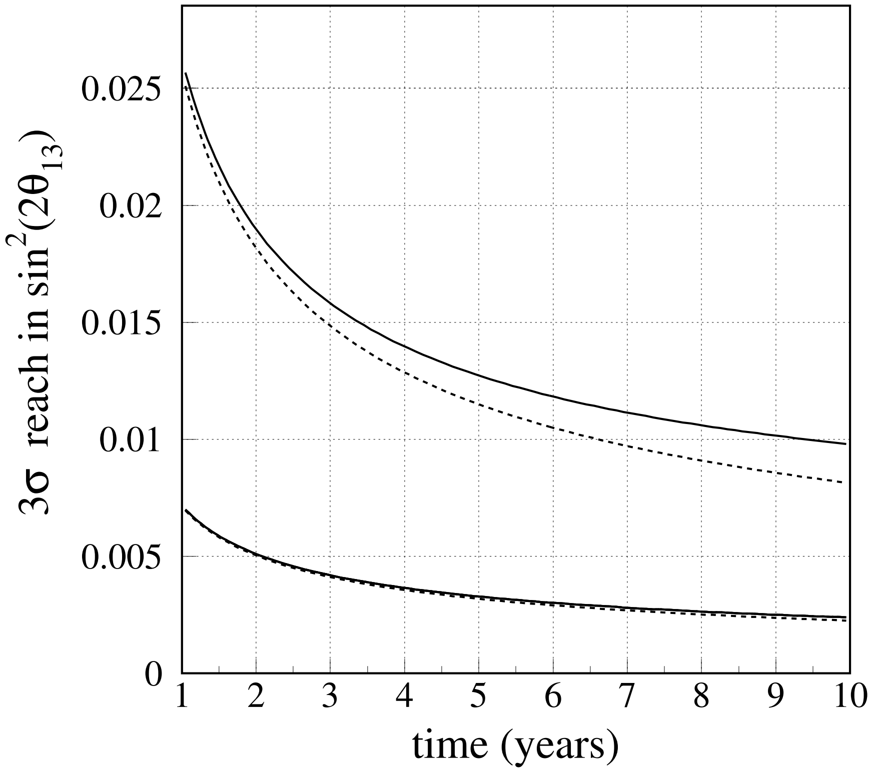
JHF phase 1:

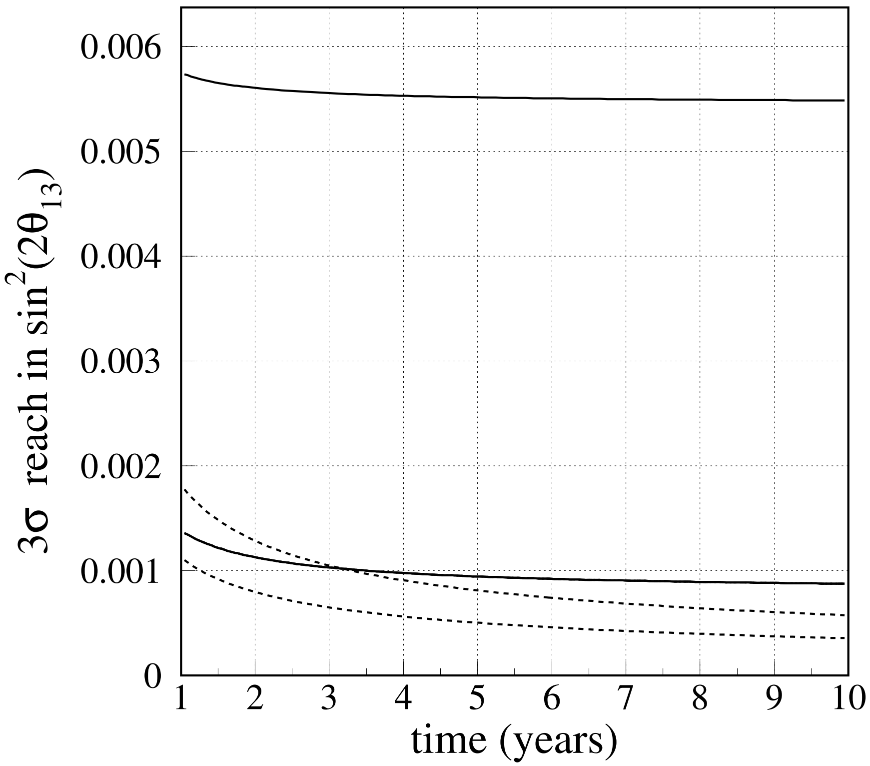
- $S = 0.11$ events/kton-year (0.55 in phase 2).
- $f_B = 0.51\%$

Fermilab:

- $S = 0.21$ events/kton-year
- $f_B = 2.5\%$
  $f_B = 0.13\%$ after scaling by matter amplification.

Reach in $\sin^2(2\theta_{13})$





With Super-K detector. With Hyper-K detector.

Upper curves: JHF phase 1

Lower curves: Fermilab beam.

Solid curves: 10% systematic uncertainty on the background.

Dashed curves: no systematic uncertainty.

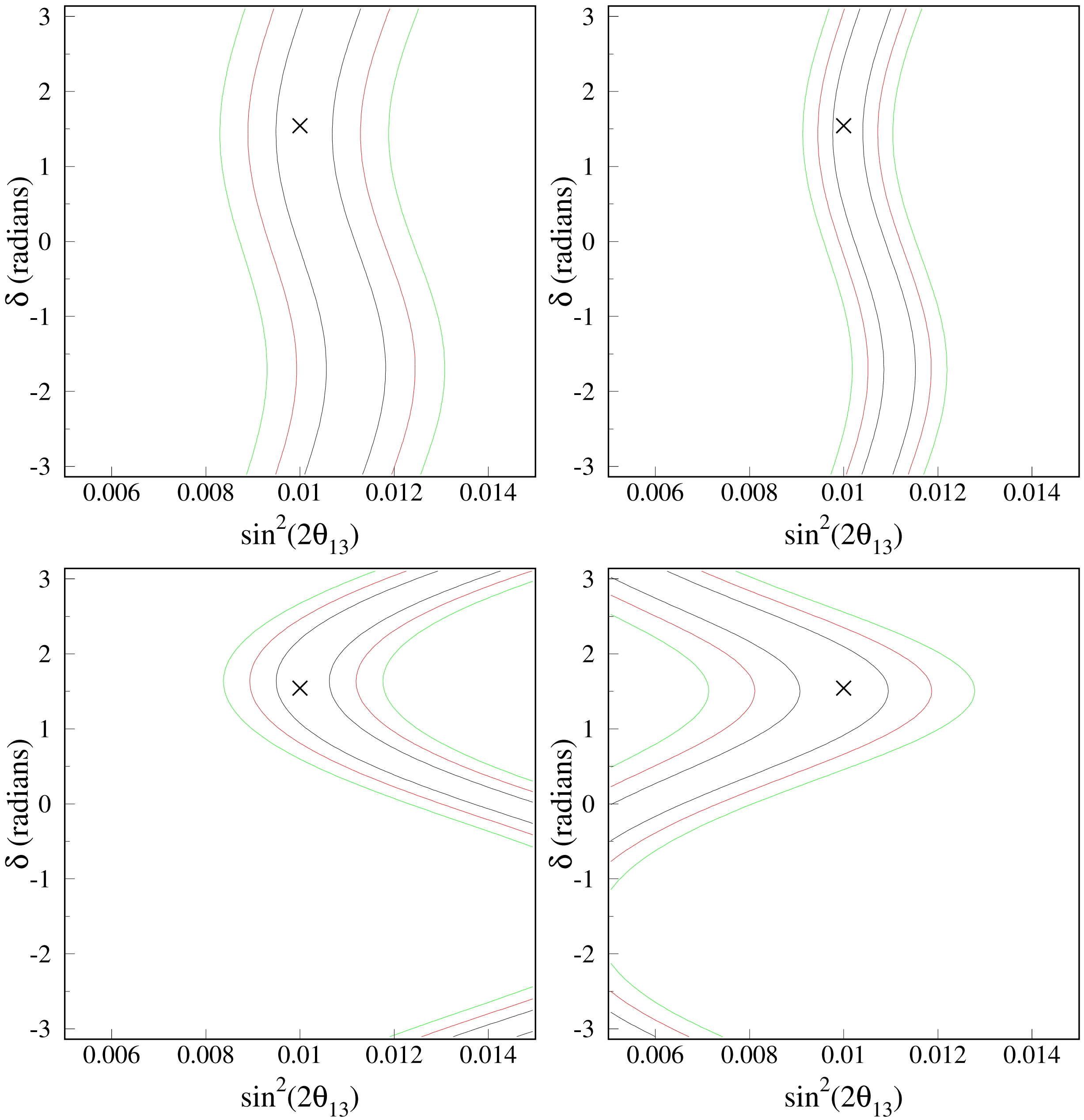
Constraints on CP violating phase with Hyper-K

We start with the following oscillation probability measurements which assume:

- Systematic uncertainty on B of 2% (JHF) 5% (Fermilab).
- No flux uncertainty (it will need to be very well known for large $\sin^2(2\theta_{13})$).
- f_B same for ν and $\bar{\nu}$.
- 6 year JHF $\bar{\nu}$ run equivalent to 2 year JHF ν run.

Beam	ye-ars	$\sin^2(2\theta_{13})$ 0.01	0.05	0.001
Fermi	2	0.104 ± 0.0060	0.501 ± 0.012	0.012 ± 0.0034
Fermi	8	0.104 ± 0.0032	0.501 ± 0.0061	0.012 ± 0.0021
JHF ν	2	$(7.9 \pm 0.37) \cdot 10^{-3}$	$(3.2 \pm 0.052) \cdot 10^{-2}$	$(1.5 \pm 0.32) \cdot 10^{-3}$
JHF ν	8	$(7.9 \pm 0.25) \cdot 10^{-3}$	$(3.2 \pm 0.031) \cdot 10^{-2}$	$(1.5 \pm 0.24) \cdot 10^{-3}$
JHF $\bar{\nu}$	6	$(2.8 \pm 0.33) \cdot 10^{-3}$	$(1.8 \pm 0.044) \cdot 10^{-2}$	$(0.0 \pm 0.31) \cdot 10^{-3}$

$\Rightarrow \chi^2$ constraints in $\sin^2(2\theta_{13}) - \delta$ plane
(uncertainties on other parameters not yet included)

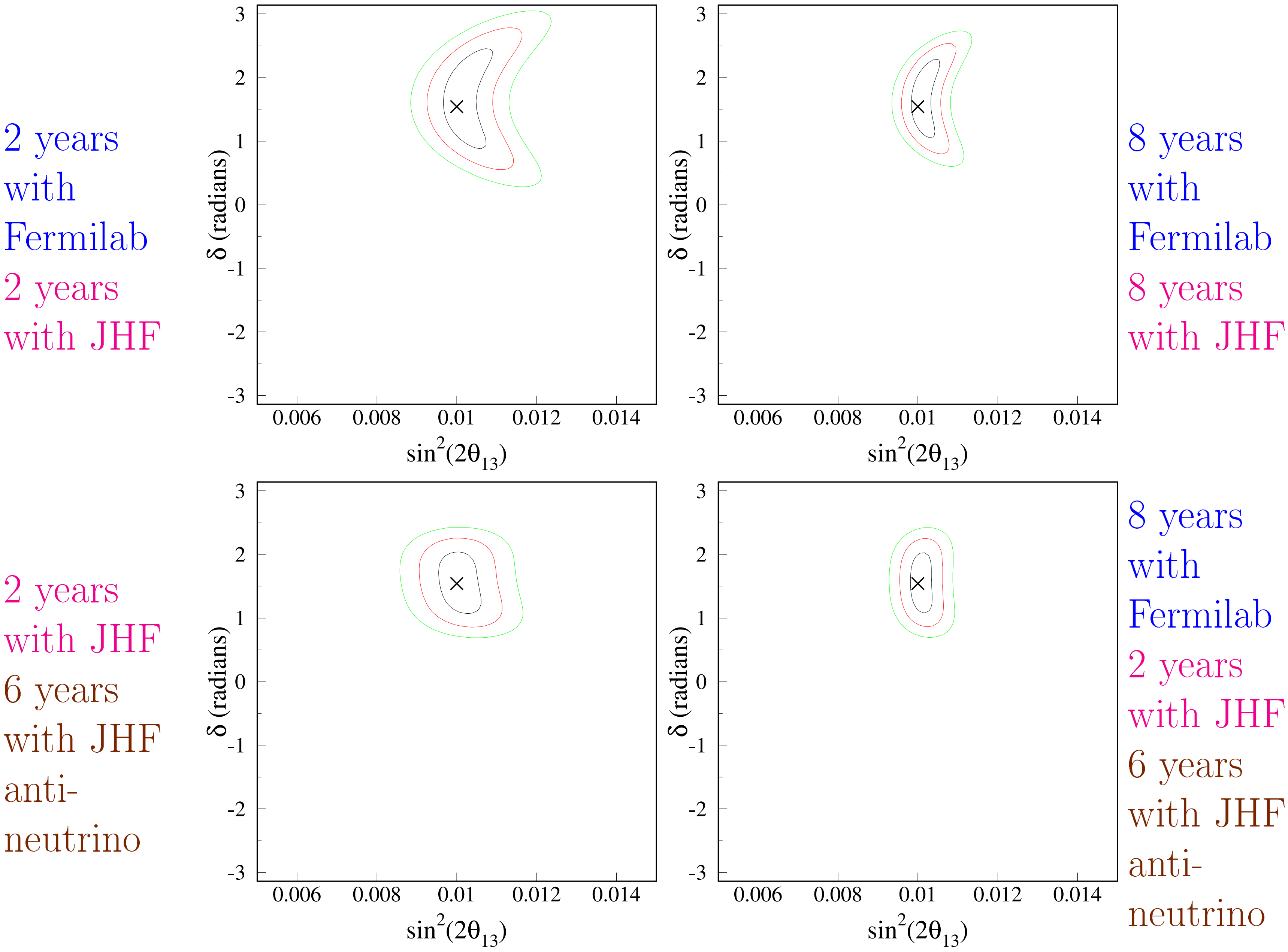


2 years with Fermilab beam.

8 years with Fermilab beam.

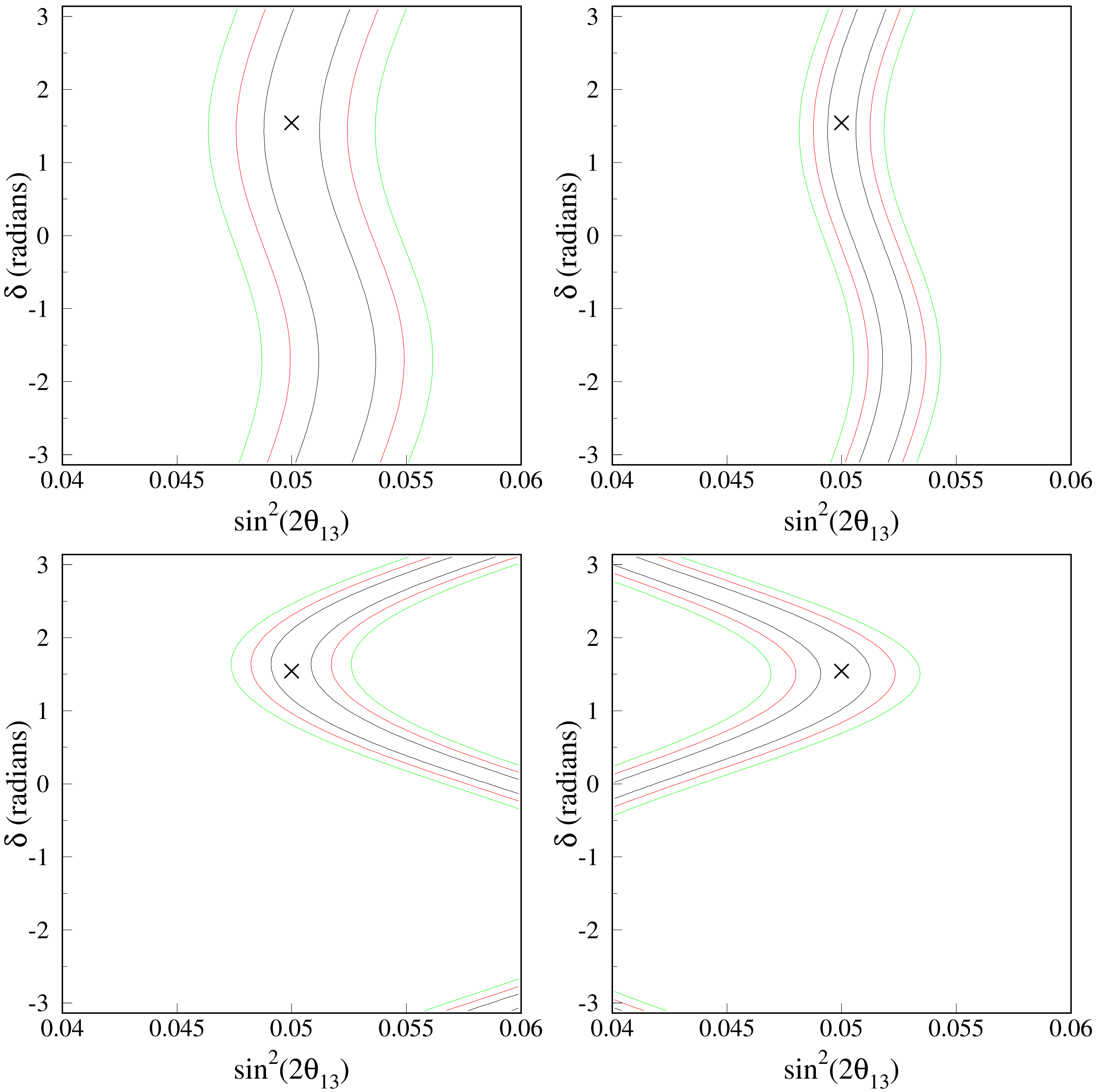
2 years with JHF beam.

6 years with JHF anti-neutrino beam.


2 years with Fermilab
2 years with JHF
8 years with Fermilab
8 years with JHF
2 years with JHF
6 years with JHF anti-neutrino
8 years with Fermilab
2 years with JHF
6 years with JHF anti-neutrino
δ (radians)
sin²(2θ₁₃)

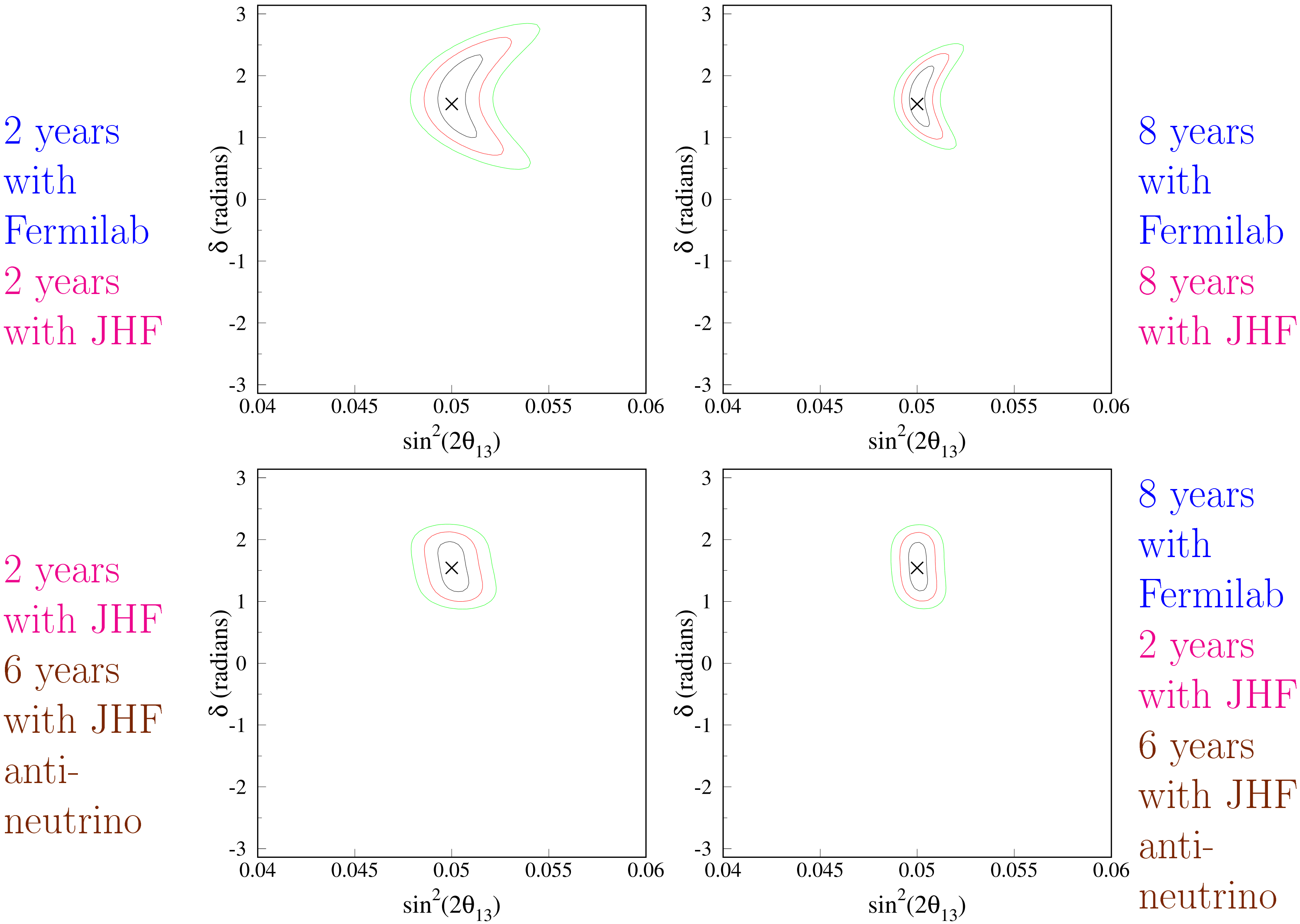
2 years with Fermilab beam.

8 years with Fermilab beam.



2 years with JHF beam.

6 years with JHF anti-neutrino beam.

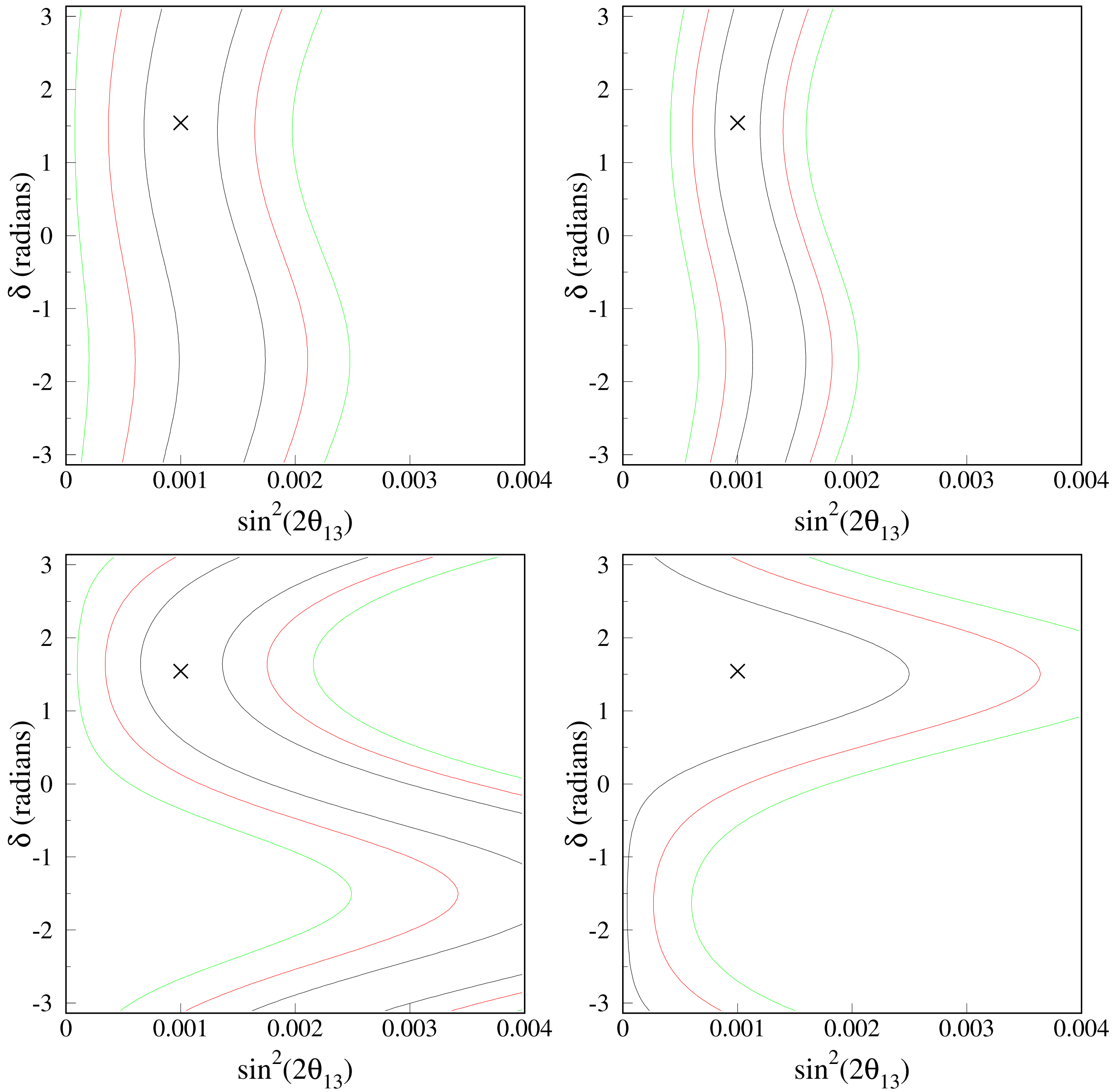

2 years with Fermilab
2 years with JHF
8 years with Fermilab
8 years with JHF
2 years with JHF
6 years with JHF anti-neutrino
8 years with Fermilab
2 years with JHF
6 years with JHF anti-neutrino
δ (radians)
$\sin^2(2\theta_{13})$
3
2
1
0
-1
-2
-3
0.04
0.045
0.05
0.055
0.06

2 years with Fermilab beam.

8 years with Fermilab beam.

2 years with JHF beam.

6 years with JHF anti-neutrino beam.

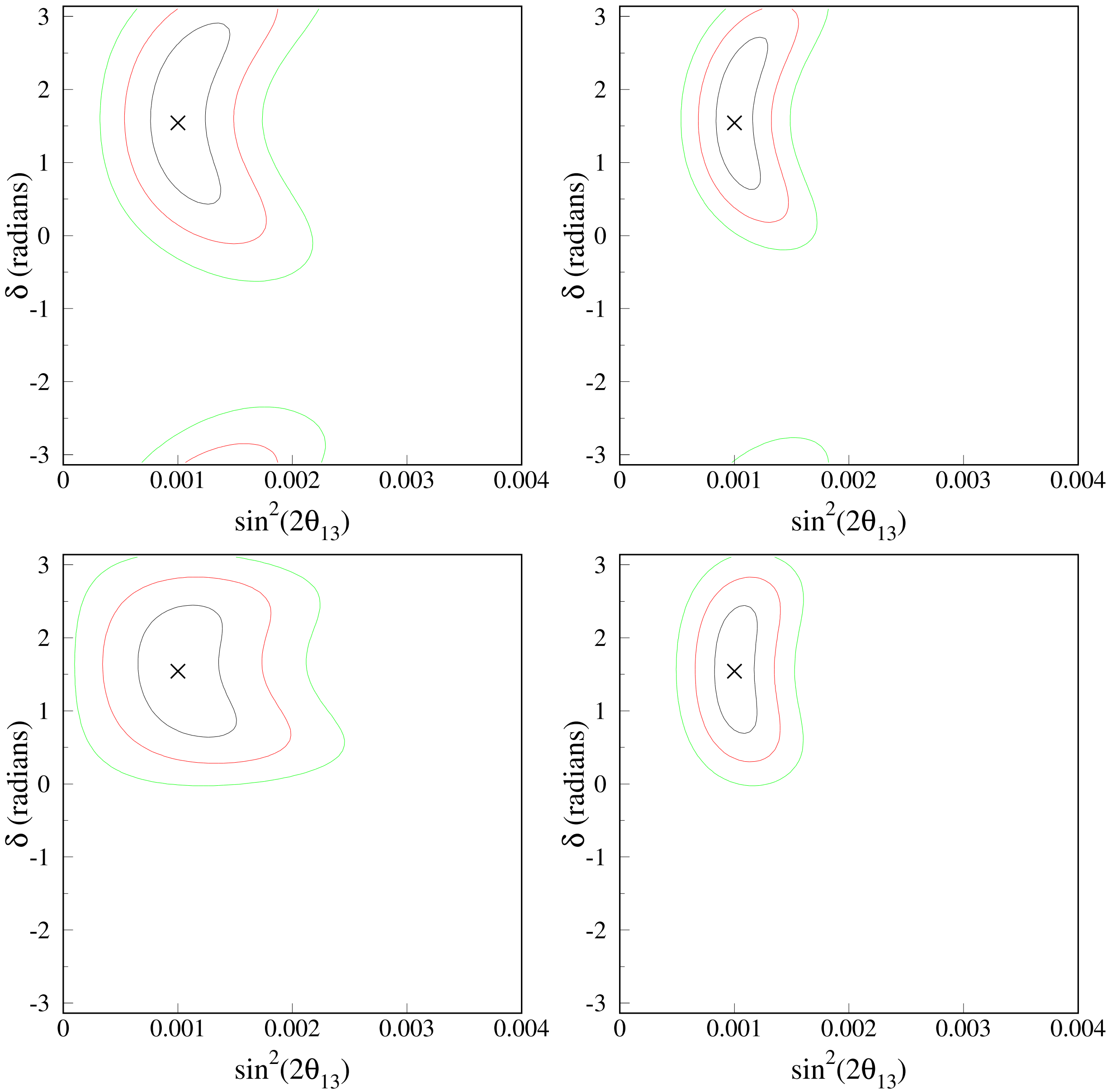


2 years with Fermilab 2 years with JHF

8 years with Fermilab 8 years with JHF

2 years with JHF 6 years with JHF anti-neutrino

8 years with Fermilab 2 years with JHF 6 years with JHF anti-neutrino



Plans

- Detector simulation
  (With Panagiotis) Obtain simulation code from Dave Casper
- Beamline layout, simulation
  Steve Geer is working on layout. Simulation will be needed later.
- Effects of uncertainties on other parameters
- Less than maximal CP violation
- Measurement of 2nd ν_μ disappearance
- Neutrino magnetic moment
  With John Krane

You are welcome to join these activities (and be part of journal pubs)