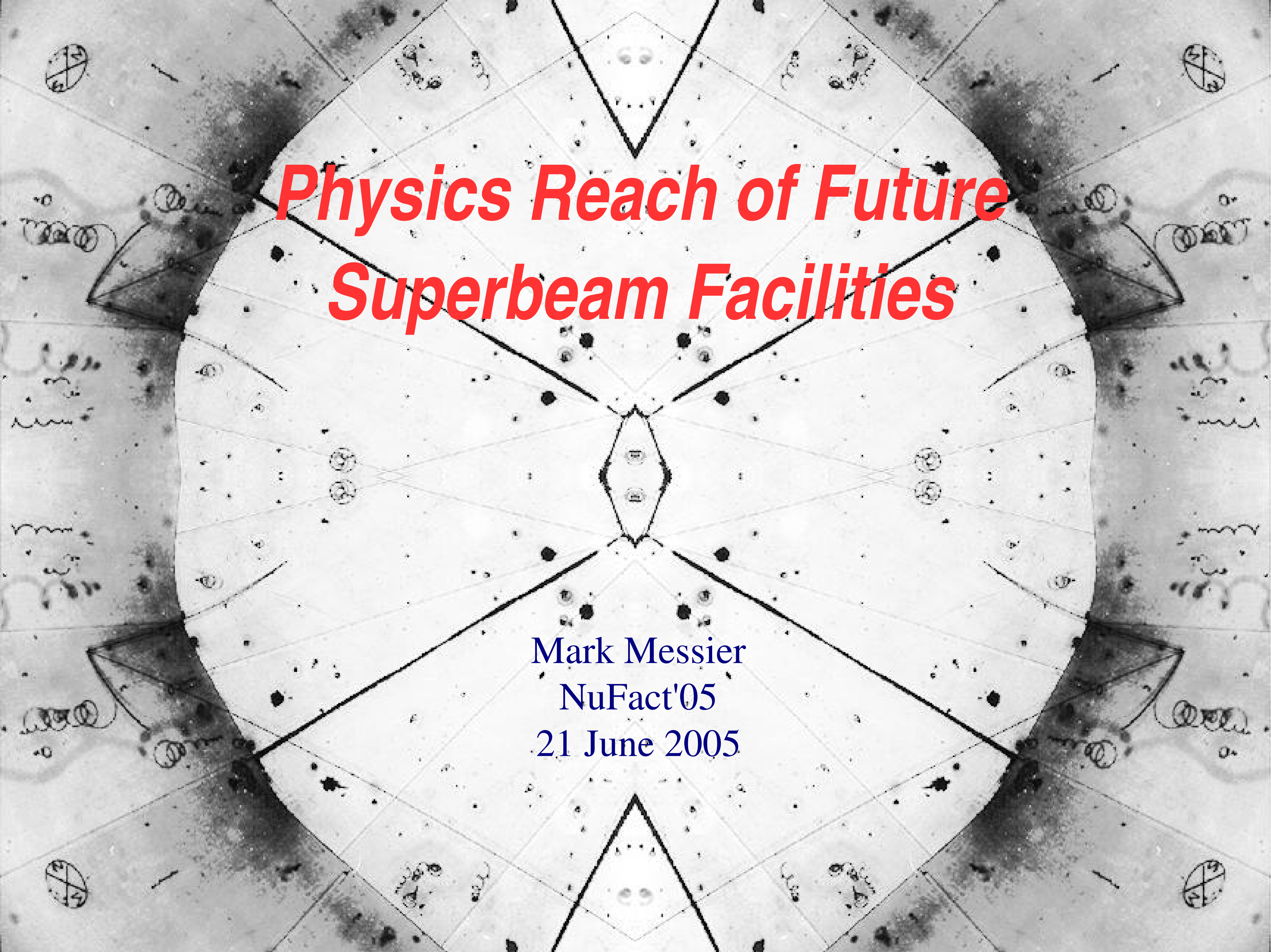


Physics Reach of Future Superbeam Facilities

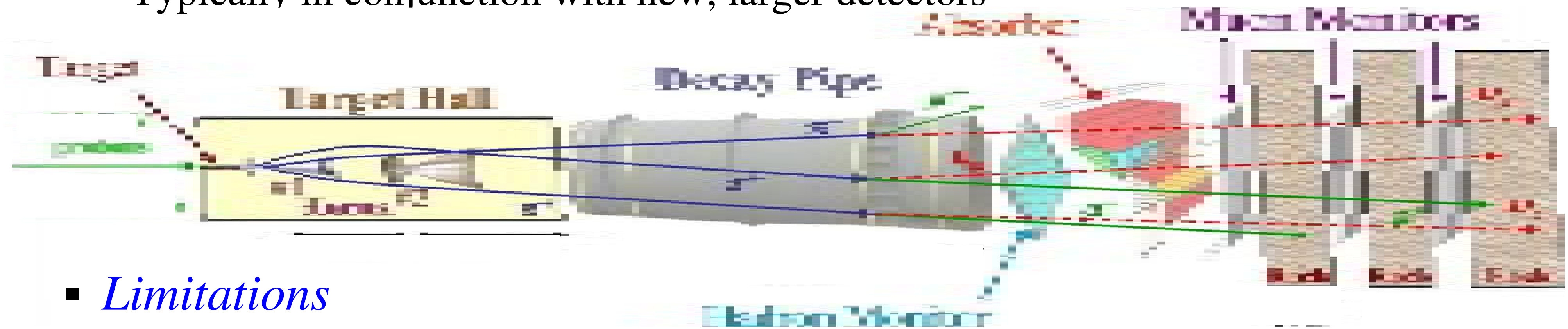
Mark Messier

NuFact'05
21 June 2005

What is a superbeam?

The term “superbeam” has come to refer to future beam lines that push the current neutrino beam technology to its limit

- Higher proton intensities, faster repetition rates
- Typically in conjunction with new, larger detectors



- *Limitations*
  - ✗ $\tau_\pi / \tau_\mu = 1\%$ difficult to achieve ν_e fractions lower than 0.5%
  - ✗ ν_μ-bar rates typically ~10%; Regions of low horn acceptance scraping on beam line element
- *Advantages*
  - ✓ Builds on existing facilities
  - ✓ Problems mostly well understood
  - ✓ Wide band beam for detectors on beam axis
  - ✓ Narrow band beam for detectors off the beam axis

Goals of superbeam experiments

Expect current generation of experiments to

- Confirm atmospheric neutrino oscillations *[K2K ✔]*
- Measure Δm^2_{23} to 10% *[MINOS]*
- Measure $\sin^2 2\theta_{23}$ to ~10% *[MINOS]*
- Observe appearance of ν_τ *[OPERA/ICARUS]*
- Push upper limits on θ_{13} *(observation if lucky!) [MINOS/OPERA/ICARUS]*
- Confirm/refute LSND signal *[MiniBooNE]*

Follow ons to these will

- Measure Δm^2_{23} to ~2% *[T2K, NOvA]*
- Measure $\sin^2 2\theta_{23}$ to ~2% *[T2K, NOvA]*
- Expect to *find non-zero θ_{13}: ν_μ–ν_e oscillations[T2K,NOvA,reactor experiments]*
- *Begin* exploration of mass hierarchy *[NOvA]* and CP violation *[T2K,NOvA]*

Next generation "superbeam" experiments hope to

- Measure Δm^2_{23} to 1%
- Measure $\sin^2 2\theta_{23}$ to 1%
- Measure θ_{13} to a few%
- Determine the mass hierarchy
- Search for CP violation

T2K

- Begin operations in 2009 with
  - 50 kilo-ton SK detector
  - Beam power ramping up to 0.7 MW
- 2015+
  - Beam power increases to 4 MW
  - 1 Mton Hyper-Kamiokande

BNL

- Still in proposal stage
- New 1 MW neutrino beam
- New megoton detector at Homestake

NOvA

- Begin operations in 2009 with
  - 0.7 MW NuMI beam
  - 30 kilto-ton liquid scintillator tracker
- 2015+
  - Beam power increases to 2 MW
  - Add 2nd ~100 kilo-ton detector?

CERN SPL-Frejus

- Still in proposal stage
- New 4 MW neutrino beam
- New ~megton detector at Frejus

T2K

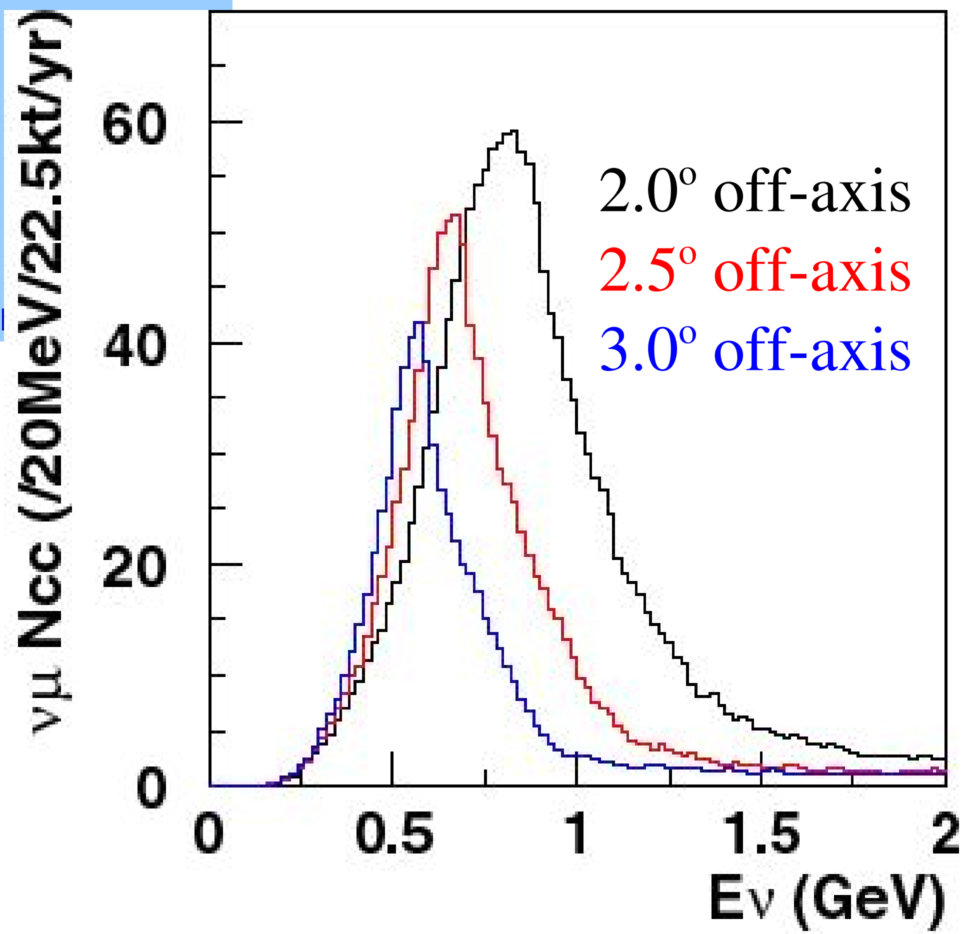
(Tokai-mura to Kamioka)

T2K Phase I:

- 0.75 MW to Super-K (22.5 kt fiducial volume)

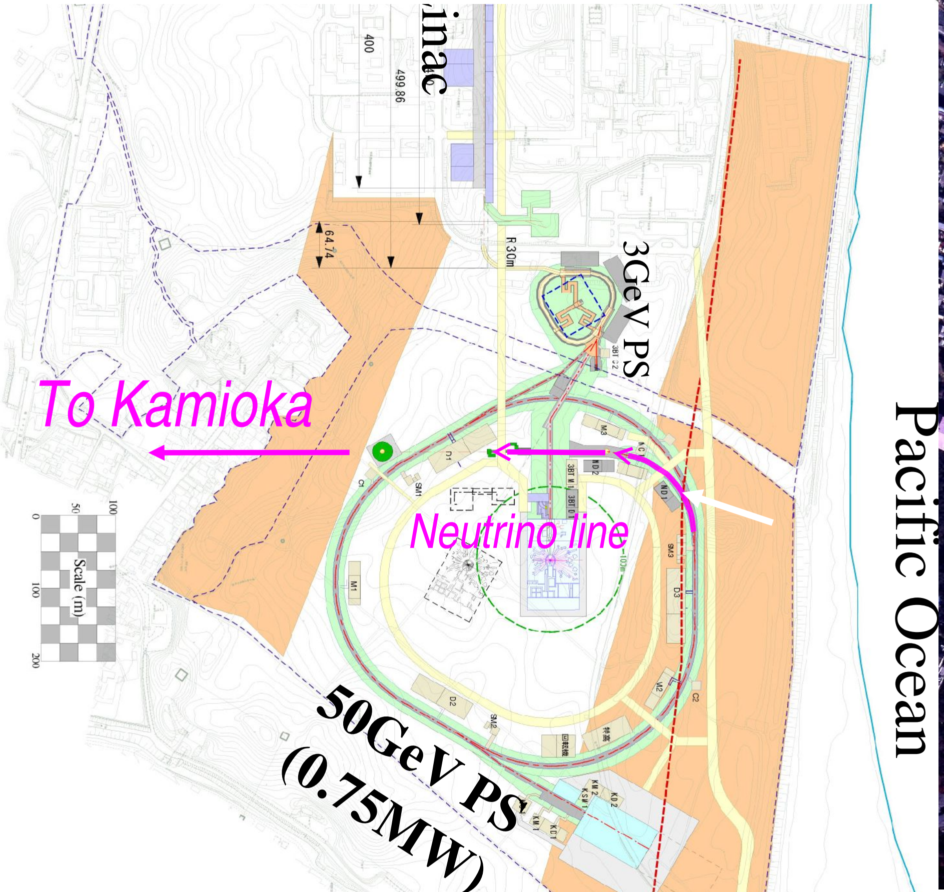
T2K Phase II (*"Superbeam" phase*):

- 50 GeV PS @ J-PARC, E_ν = 0.5-0.8 GeV
- 4 MW to Hyper-K (1 Mton mass)
- 360,000 ν_μ CC events / year
- L=295 km : small matter effect. Helps breaks degeneracies when combined with longer baseline experiments

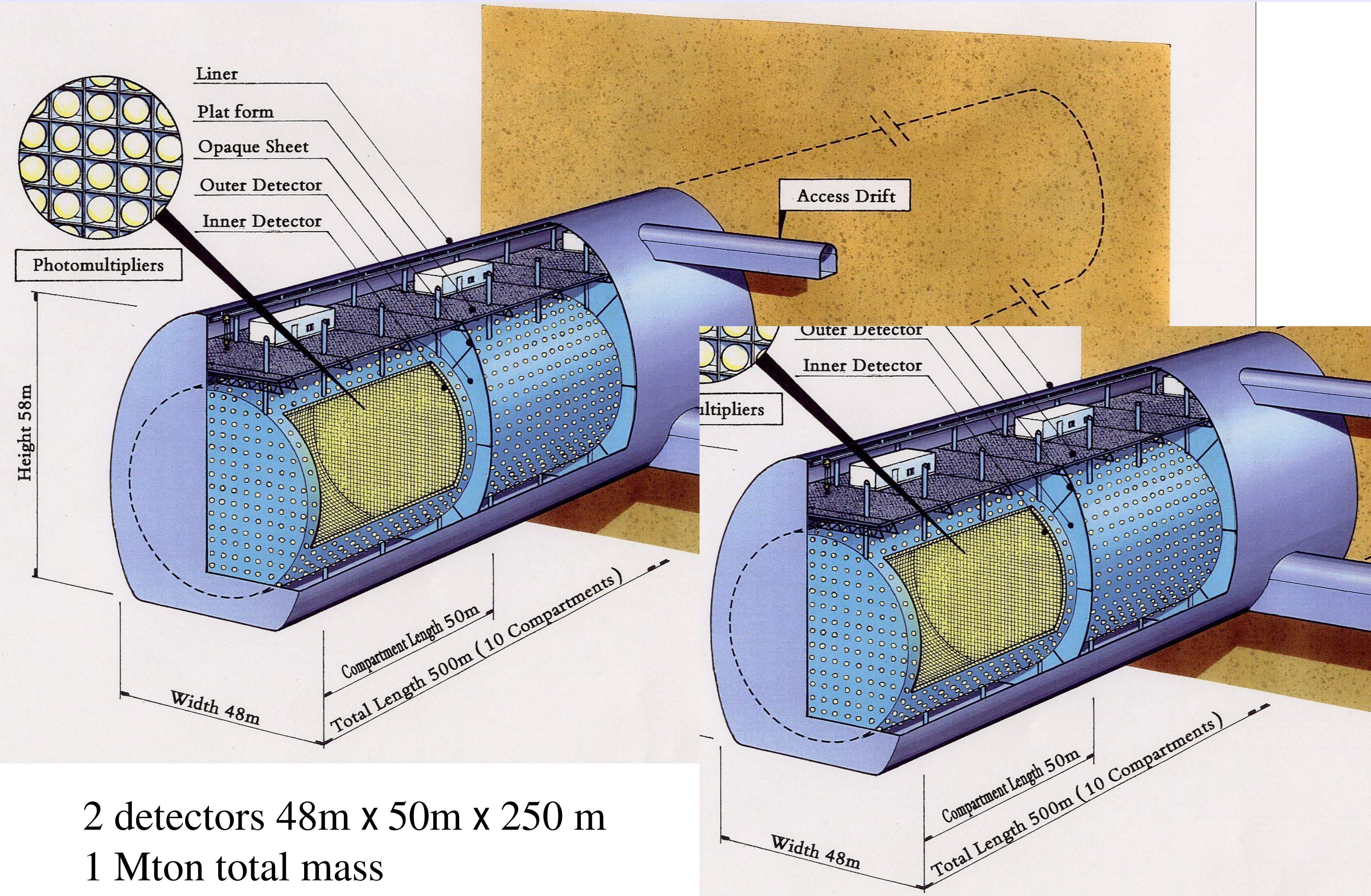


Japan Proton Accelerator Research Complex (J-PARC)

- Construction 2001-2007
- 0.75 MW 50 GeV-PS
- Planned upgrade to 4 MW
  - Increase repetition rate x2.5
    - Double RF cavities
    - Eliminate idling time in accelerator cycle
- Double number of bunches using barrier buckets

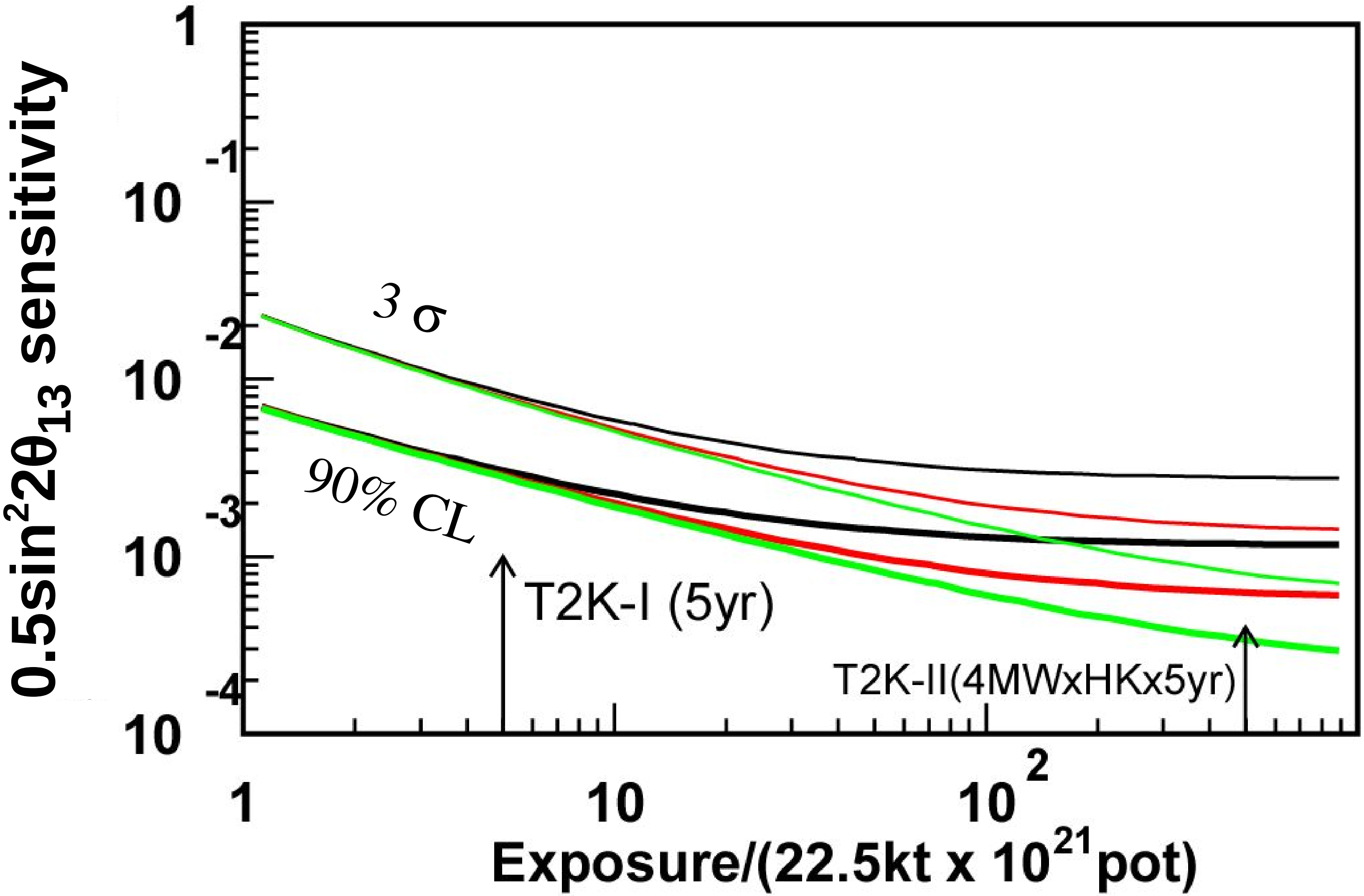


Hyper-Kamiokande



2 detectors 48m x 50m x 250 m
1 Mton total mass

T2K Phase 2 Sensitivity



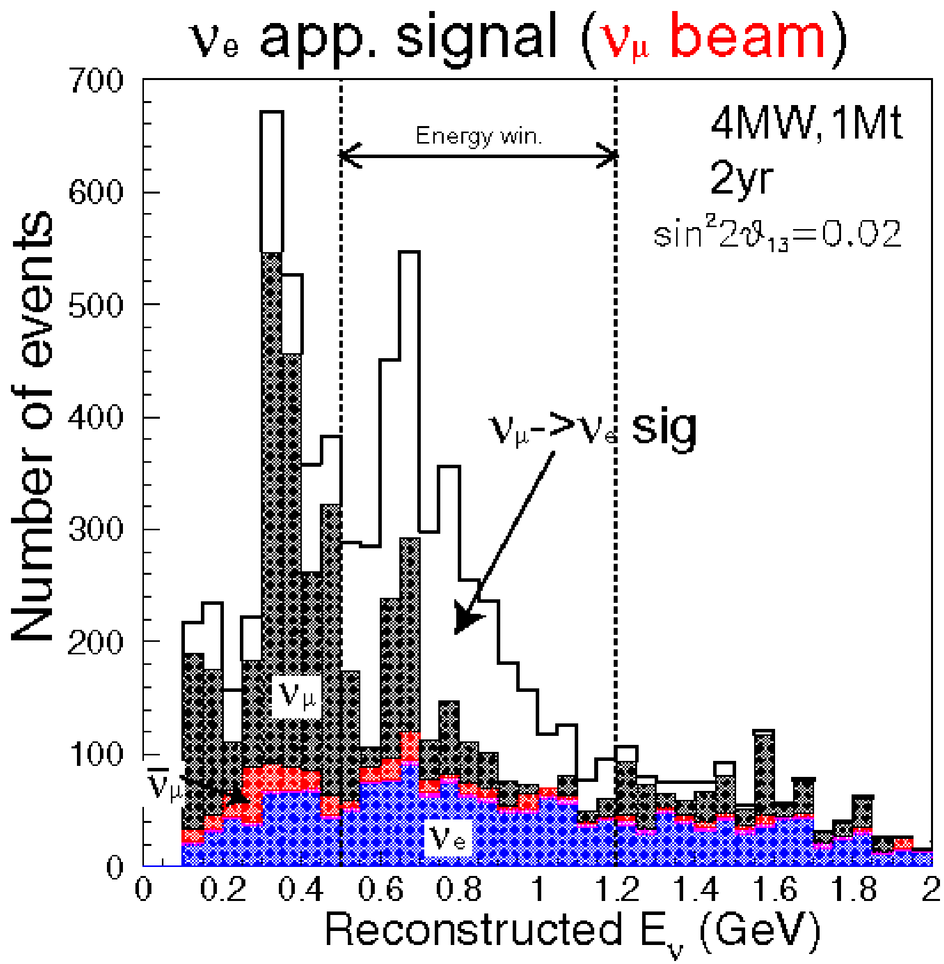
Systematic error on background

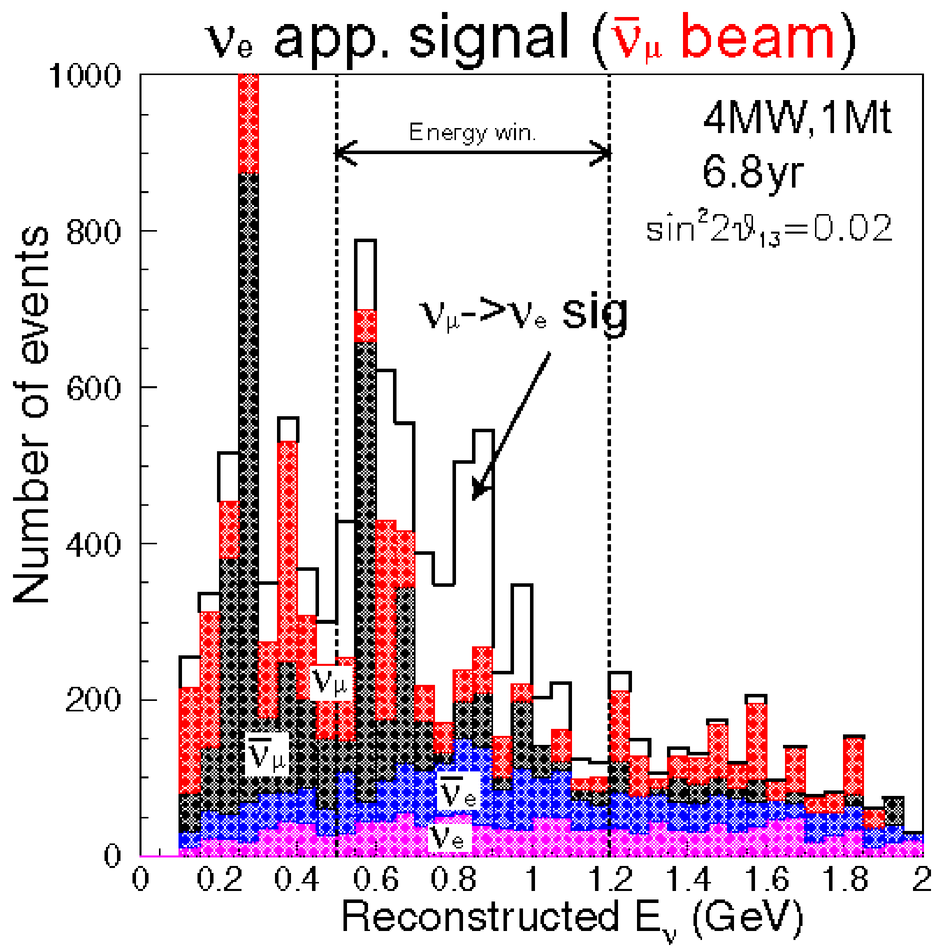
10%

5%

2%

Reconstructed event rates

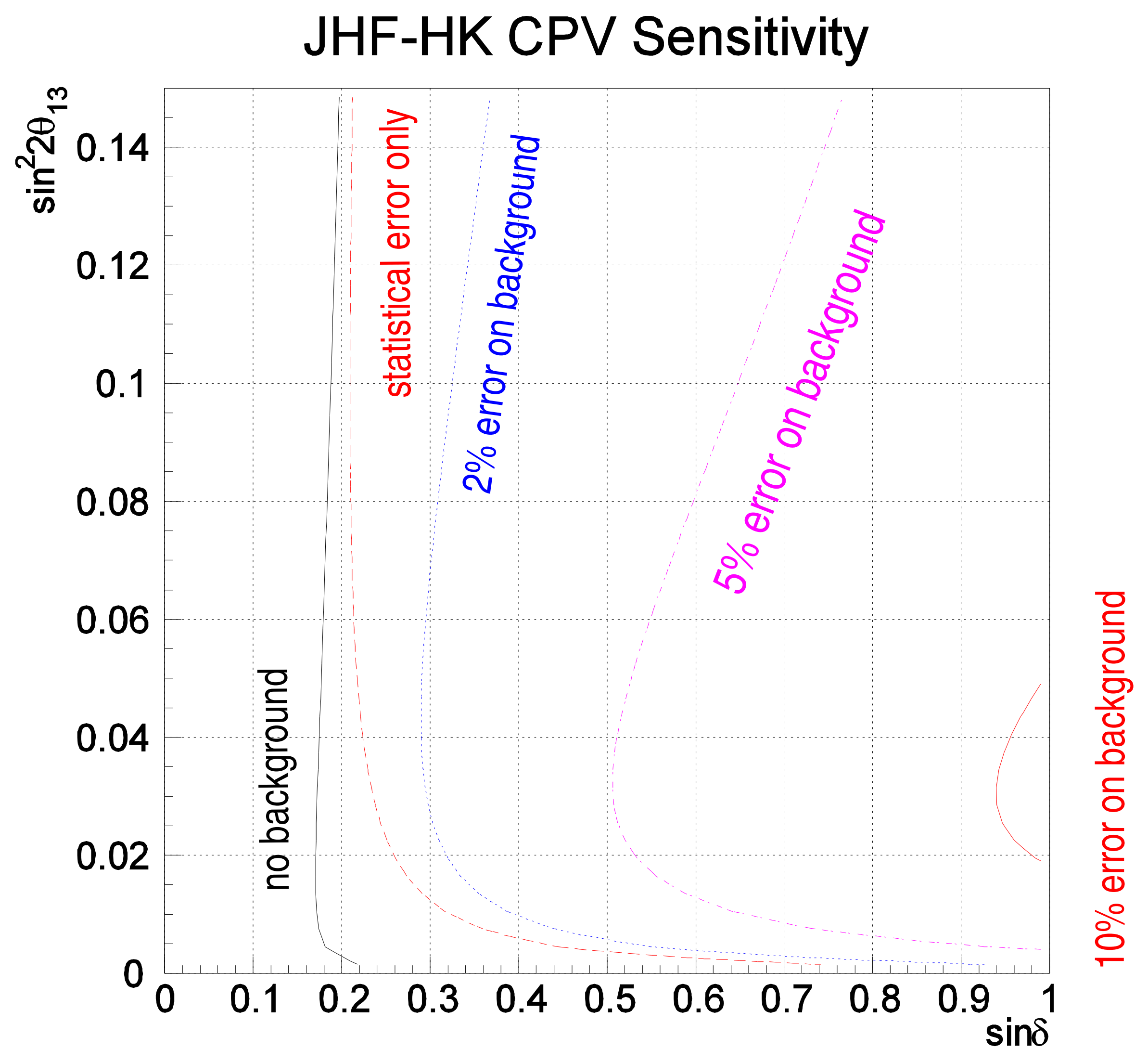




$\Delta m^2_{21} = 6.9\text{x}10^{-3}$ eV^{2,} $\Delta m^2_{32} = 2.8\text{x}10^{-3}$ eV^2

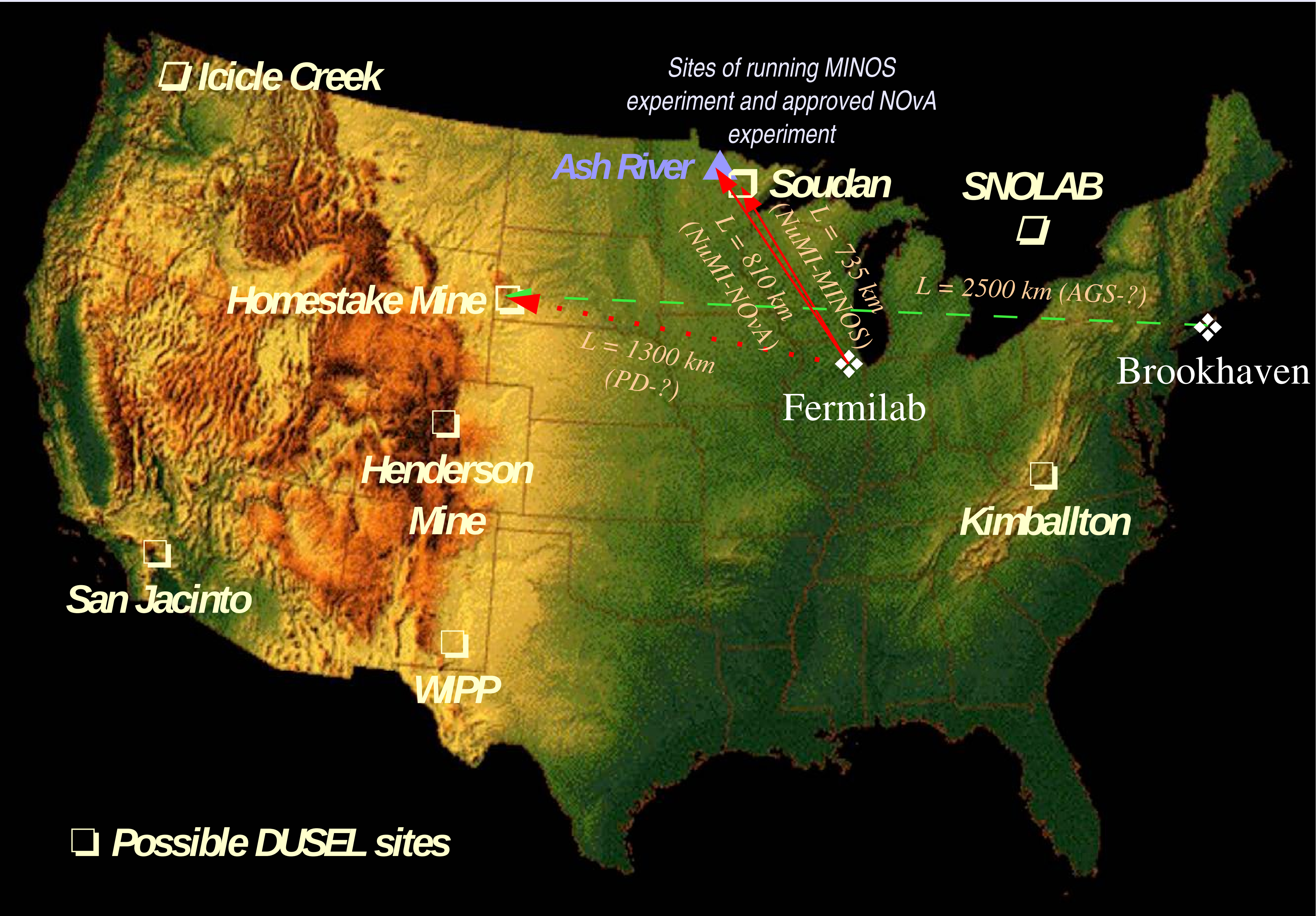
$\theta_{13} = 0.594$, $\theta_{23} = \pi/4$, $\theta_{13} = 0.05$

T2K Phase II: CPV Sensitivity



2 year neutrino run 7 year anti-neutrino run

Superbeams in the United States



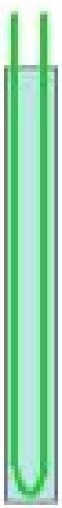
NOvA Detector

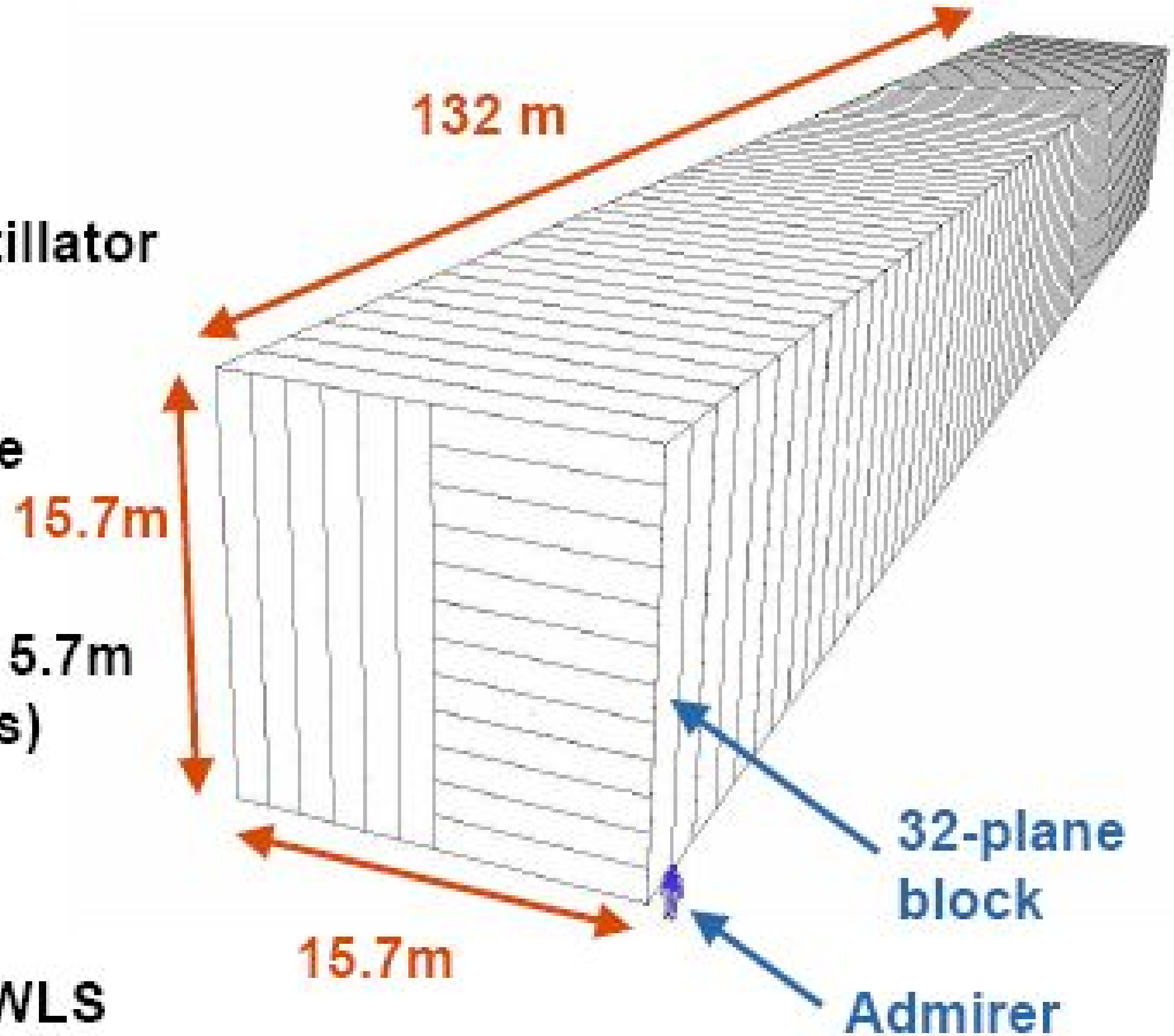
"Totally Active"
30 kT:
- 24 kT liquid scintillator
- 6 kT PVC

32 cells/extrusion
12 extrusions/plane
1984 planes
Cell dimensions:
- 3.9 cm x 6 cm x 15.7m
- (0.15 X_0 thickness)

Extrusion walls:
- 3 mm outer
- 2 mm inner

U-shaped 0.8 mm WLS fiber into APD



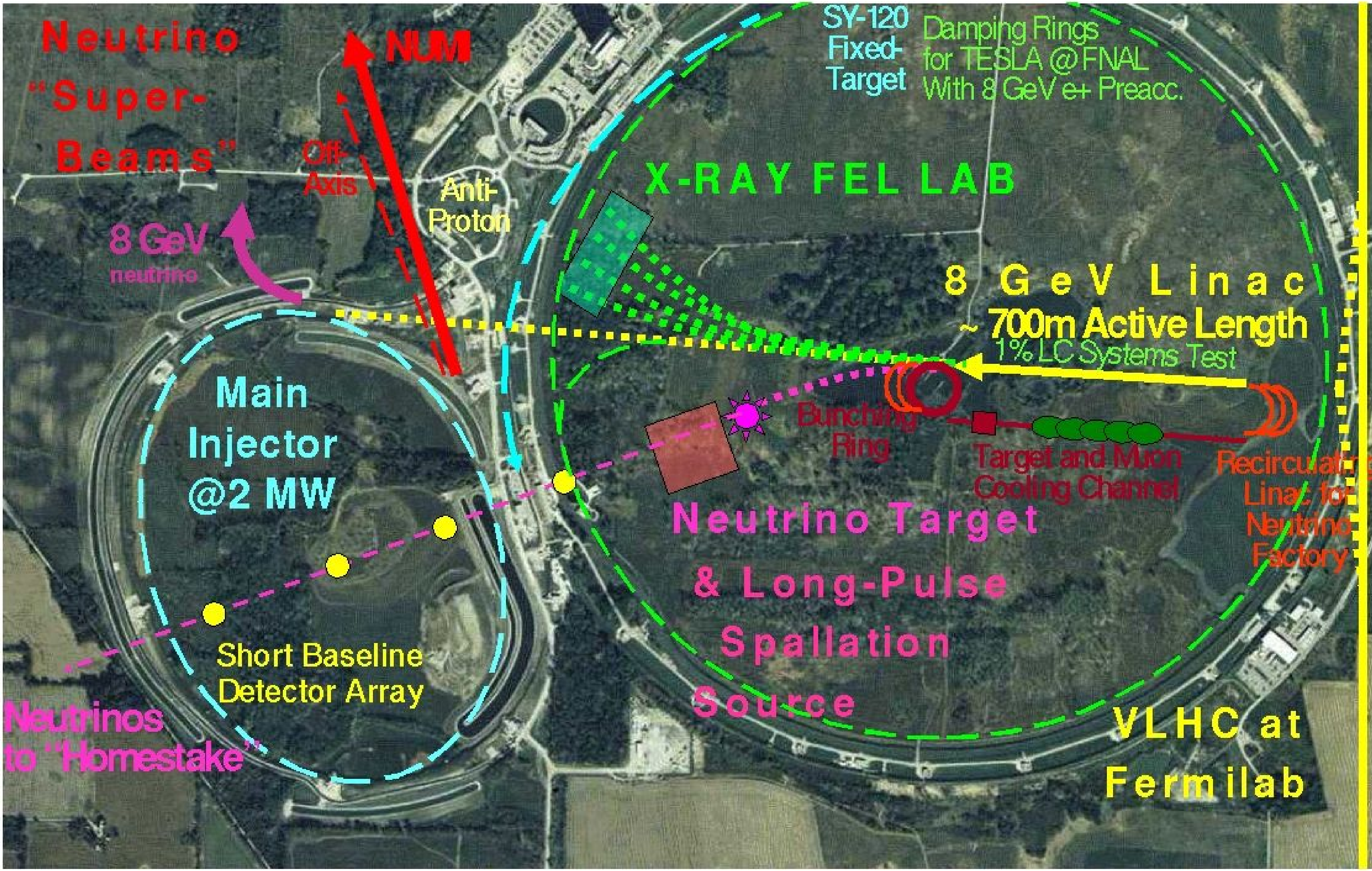


Upgrading proton intensity at Fermilab

Currently on track to get to intensity to 2.5×10^{20} protons/year this year

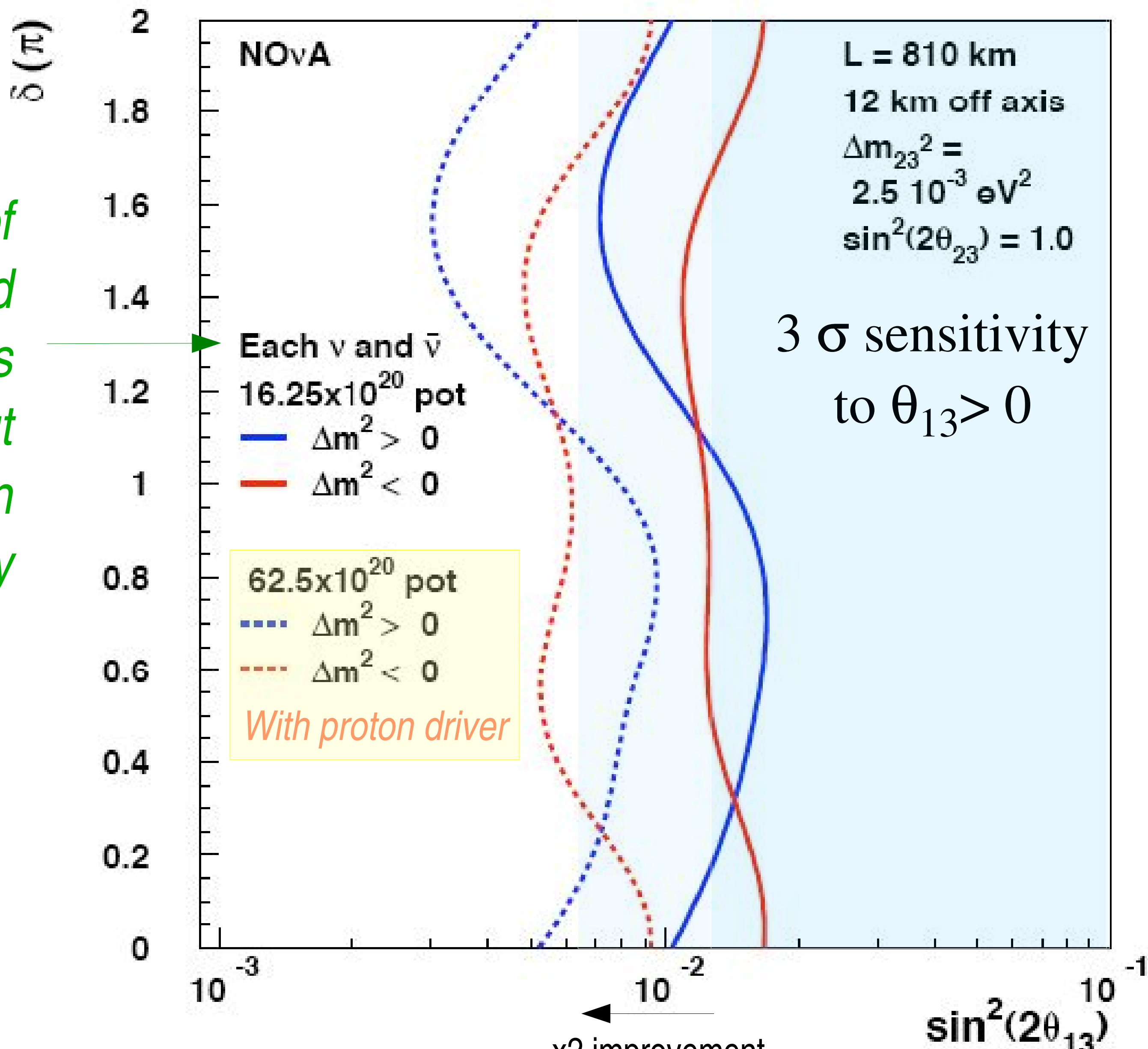
- Measures while running collider
  - 9 of 11 Booster batches for NuMI
  - Decrease repetition rate to 2.2 s
  - Reduce shot setup time to 10% for collider and 5% for p-bar
  - ☛ 3.4×10^{20} protons/year
- Post-collider
  - 11 of 11 Booster batches for NuMI
  - Reduce cycle time to 1.5 s using recycler
  - Improve duty factor: no shot setups
  - ☛ 7.3×10^{20} protons/year. Negotiated rate is 6.5×10^{20} protons/year
- Proton driver boosts this a factor ~4-5 to 25×10^{20} protons/year

Possibilities for new proton driver at Fermilab



NOvA sensitivity with proton driver

Mixture of neutrinos and anti-neutrinos evens out variations in sensitivity



x2 improvement in sensitivity

Gary Feldman WIN'05

"Super-NOvA?" Add 2nd detector at short baseline

30kt liquid scintillator NOvA detector

Add 50kt Liquid Argon detector?

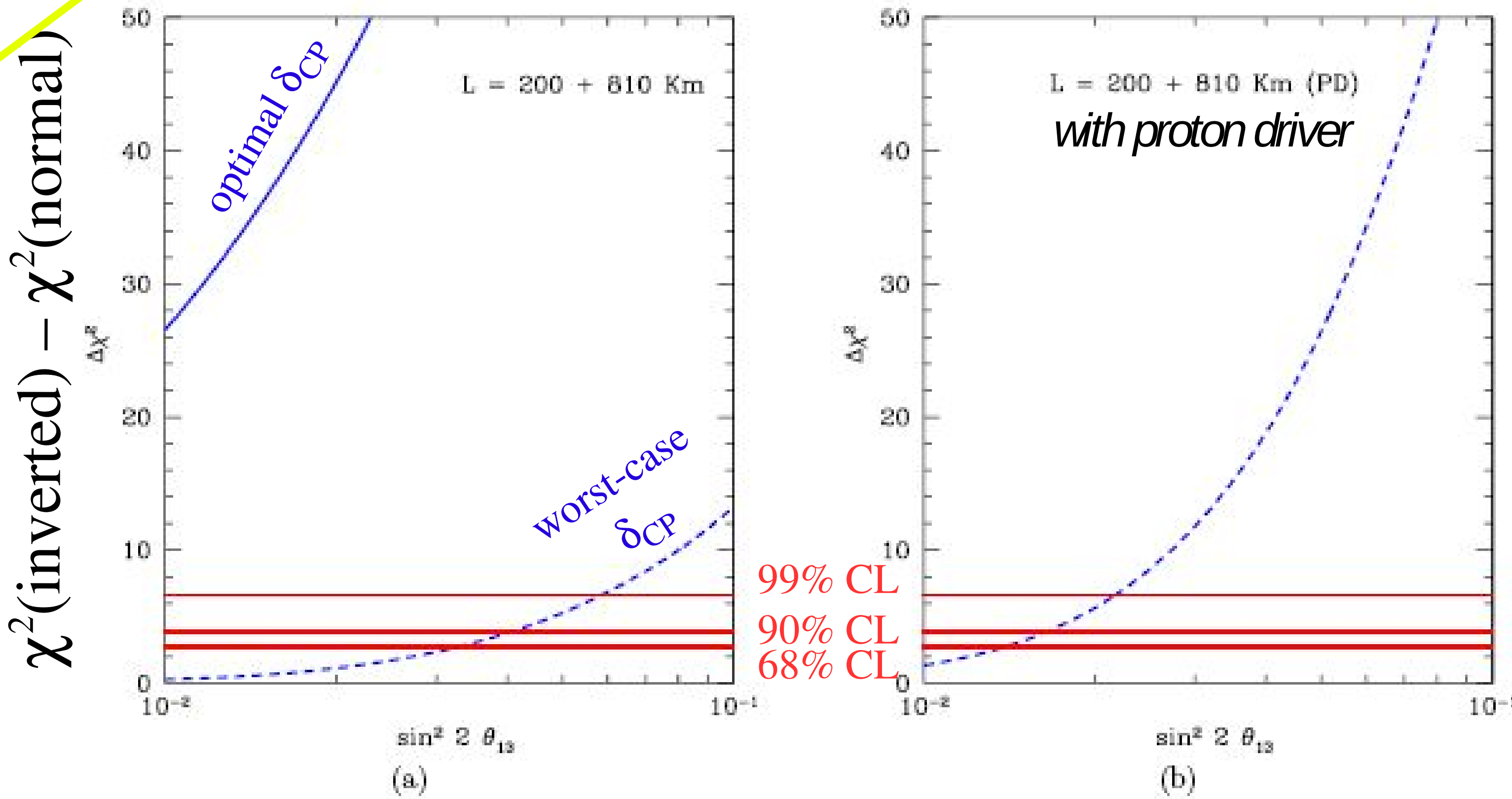


FIG. 6: *(a) Results of the* χ^2 *analysis to the sign of the atmospheric mass difference extraction versus* $\sin^2 2\theta_{13}$*, by exploiting the data from a far long-baseline experiment at 810 km and from a short-baseline experiment at 200 km, for* $|\Delta m^2_{31}| = 2.4\times10^{-3}$ eV^2*. The corresponding 90%, 95% and 99% C.L.s are shown. As a function of* $\sin^2 2\theta_{13}$*, we depict the maximum (solid line) and minimum (dashed line) of* $\Delta\chi^2$*, which are obtained for different values of* δ *depending on* $\sin^2 2\theta_{13}$*. (b) Same as (a) but with a Proton Driver.*

Meno, Palomares-Ruiz, Pascoli, hep-ph/0504015

Letter of Intent

FLARE

Fermilab Liquid ARgon Experiments

Version 1.0

August 23, 2004

Bartoszek Eng. - Duke - Indiana - Fermilab - LSU - MSU -
Osaka - Pisa - Pittsburgh - Princeton - Silesia South Carolina - Texas A&M -
Tufts - UCLA - Warsaw University -
INS Warsaw - Washington - York-Toronto

Build small prototype LAr detector
at Fermilab.

Ultimate goal: 50 kt LAr detector

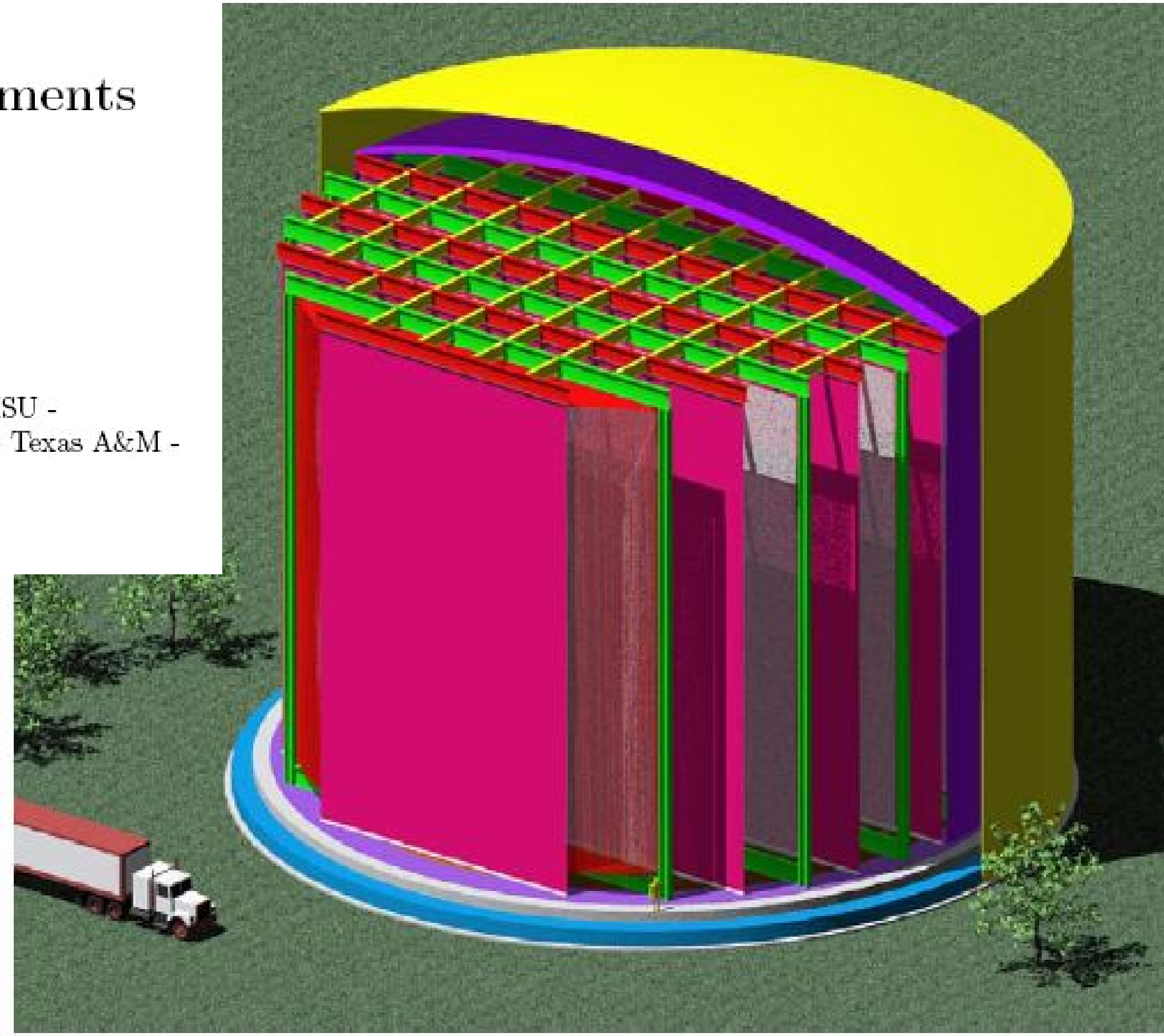
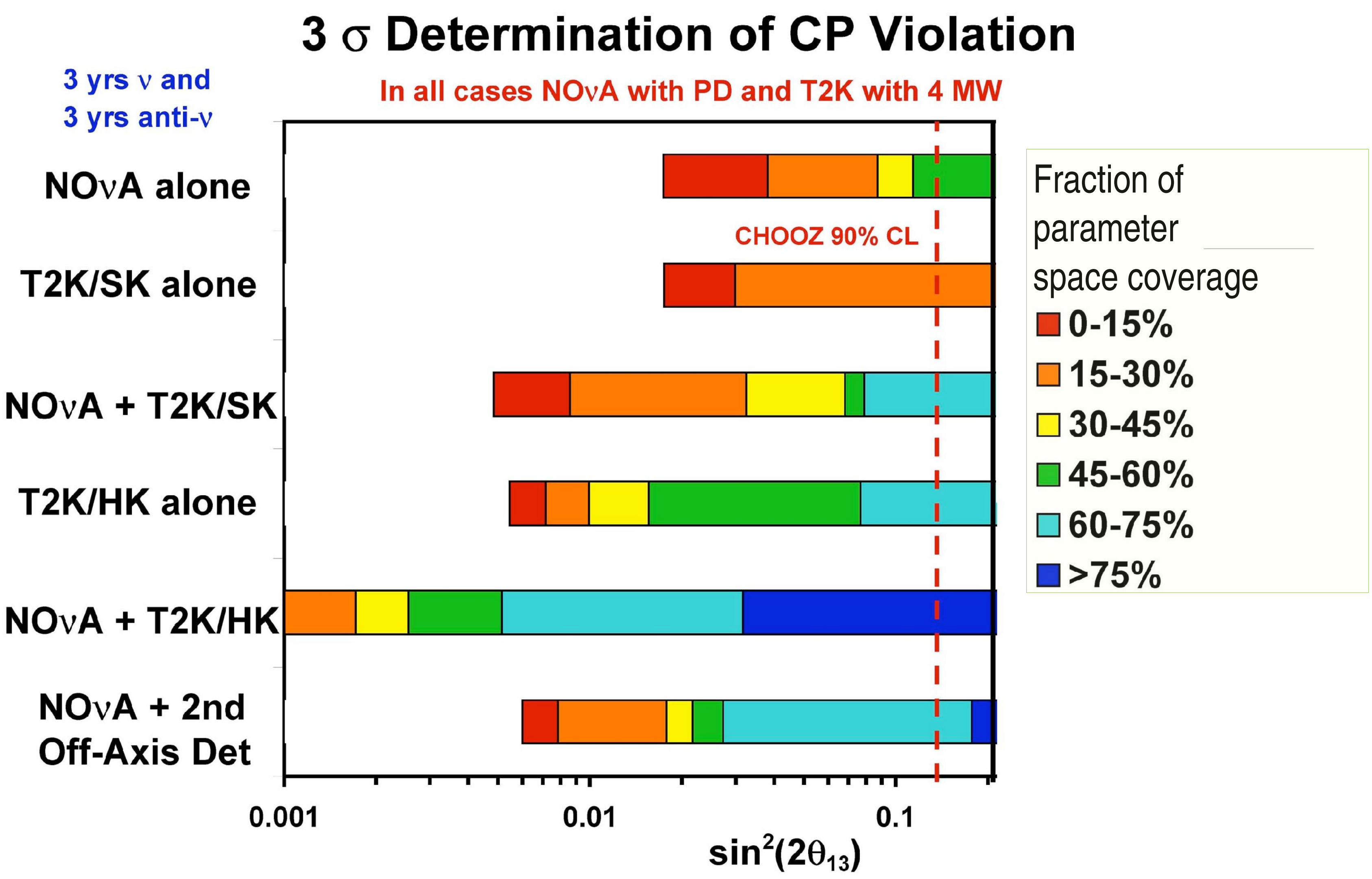
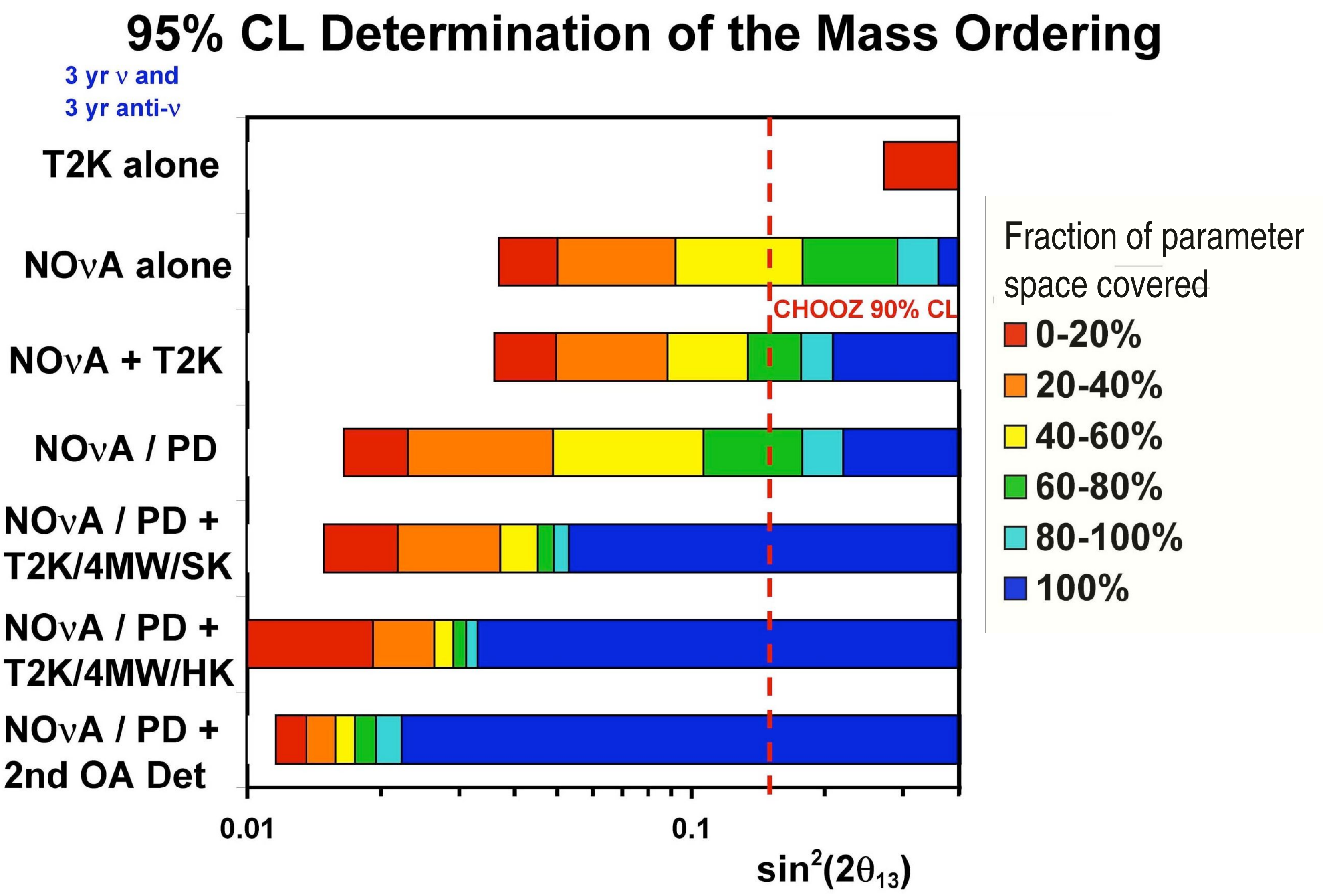


Figure 5.3: Overview of the detector inside the tank. Green planes are the wire chambers, cathode planes are in pink, field shaping frames are red (only one set is shown for clarity) . Most of the volume is free of instrumentation and it is filled with liquid argon. [Bartoszek Engineering]

Search for CP violation



Mass Hierarchy

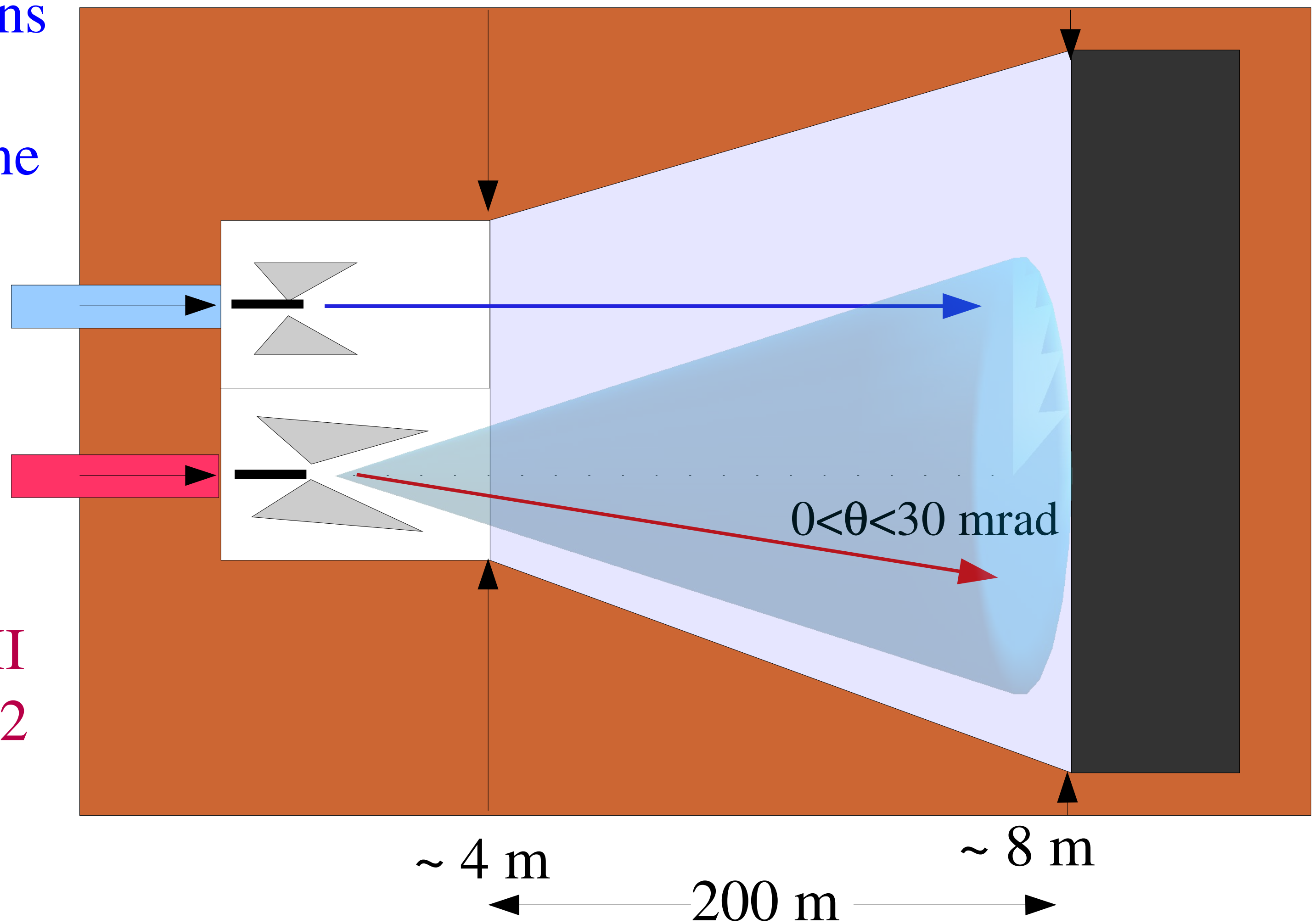


Gary Feldman WIN'05

“FeHo” (Fermilab to Homestake) Concept

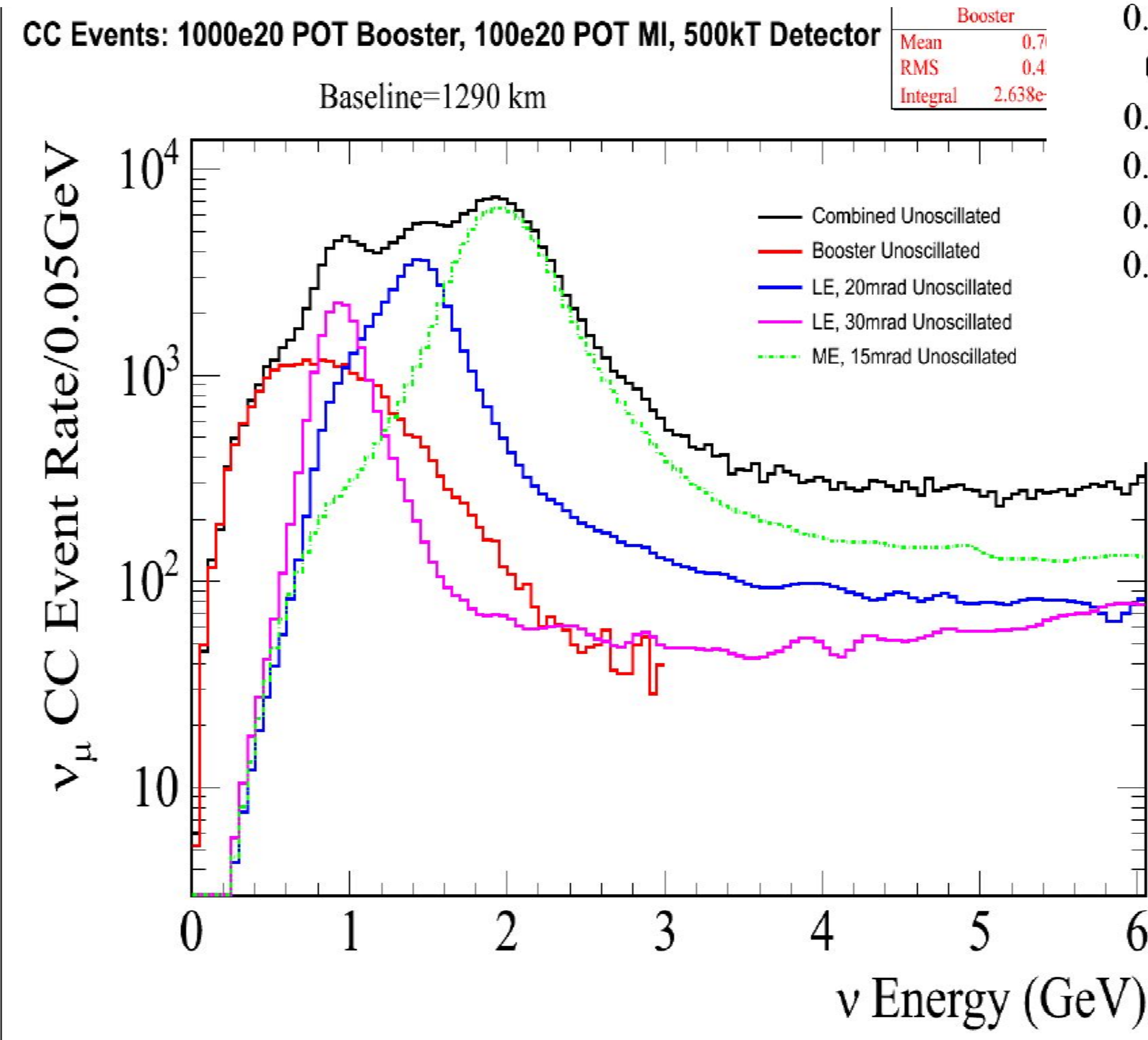
8 GeV protons from new extraction line @ 2 MW

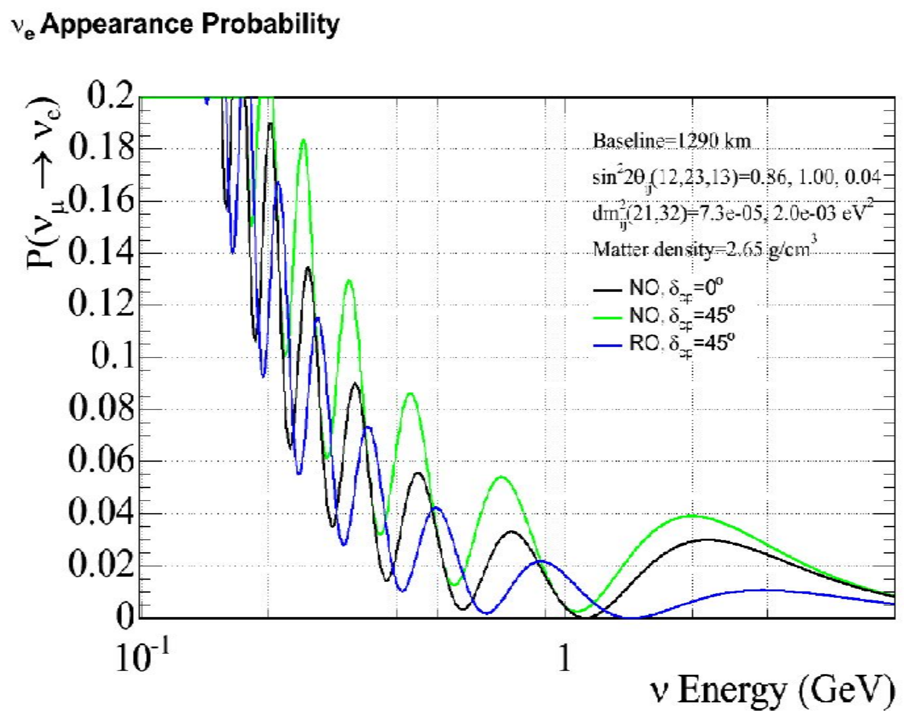
120 GeV protons from existing NuMI extraction @ 2 MW



Doug Michael
APS Workshop 13 May 2004

FeHo neutrino event rates



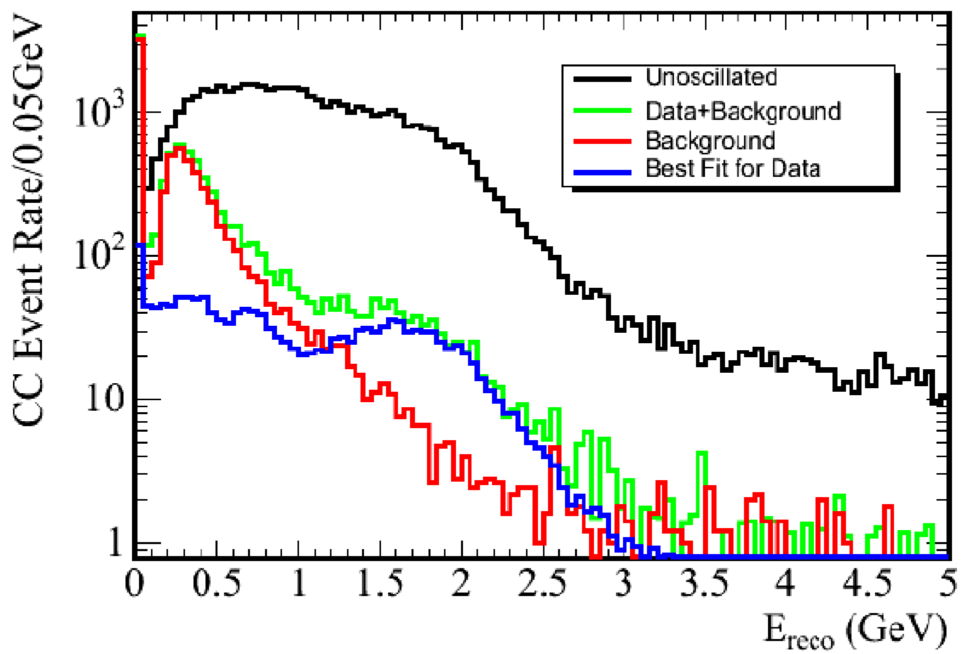


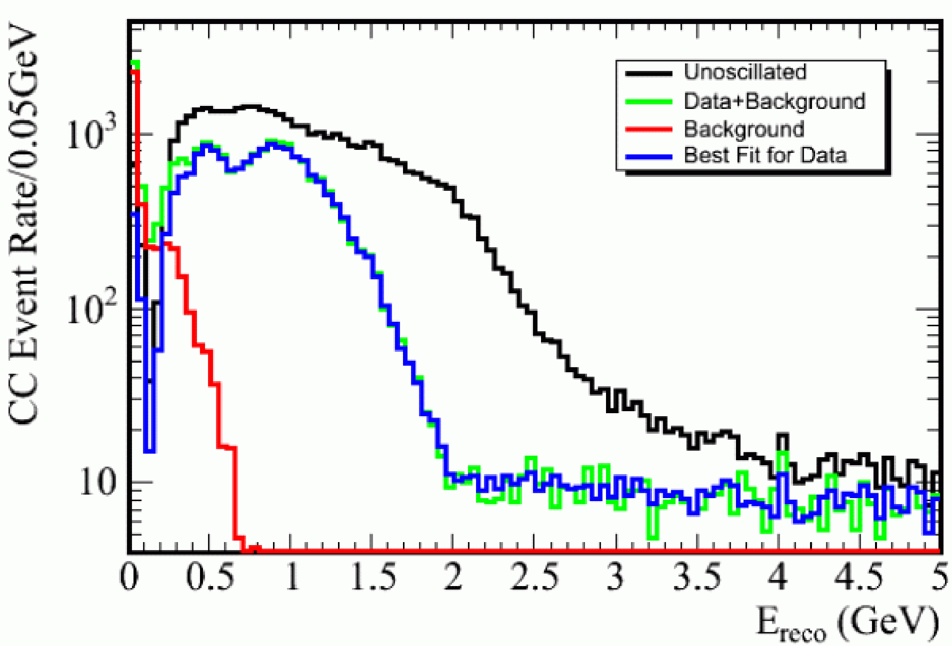
8 GeV and 120 GeV lines based on existing miniBooNE and NuMI lines

Combines advantages of both wide (wide L/E range) and narrow band beams (background rejection)

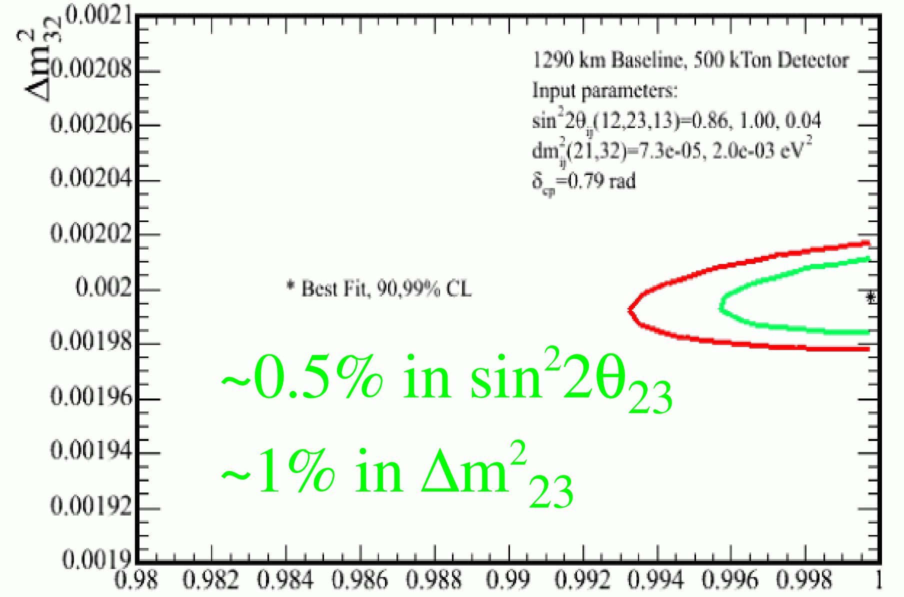
FeHo Performance with 0.5 Mton Water Cherenkov detector

QE CC Reconstructed Energy Spectra

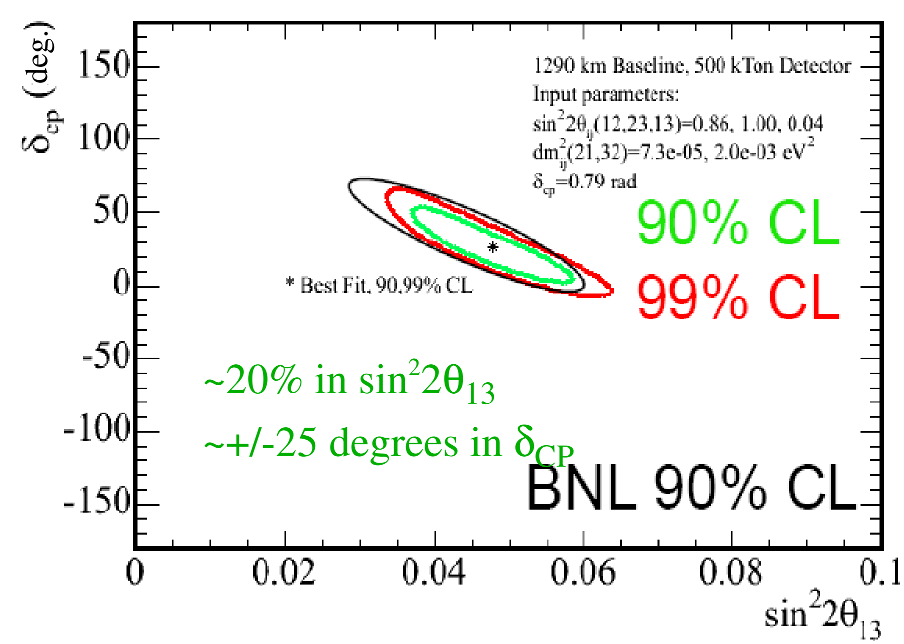




Confidence Levels

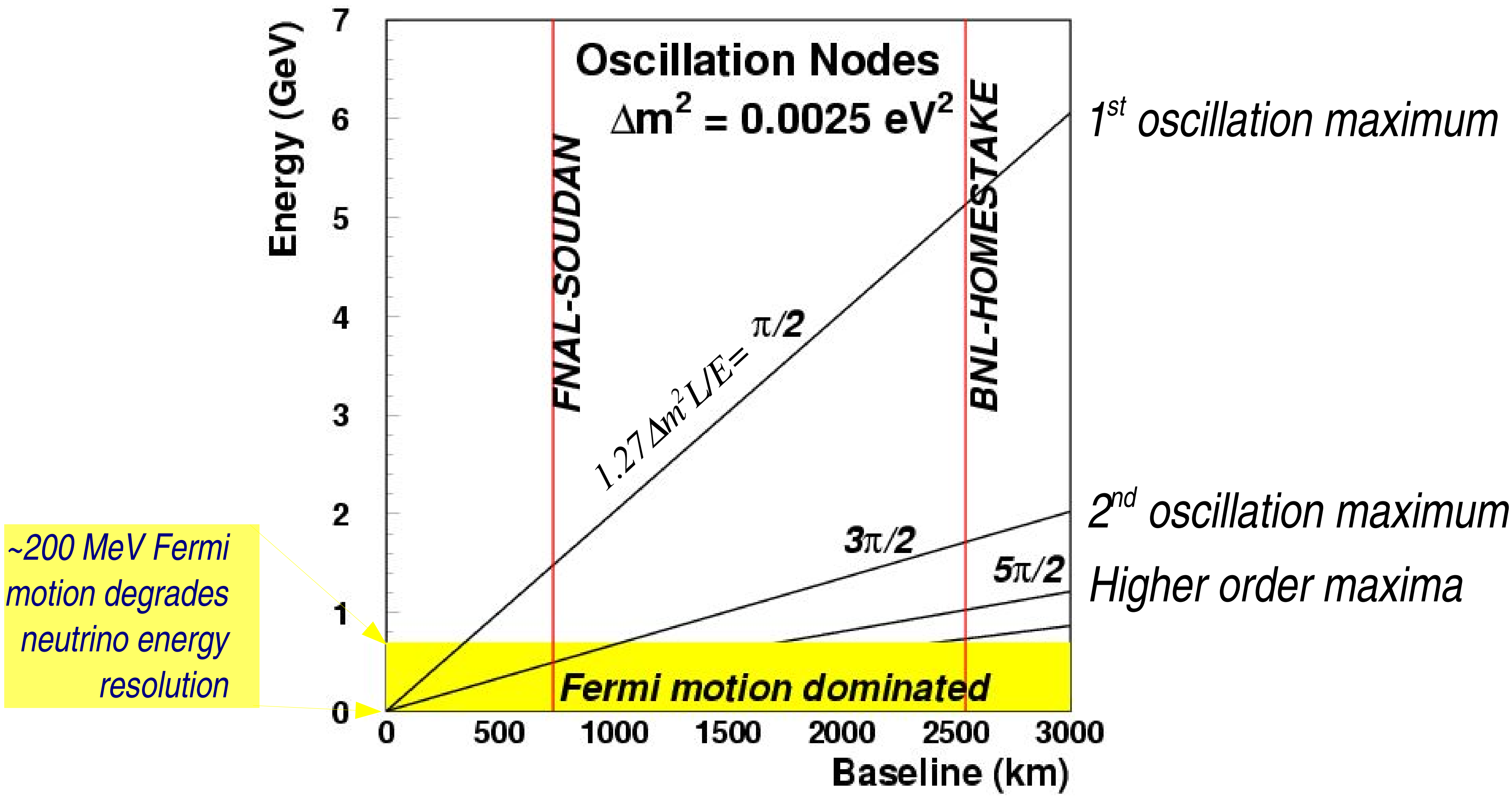


Confidence Levels



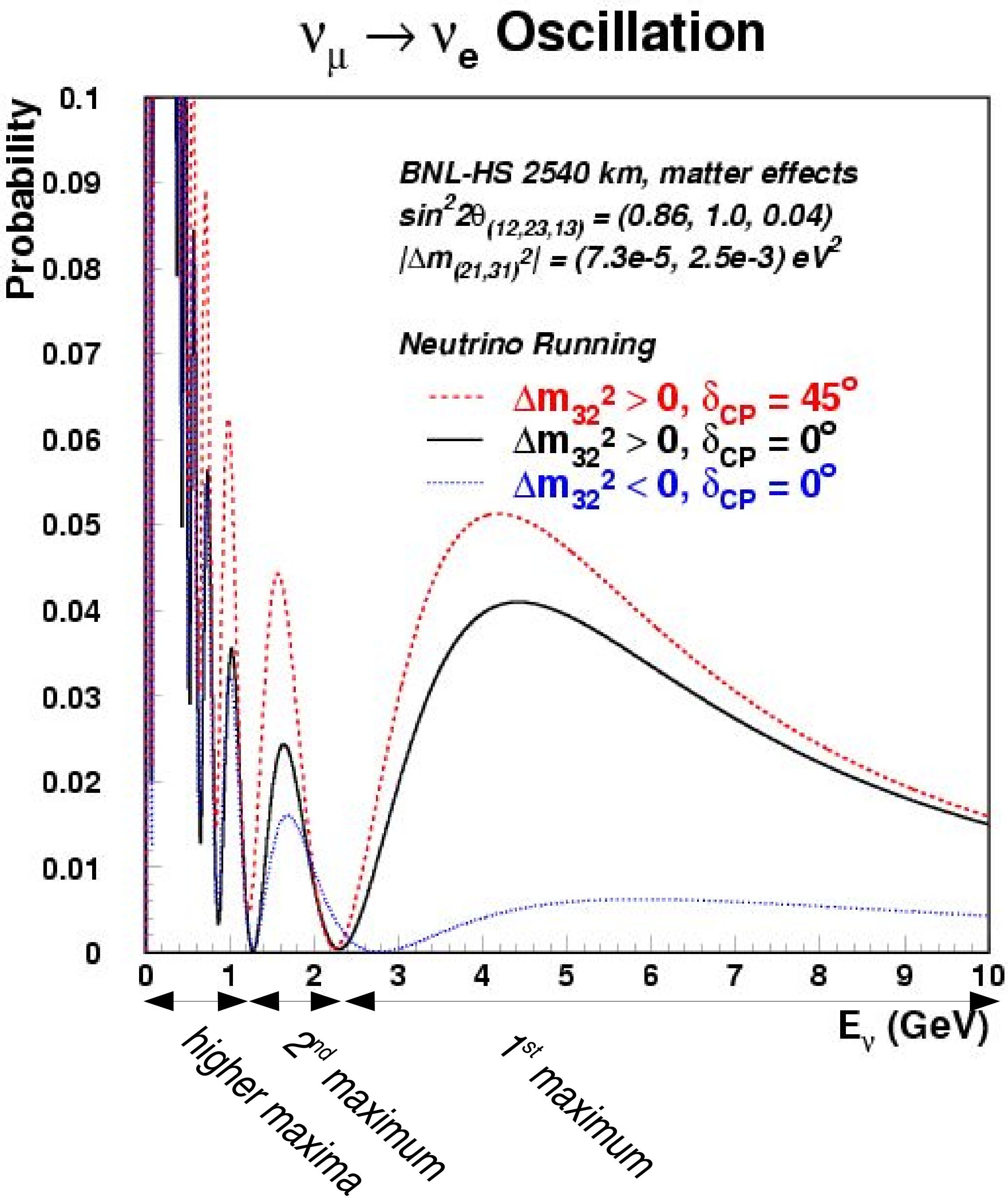
In ~2015 perhaps large liquid Argon may be best detector choice?

The "very" long baseline idea



- Very long baseline moves 2^{nd} oscillation maximum to an energy where it can be resolved
- Matter effect increases (needed for mass hierarchy determination)
- Larger CP asymmetry (~*L*) compensates for decreased statistics (~$1/L^2$)

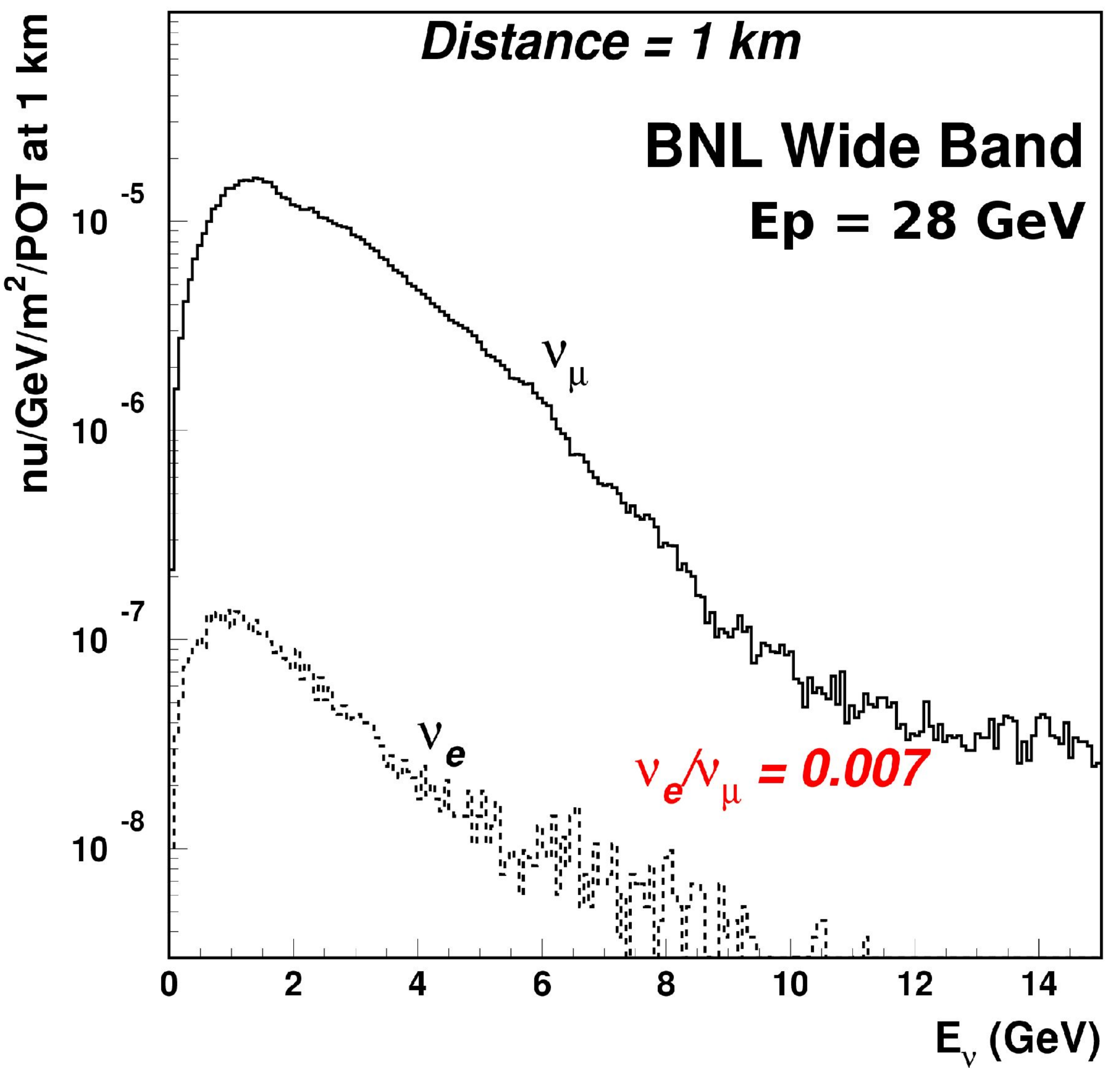
Oscillation probabilities BNL-Homestake



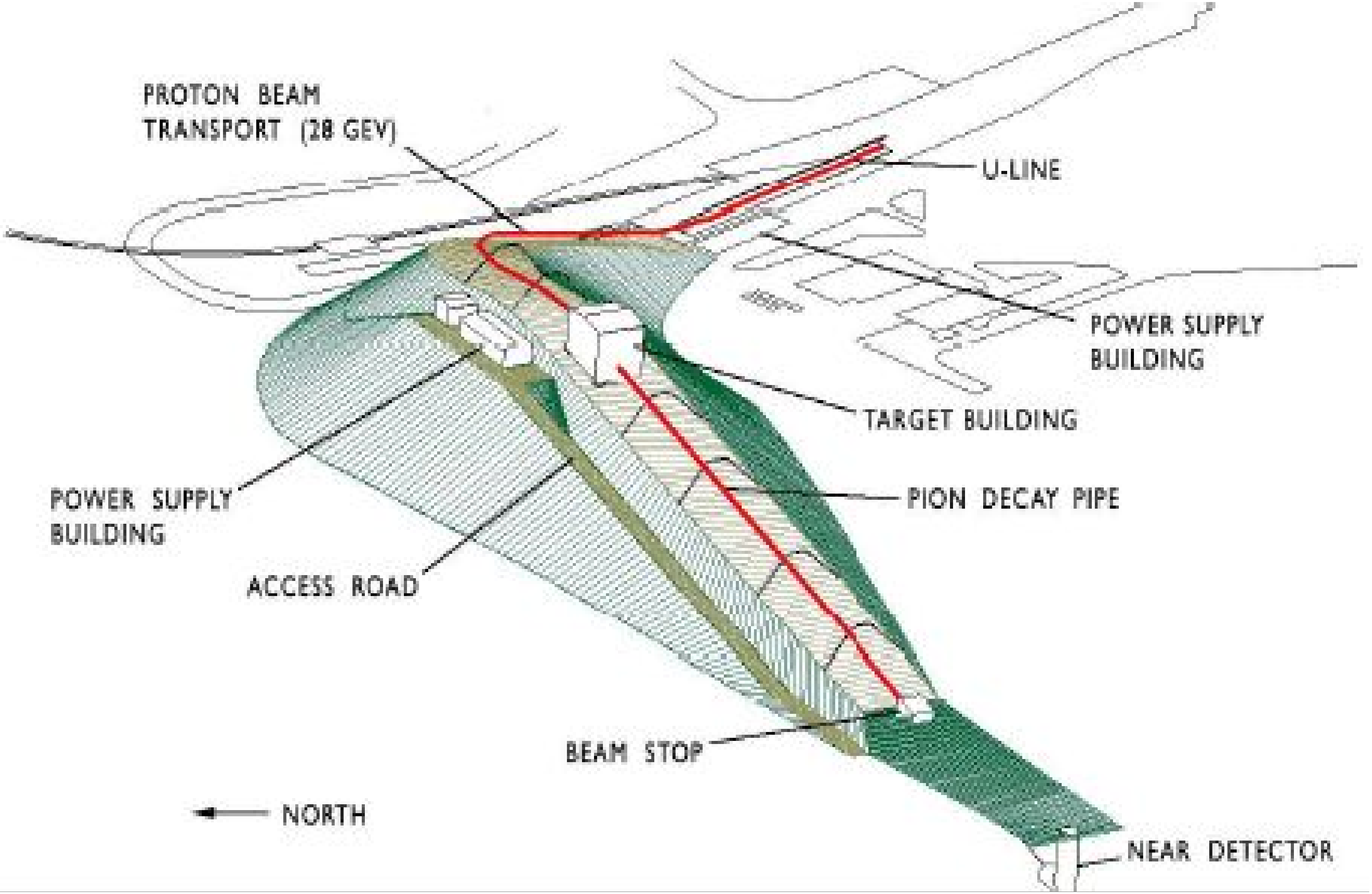
- *Use broad-band beam to cover three energy regions:*
  - All three regions contribute to θ_{13} measurement
  - 1st maximum sensitive to mass hierarchy
  - 2nd maximum has strong CP asymmetry
  - higher maxima sensitive to solar oscillations

Neutrino beam from upgraded AGS proton source

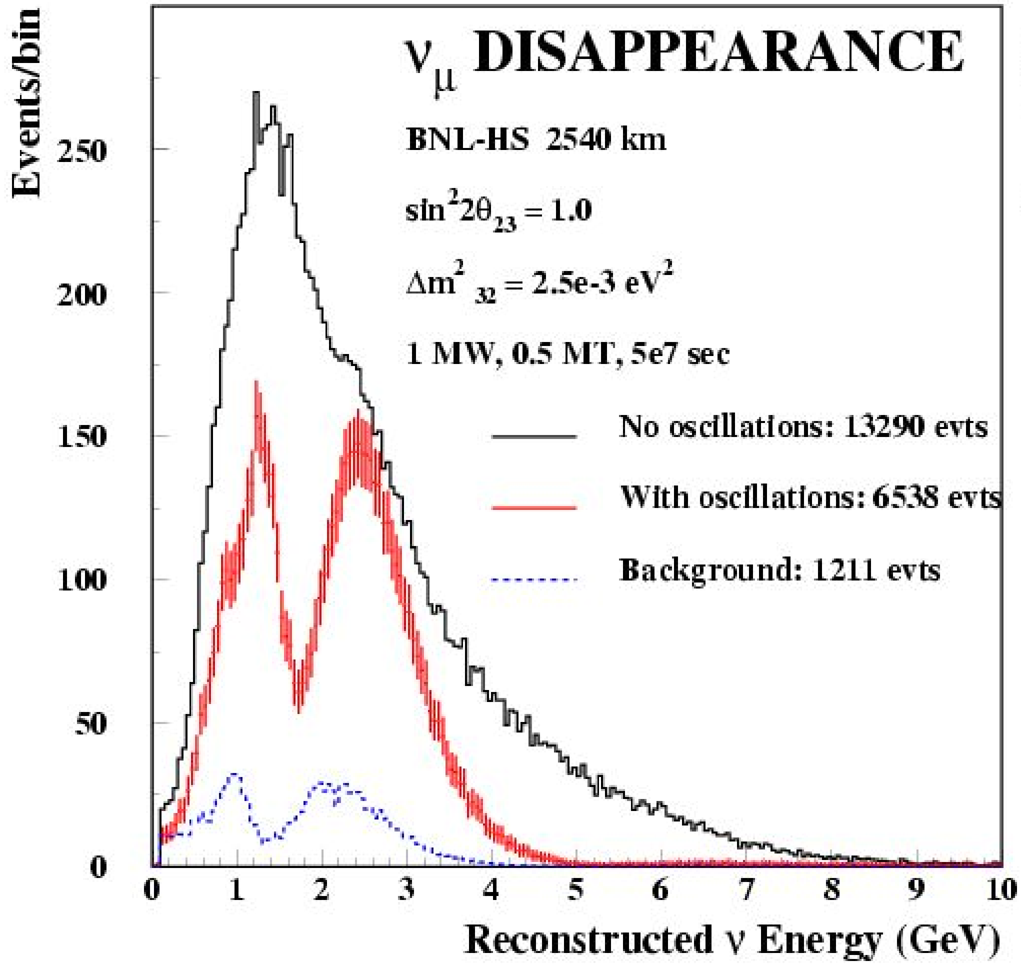
- *Upgrades to the AGS 28 GeV proton source from 0.14 MW to 1.0 MW:*
  - Modest increase from 7E13 protons per pulse to 9E13 protons per pulse
  - Factor 5 increase in repetition rate from 0.5 Hz to 2.5 Hz
    - New power supplies and RF
    - New 1 GeV superconducting linac
- $270M USD (w/o contingency)
- Estimated 6 year project

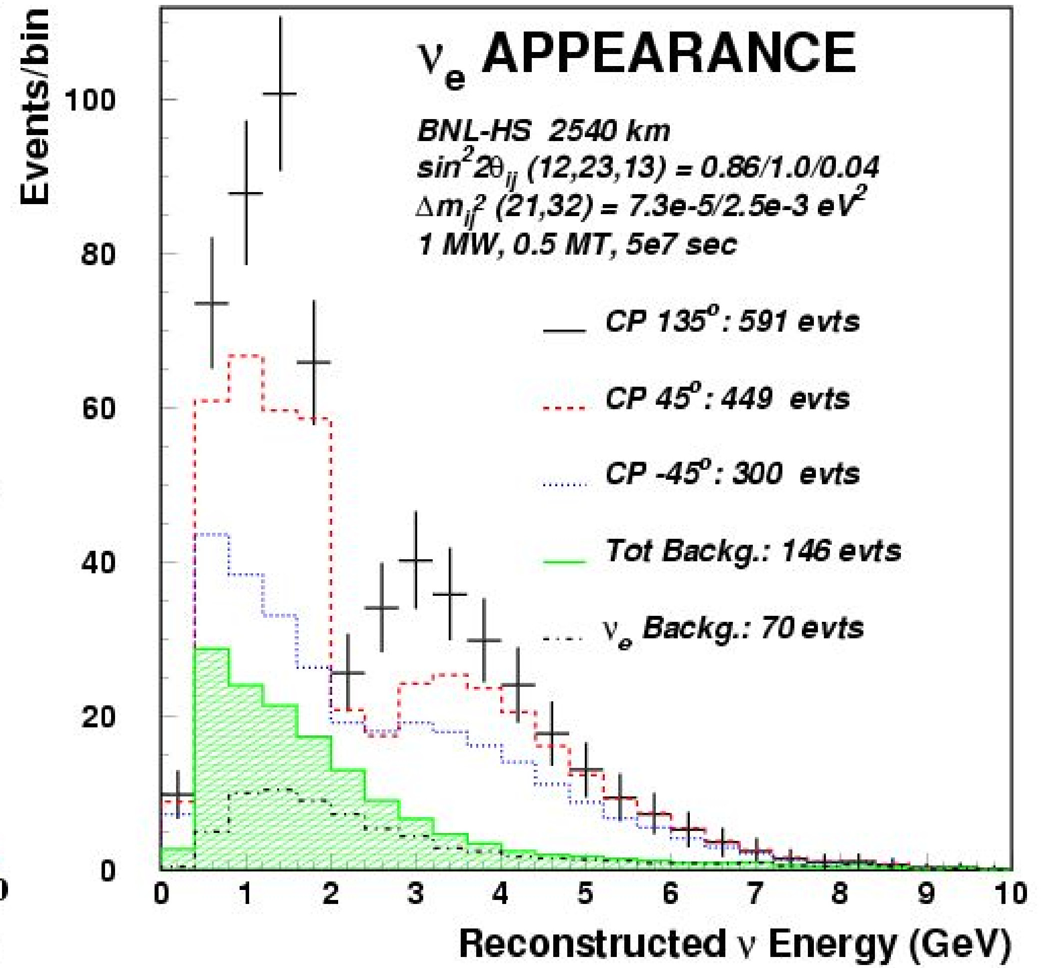


Proposed BNL-Homestake beam line



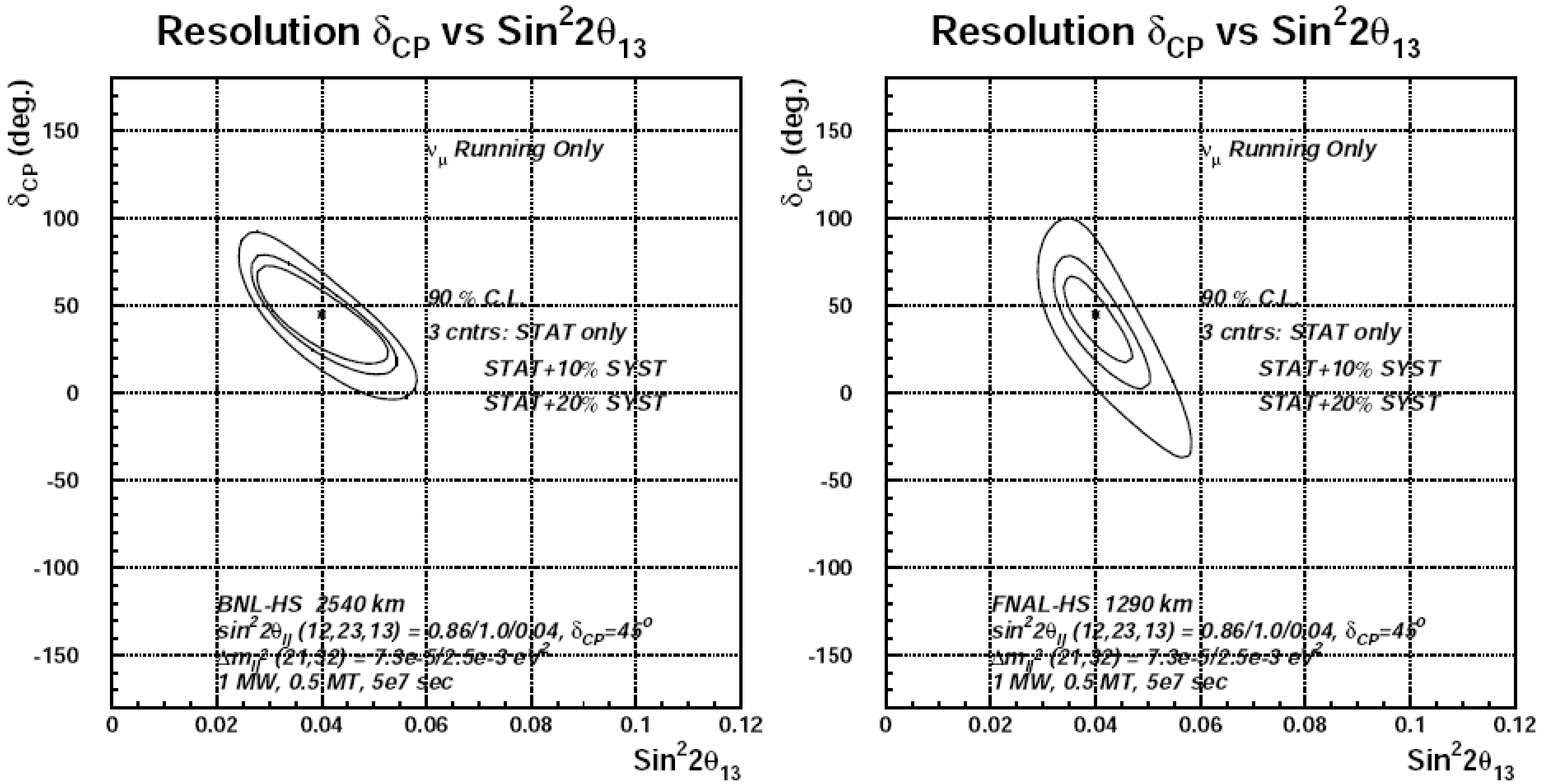
BNL-Homestake event spectra





BNL-Homestake (left) and FNAL-Homestake (right)

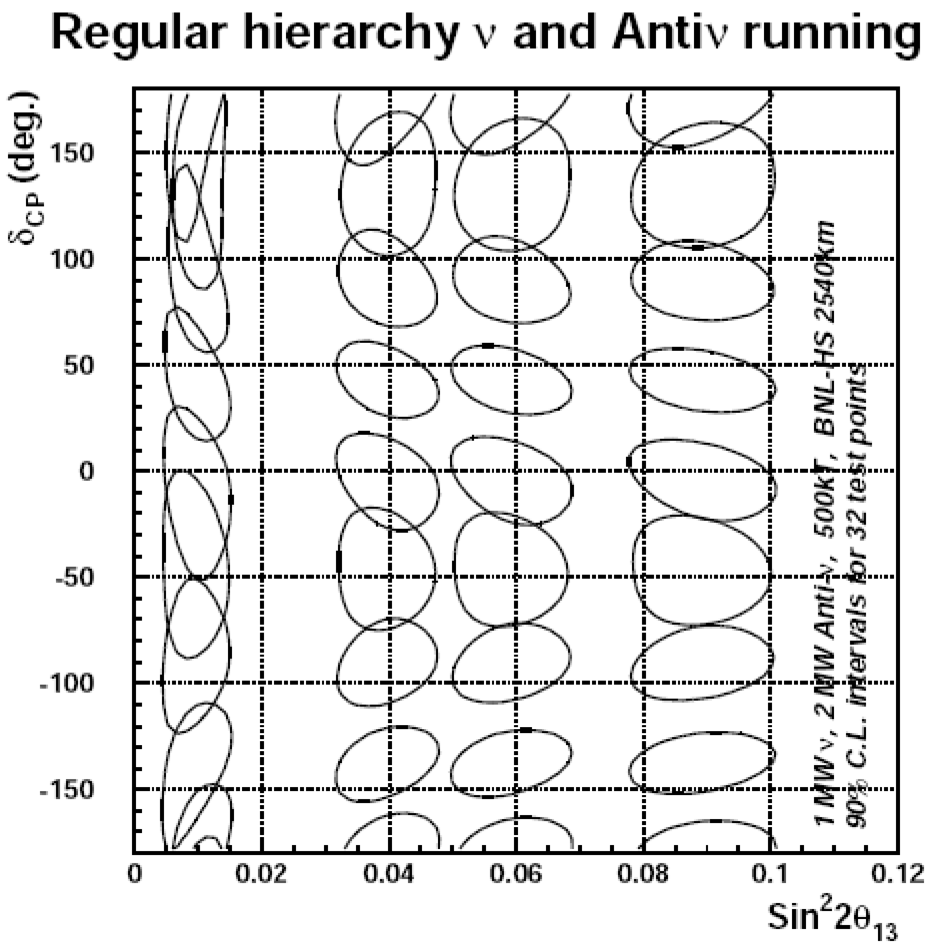
Limits for neutrino only run

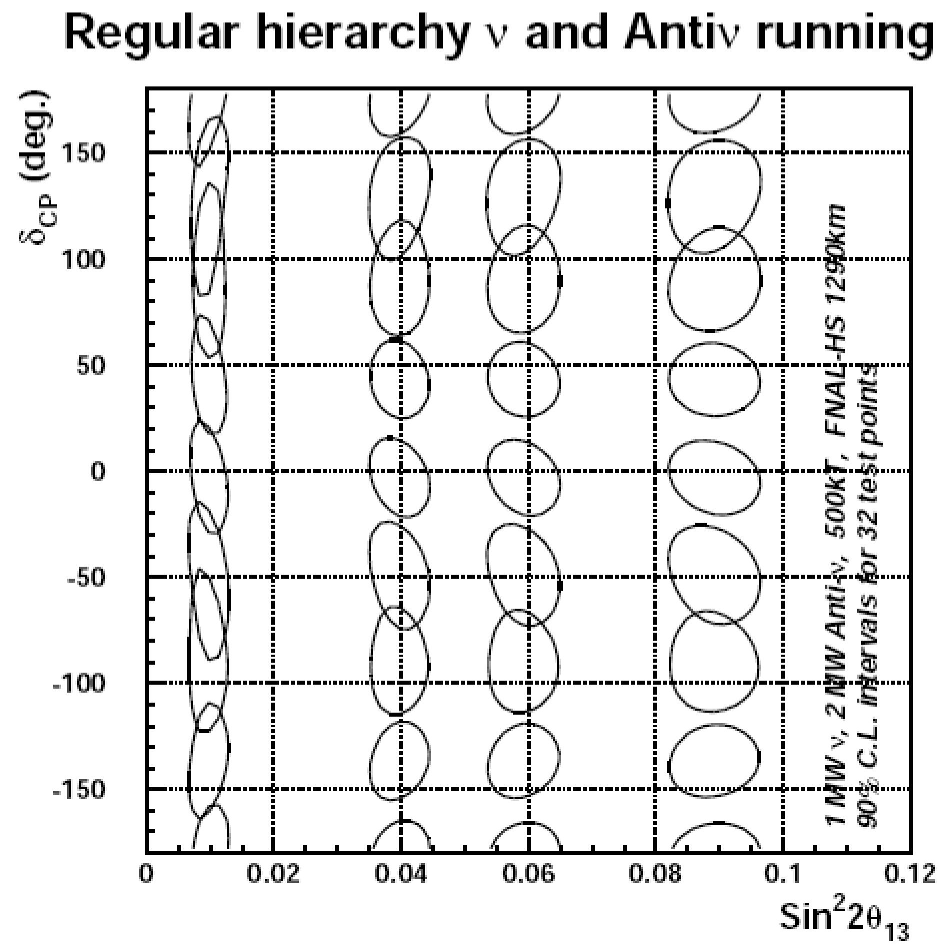


Diwan, hep-ex/0407047

BNL-Homestake (left) and FNAL-Homestake (right)

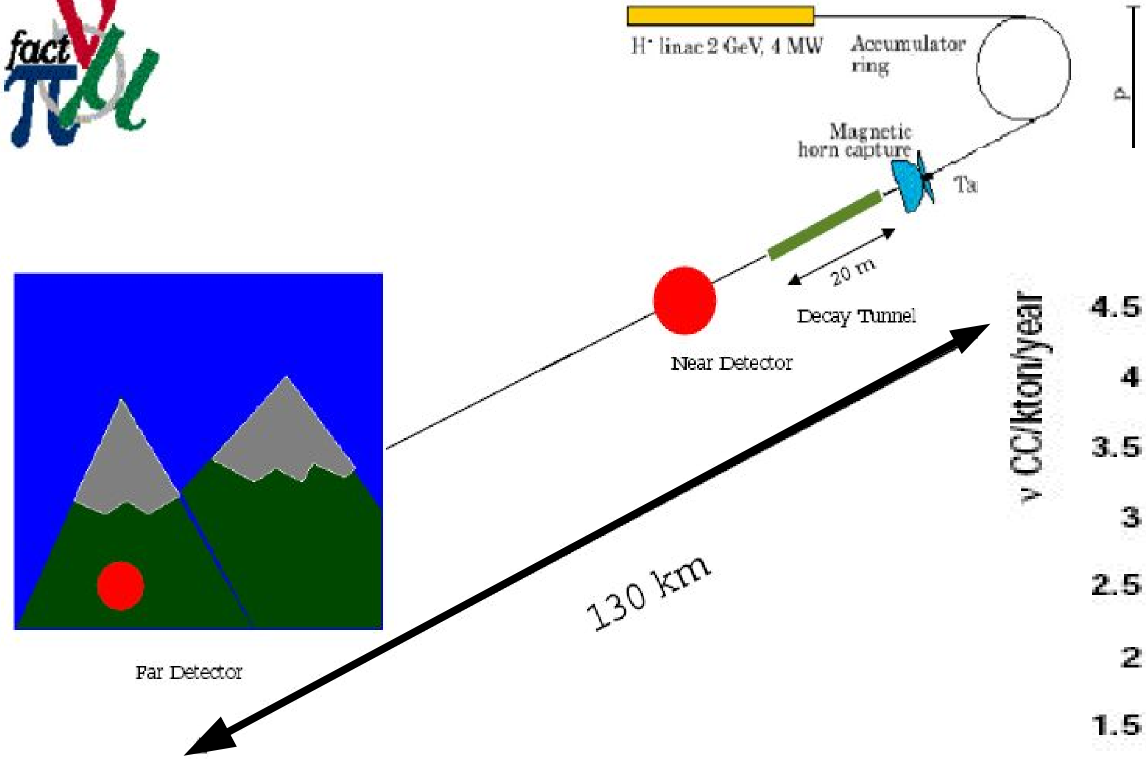
Limits for neutrino + anti-neutrino run





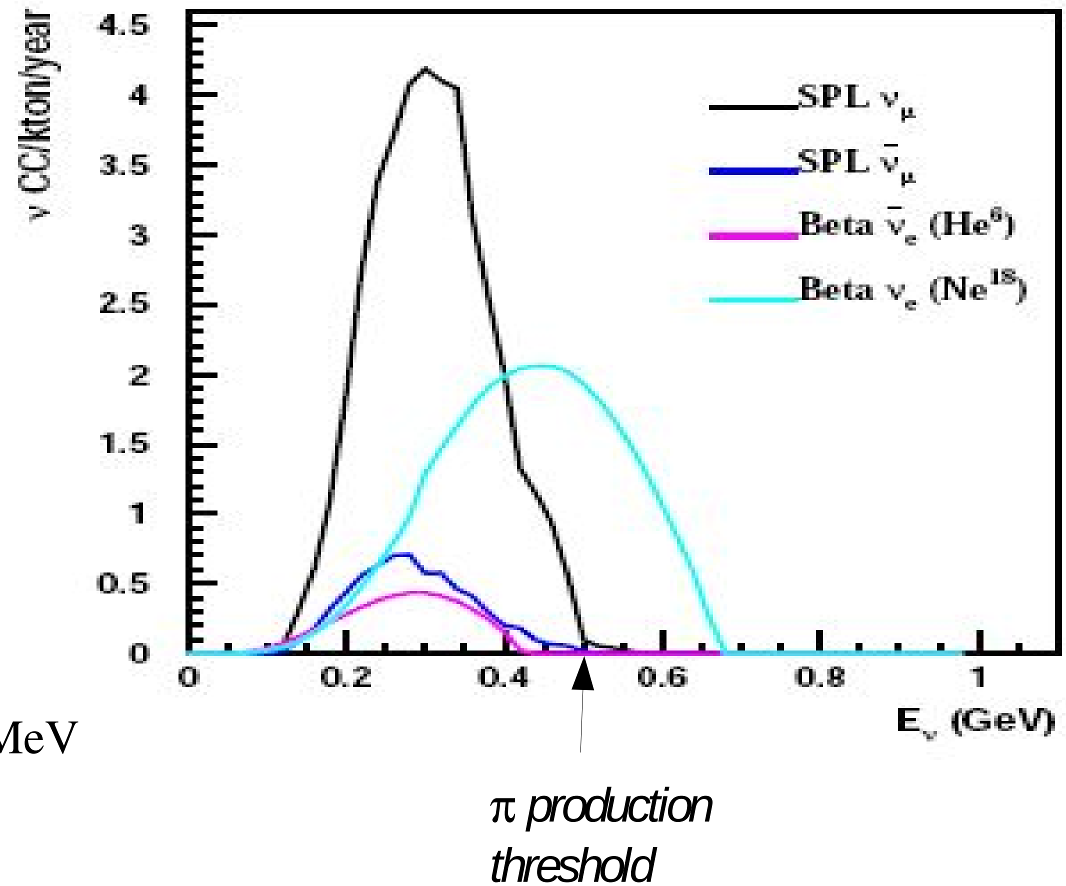
Diwan, hep-ex/0407047

SPL-Frejus



Possible Low Energy Super Beam Layout

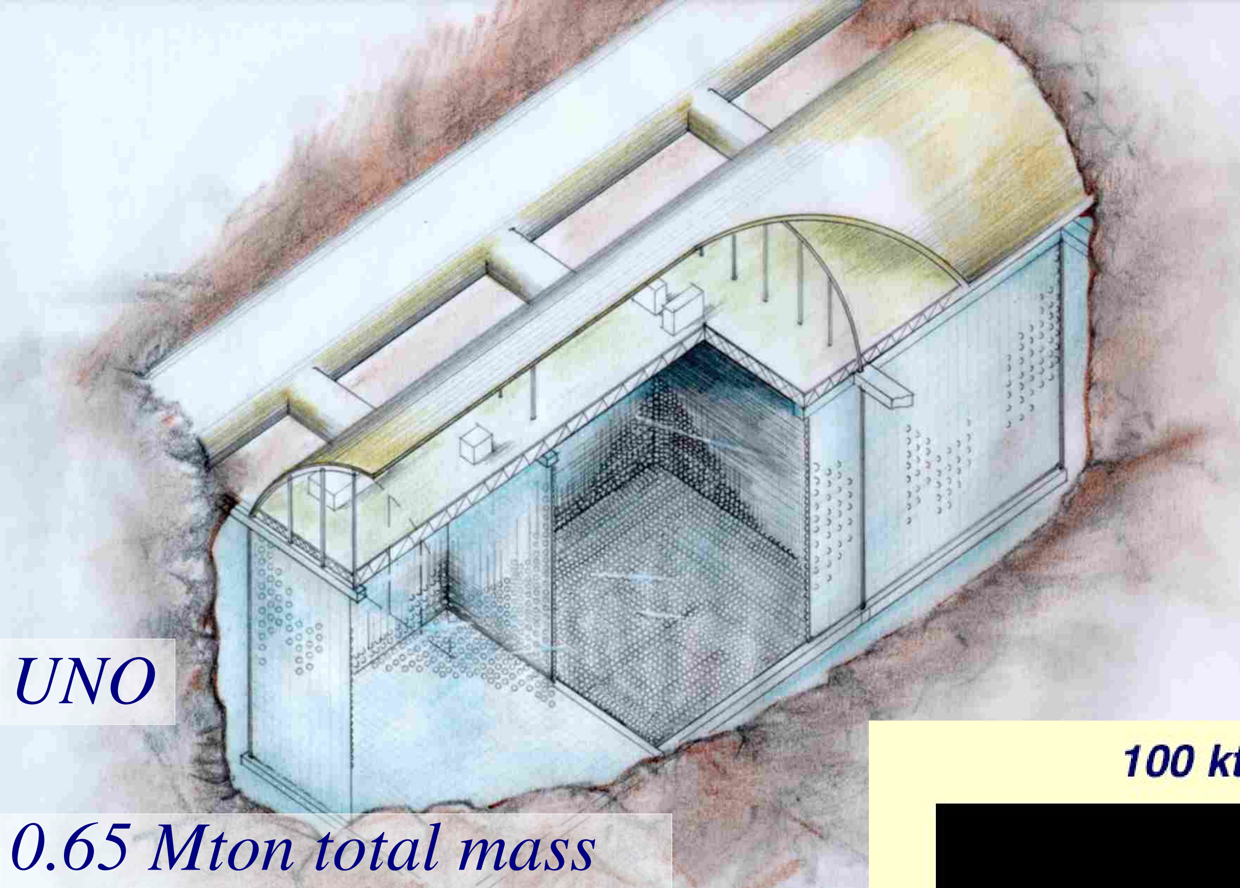
CC Rates

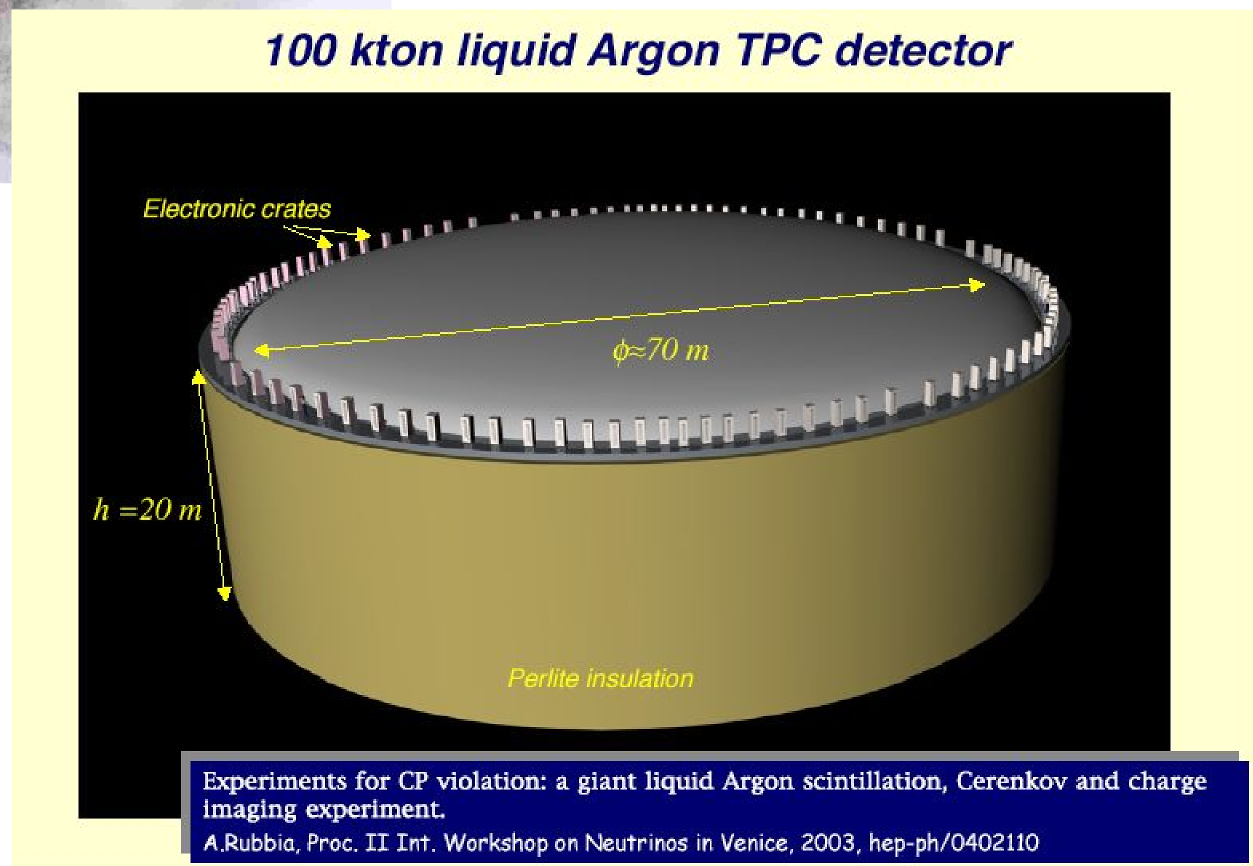


- 4 MW superconducting LINAC @CERN
- 2.2 GeV protons
- Wide band neutrino beam peaked near 270 MeV
- Target in Frejus tunnels at L=130 km
- Short baseline: small matter effect
- Target θ_{13} and CPV measurements
- Forerunner to beta-beam and ν-factory

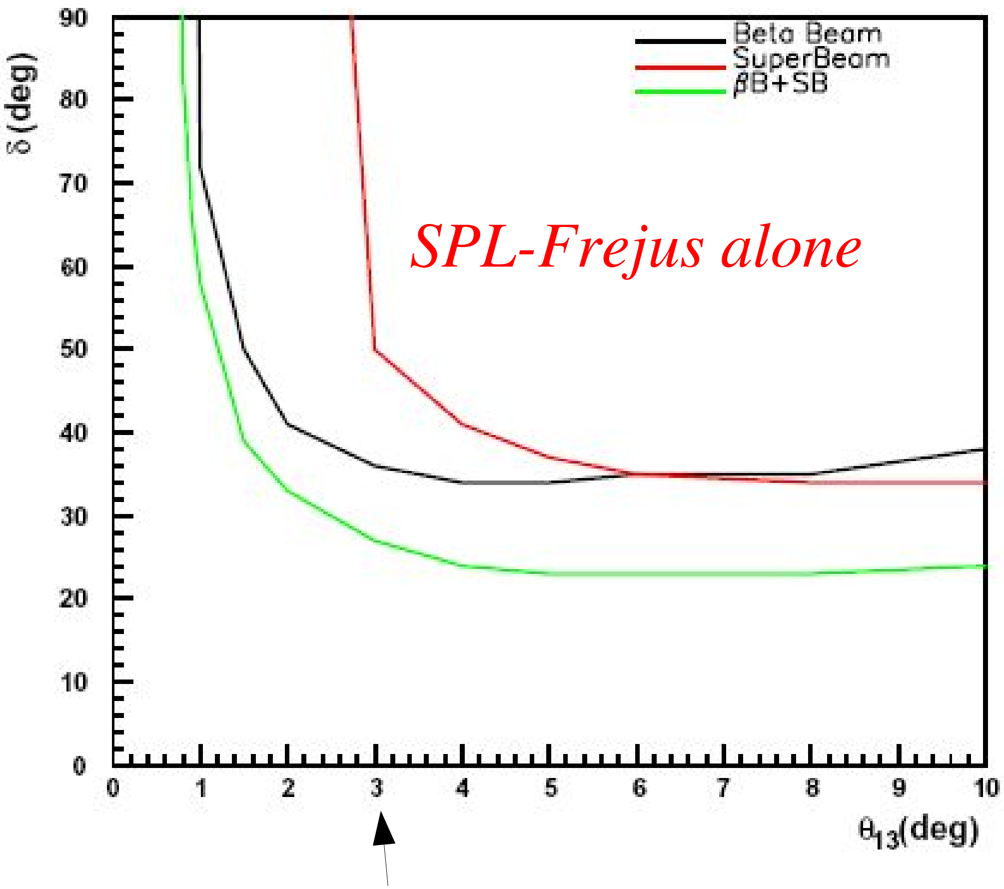
	Fluxes @ 130 km $\nu/m^2/yr$	$<E_\nu>$ (GeV)	CC rate (no osc) events/kton/yr	$<E_\nu>$ (GeV)	Years	Integrated events (440 kton × 10 years)
			SPL Super Beam			
ν_μ	$4.78 \cdot 10^{11}$	0.27	41.7	0.32	2	36698
$\overline{\nu}_\mu$	$3.33 \cdot 10^{11}$	0.25	6.6	0.30	8	23320

Detector options

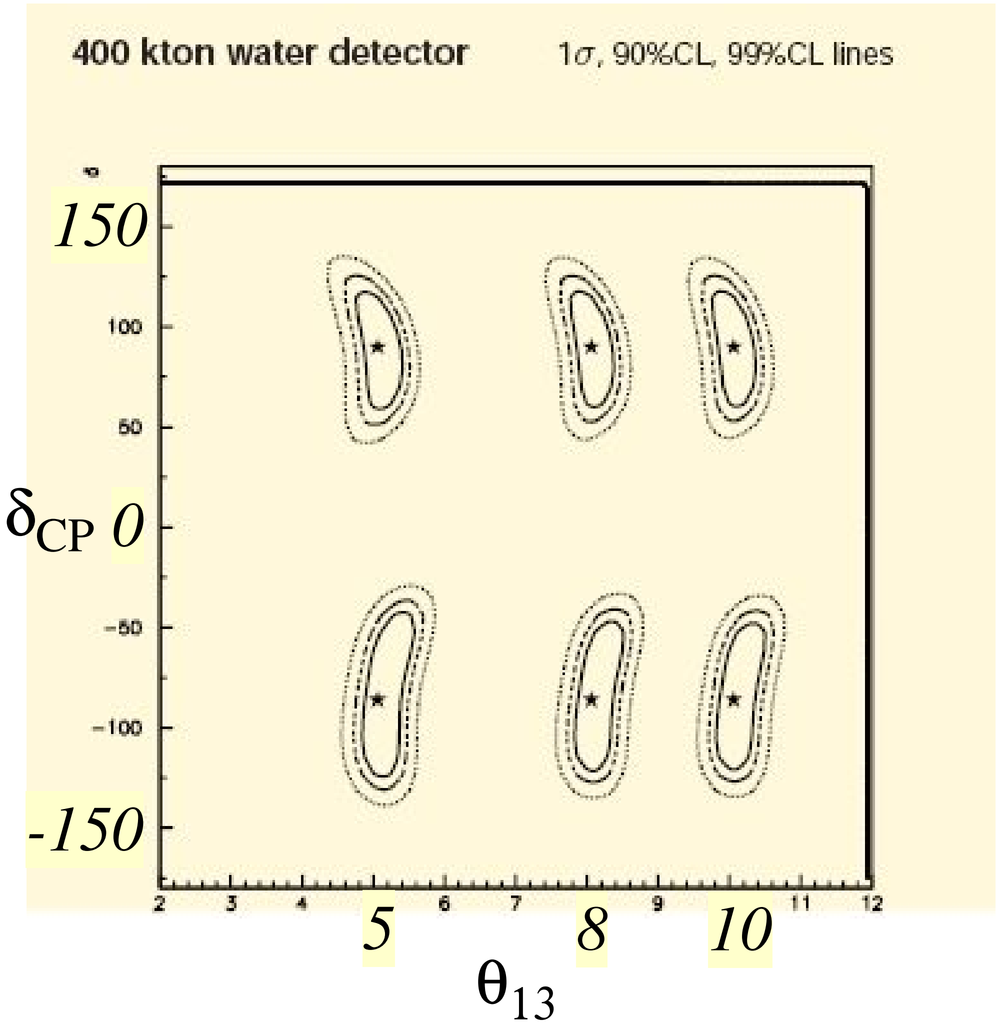


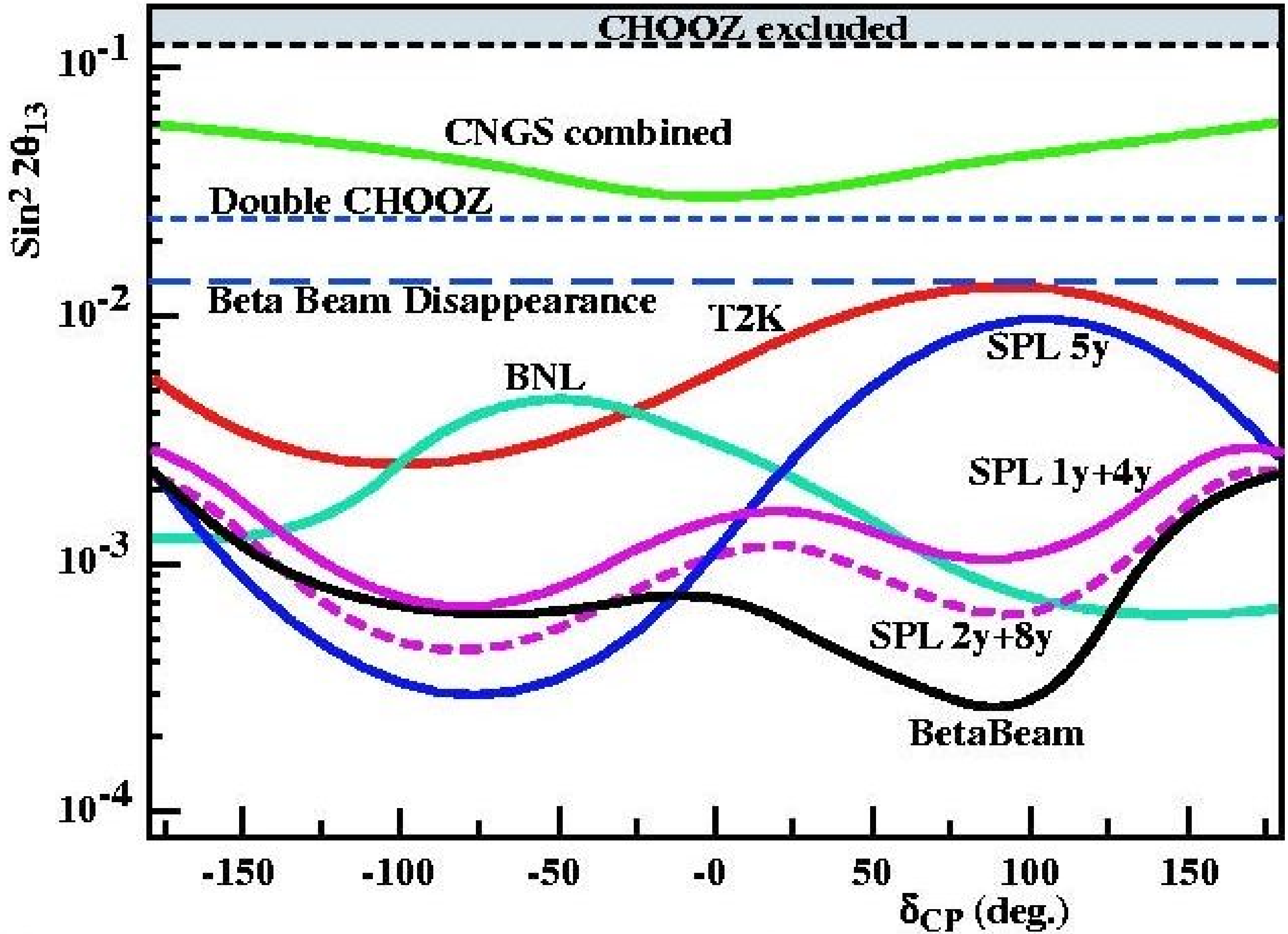


SPL CPV Sensitivities



$\sin^2 2\theta_{13} = 0.01$





CHOOZ excluded
CNGS combined
Double CHOOZ
Beta Beam Disappearance
T2K
SPL 5y
BNL
SPL 1y+4y
SPL 2y+8y
BetaBeam
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\sin^2 2\theta_{13}$
-150
-100
-50
-0
50
100
150
δ_{CP} (deg.)

Time line for SPL-Frejus: 2015

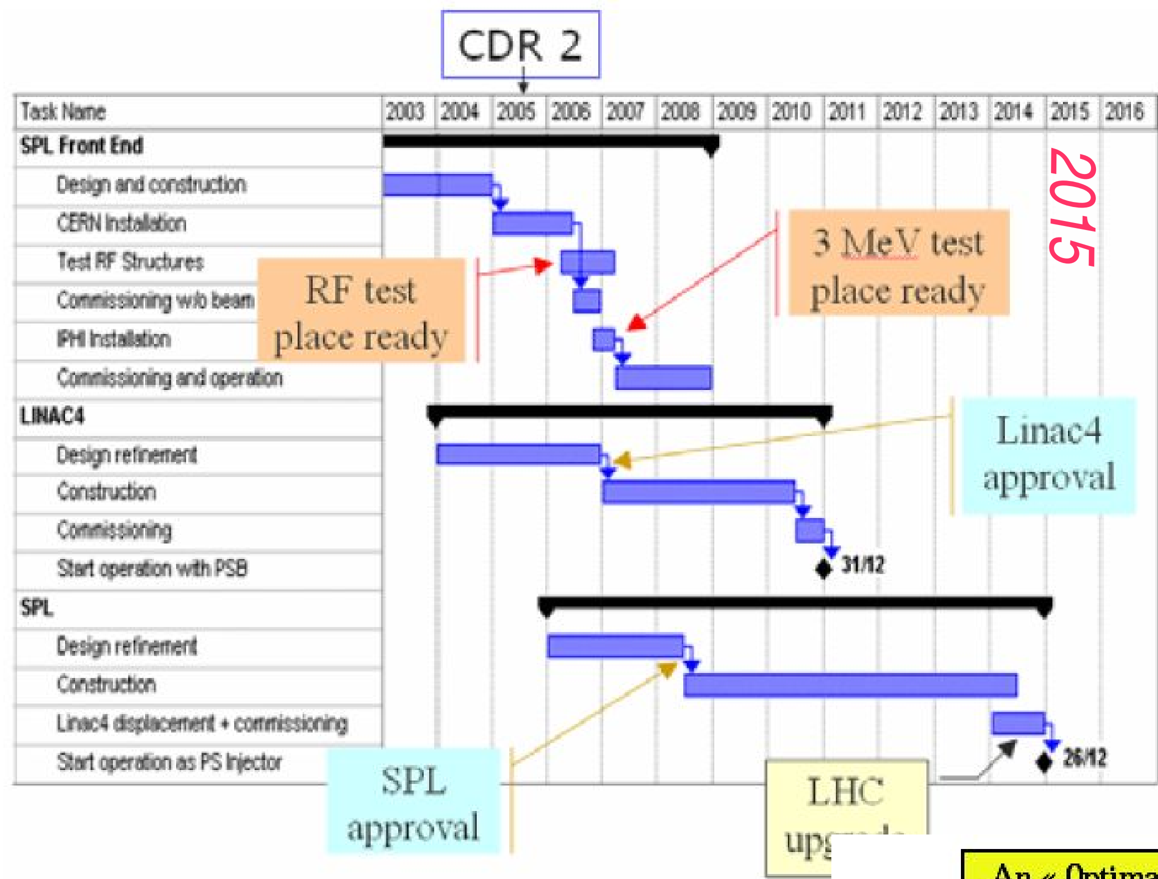
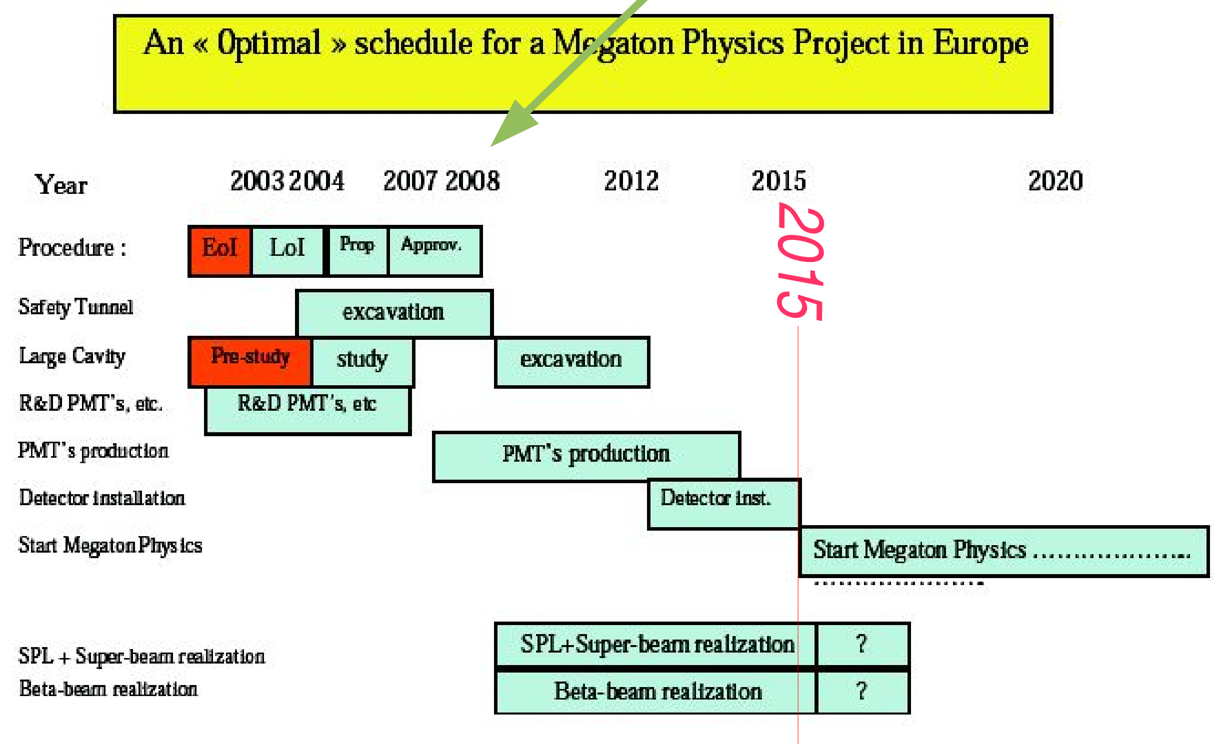
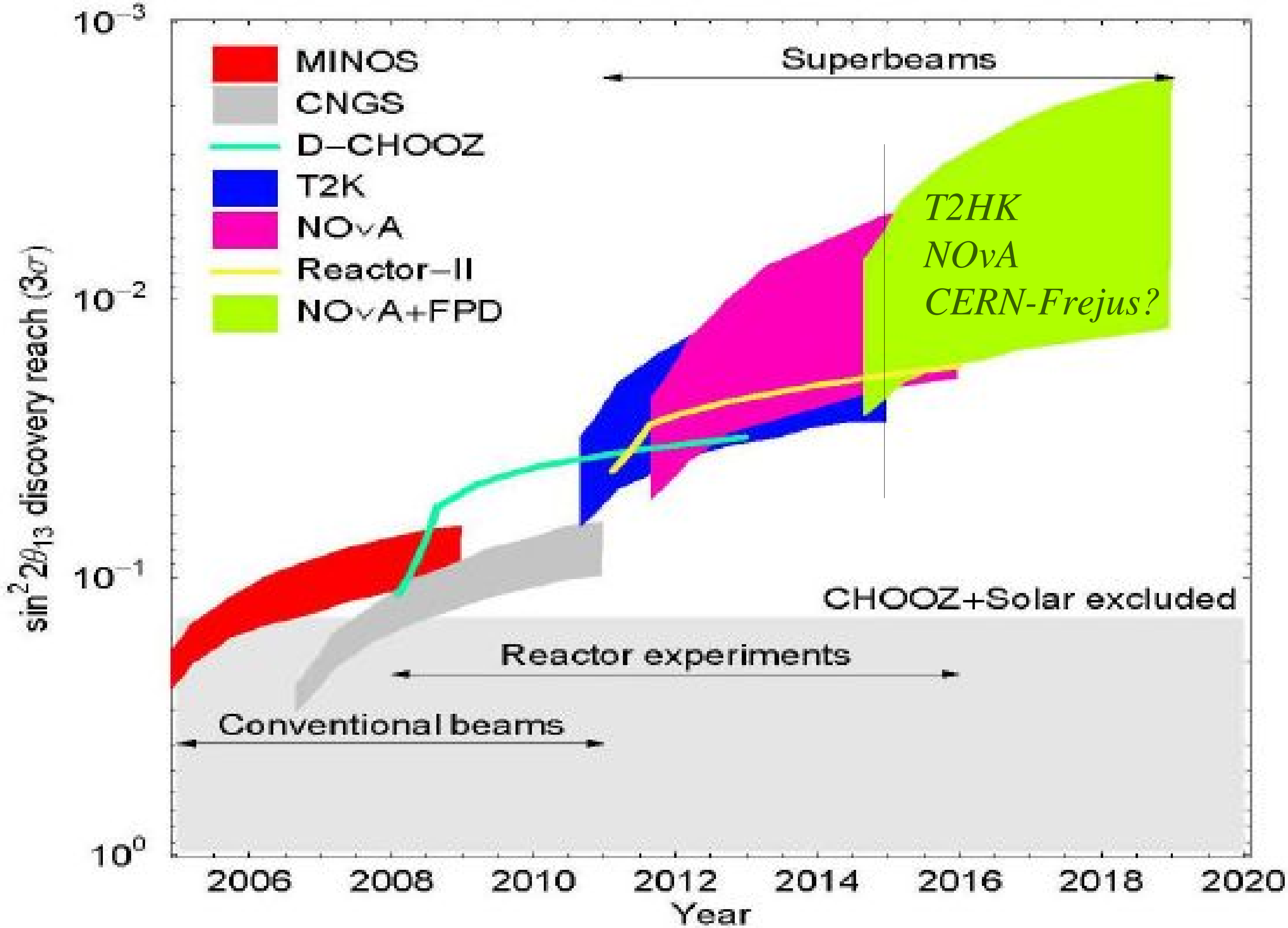


FIGURE 3. Integrated planning for

Window of opportunity for excavation in 2008





MINOS
CNGS
D−CHOOZ
T2K
NOνA
Reactor−II
NOνA+FPD
Superbeams
T2HK
NOνA
CERN-Frejus?
CHOOZ+Solar excluded
Reactor experiments
Conventional beams
10^{-3}
10^{-2}
10^{-1}
10^{0}
$\sin^2 2\theta_{13}$ discovery reach (3σ)
2006
2008
2010
2012
2014
2016
2018
2020
Year

Superbeams in the parallel sessions

Wednesday	Session 2a	15:30	Phenomenology: degeneracy resolution
	Session 2b	17:07	Phenomenology: degeneracy resolution, new beam ideas
Thursday	Session 3a	11:15	BNL-Homestake, SPL-Frejus
	Session 3b	12:50	FNAL Proton driver
	Session 4	15:00	Very long baseline ideas
	Session 5	17:30	NOvA, T2K
	Session 7	11:30	Detector options
Saturday	Session 9a	11:30	Detector options (LAr)