Super Beam Experiments

- What's a Super Beam?
- The Physics
- Some of the common features
- Specific Proposals
  - Jaeri to Super-Kamiokande
  - CERN to Frejus
  - CERN to Gulf of Taranto
  - Fermilab to "Up North" via NuMI
  - Brookhaven to NUSEL (or others?)
- Conclusions

Douglas Michael
California Institute of Technology

NuFACT 03
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Thanks

- Thanks to the following people from whom I have borrowed/collected various slides and figures which I have included in this talk:
  - J. Cooper, M. Diwan, F. Dydak, A. Kondo-Ichikawa, K. McDonald, M. Mezzetto, T. Nakaya, K. Nishikawa, A. Para, S. Wojcicki
  - Those are my sources… I appologize if they have borrowed from you and I haven't followed the chain of acknowledgement.

What’s a “Super Beam” Experiment?

- I know it when I see it. (Justice Potter Stewart)
- Any conventional neutrino beam experiment where currently there is:
  - No Accelerator or
  - No Detector or
  - No Beamline or
  - Combinations of all of the above.
- A conventional neutrino beam experiment with a whole lot of proton power and a really big detector.
- I’ll settle for defining a “Super Beam” experiment as any conventional, long baseline, high energy neutrino beam experiment seriously “proposed” but not yet approved.

Physics Goals

- Improved measurement of ν_μ disappearance oscillation parameters.
  - Any odd energy/distance features?
  - How close is $\sin^2 2\theta_{23}$ to 1.0? New symmetry?
- Measure the m_{23} mass heirarchy using matter effects.
- Measure θ_{13} or show that it is so small that it is somehow "odd" compared to the other mixing parameters… Mechanism for making it so small?
- Attempt to measure CP violation, if θ_{13} is big enough.
- Constrain CPT violation (or discover it!)
- And what if LSND is confirmed???????? Things get very interesting, and complicated.

$\nu_\mu \Rightarrow \nu_e$ oscillation experiment

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2\theta_{23} \sin^2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23} \sin^2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu};$$

$$A = \sqrt{2}G_F n_e;$$

$$B_\pm = \left|A \pm \Delta_{13}\right|;$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

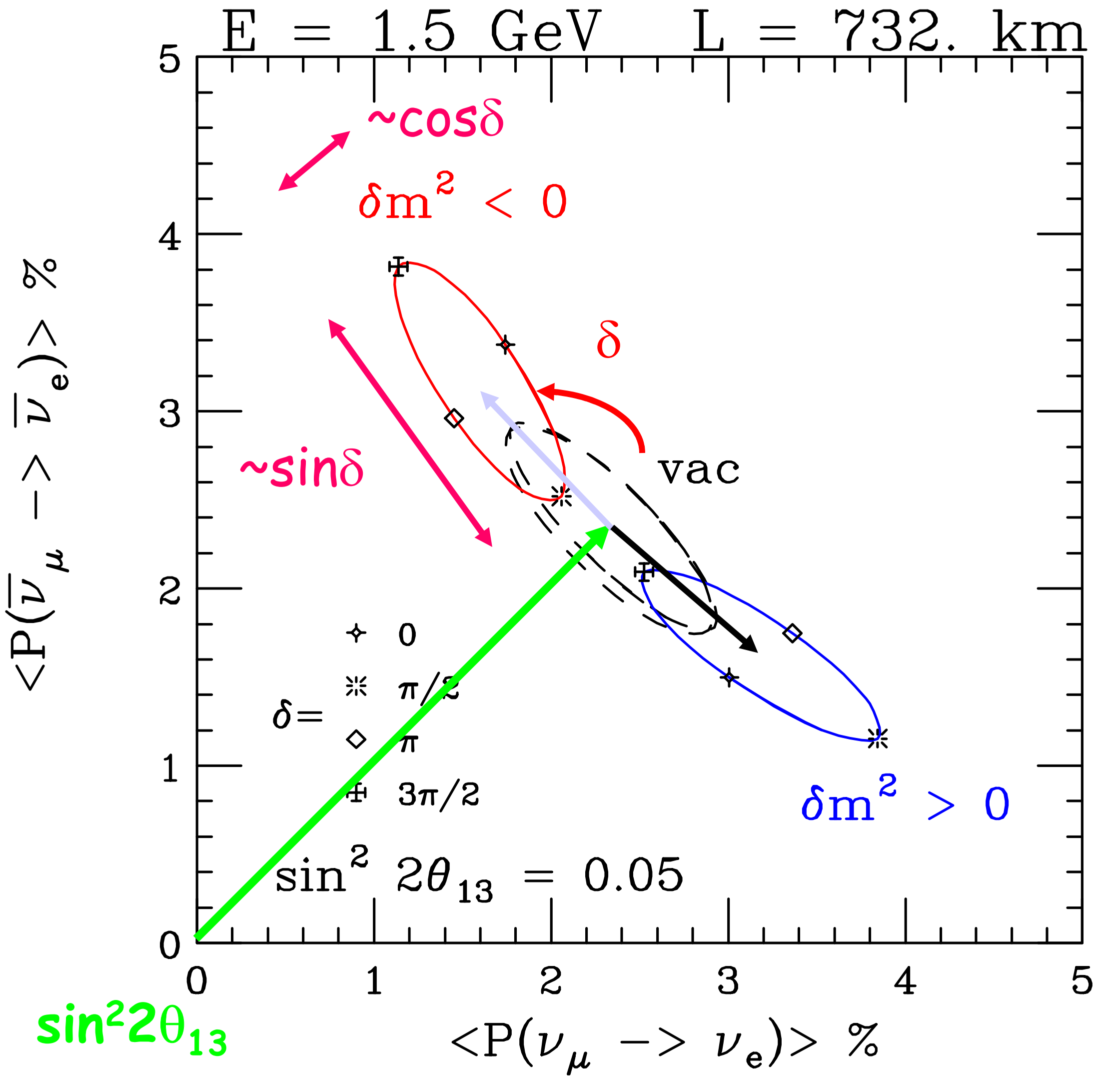
$$P = f(\sin^2 2\theta_{13}, \delta, \mathrm{sgn}(\Delta m_{13}^2), \Delta m_{12}^2, \Delta m_{13}^2, \sin^2 2\theta_{12}, \sin^2 2\theta_{23}, L, E)$$

3 unknowns, 2 parameters under control L, E, neutrino/antineutrino

Need several independent measurements to learn about underlying physics

Note, if there are any sterile ν's things can be more complicated!

Anatomy of Bi-probability ellipses



Example from NuMI Off-Axis

Minakata and Nunokawa, hep-ph/0108085

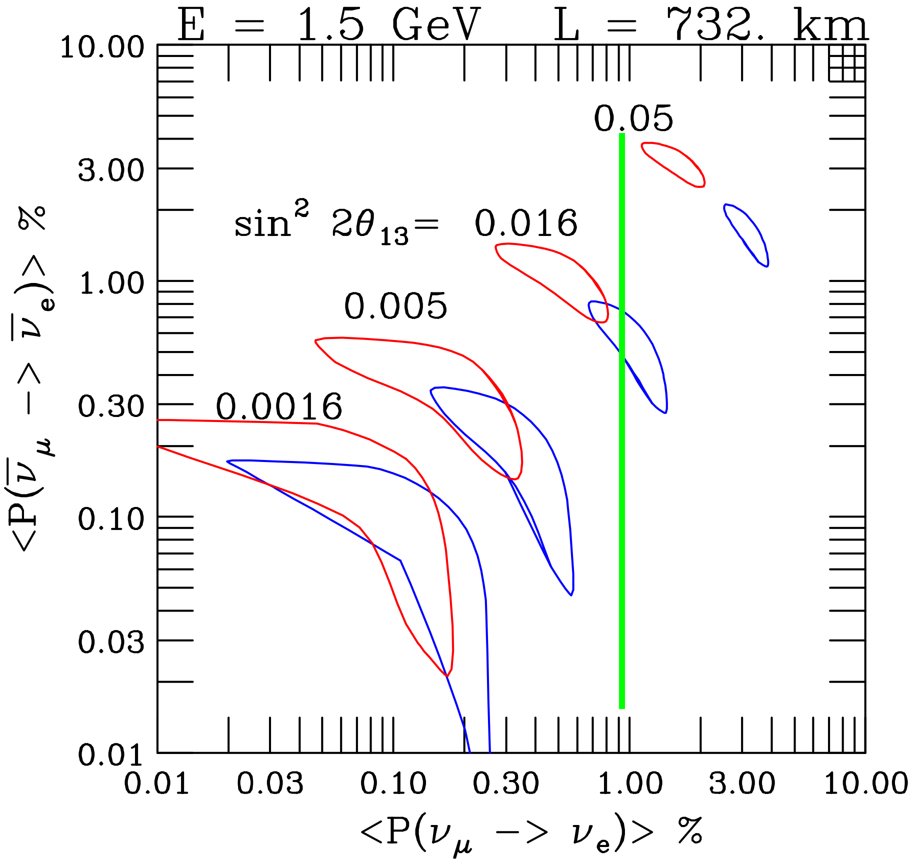
Observables are:

- P
- $\overline{P}$

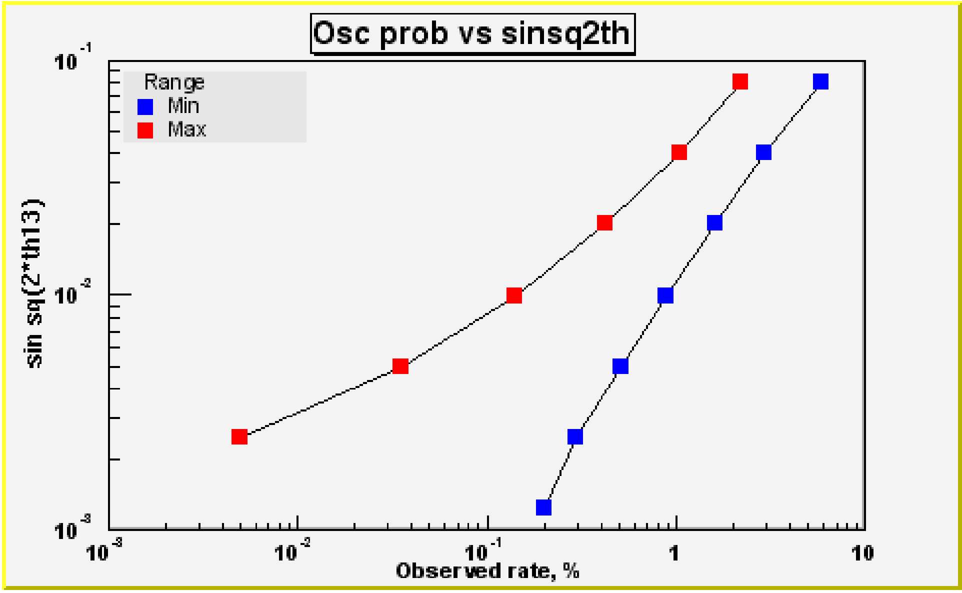
Interpretation in terms of sin^{2}2q$_{13}$, d and sign of Dm$^2_{23}$ depends on the value of these parameters and on the conditions of the experiment: L and E

Oscillation probability vs physics parameters

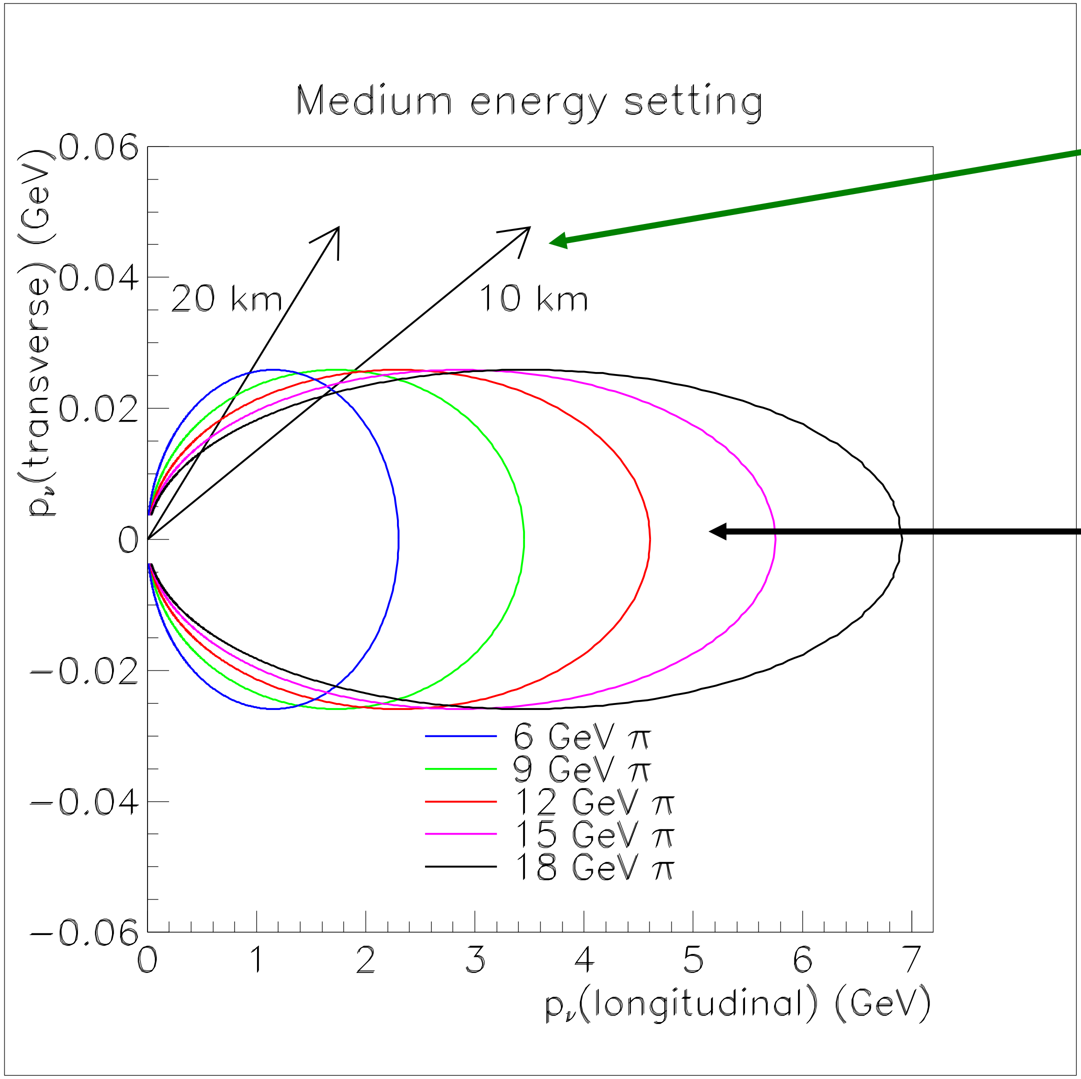
Parameter correlation: even very precise determination of P_ν leads to a large allowed range of $\sin^2 2\theta_{23}$ ➔ **antineutrino beam** is more important than improved statistics



Example from NuMI Off-Axis



The Off-Axis Trick

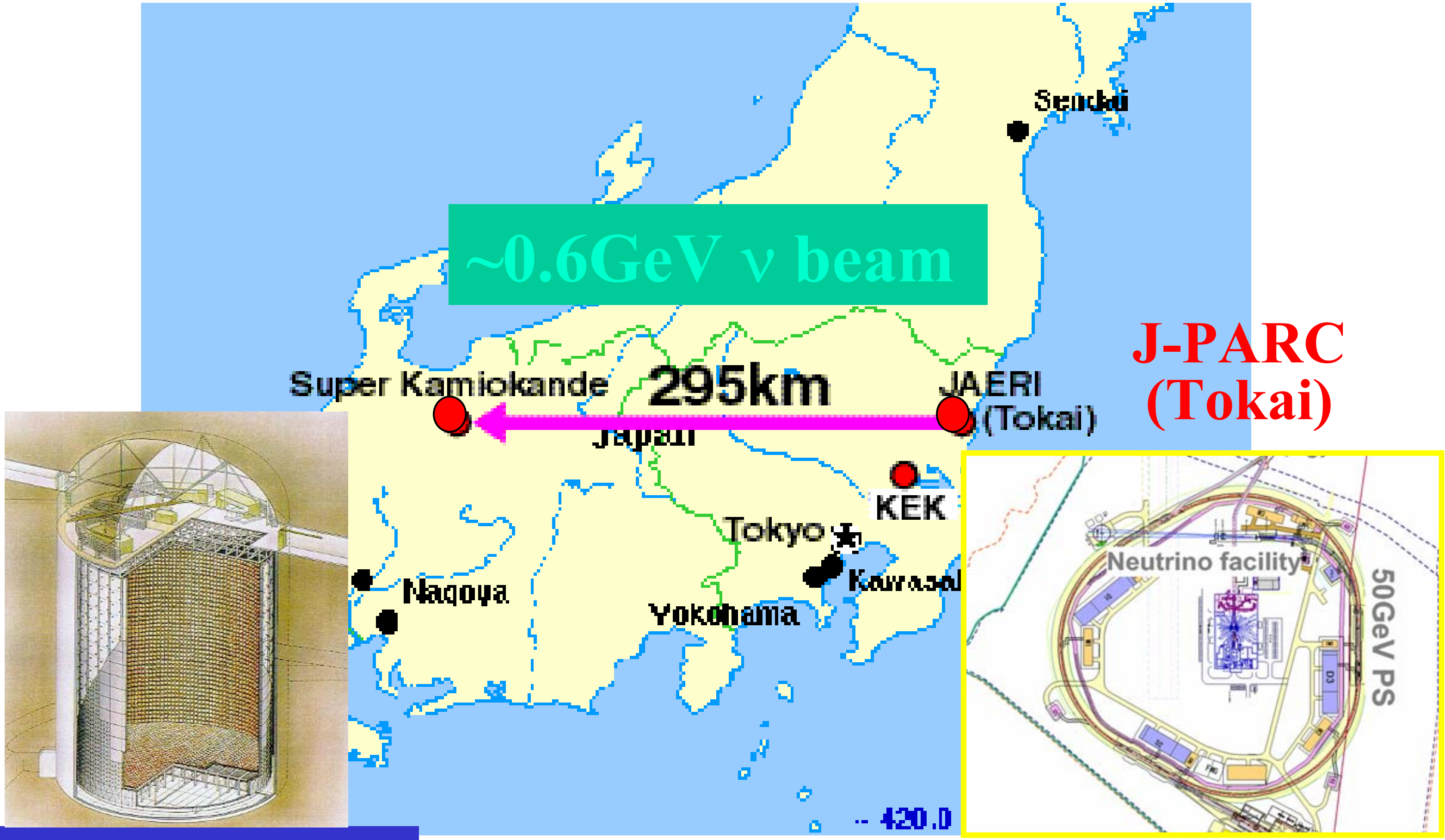


At this angle, 15 mrad, energy of produced neutrinos is 1.5-2 GeV for all pion energies ➔ very intense, narrow band beam

'On axis': $E_\nu = 0.43 E_\pi$

$$\boxed{\begin{aligned} p_L &= \gamma(p^* \cos\theta^* + \beta E^*) \\ p_T &= p^* \sin\theta^* \end{aligned}}$$

J-PARC → Super-Kamiokande project



~0.6GeV ν beam

J-PARC
(Tokai)

Super-K: 22.5 kt

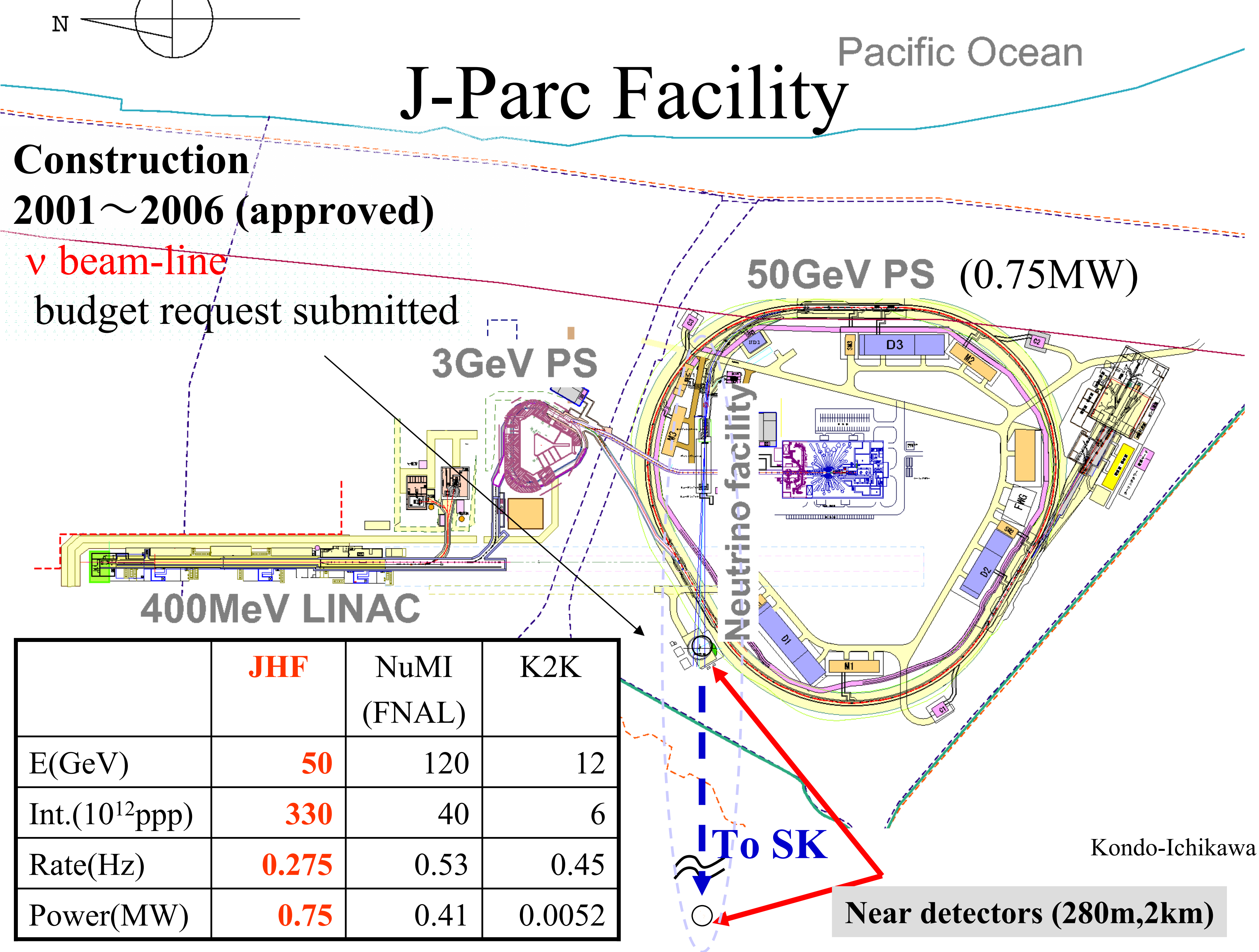
0.75MW 50 GeV PS

Kondo-Ichikawa

J-Parc Facility

Construction
2001～2006 (approved)

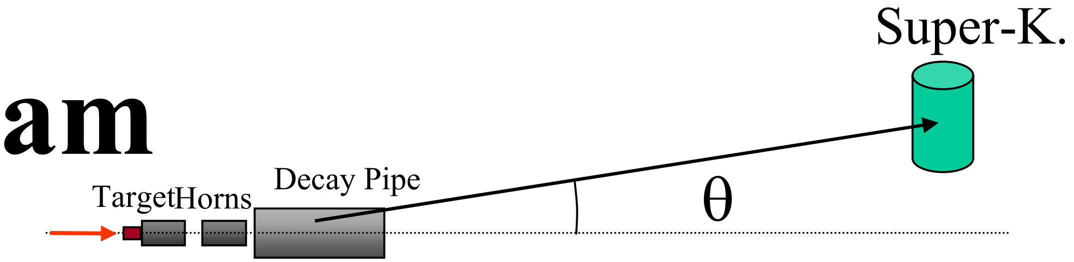
ν beam-line
budget request submitted



	JHF	NuMI (FNAL)	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.275	0.53	0.45
Power(MW)	0.75	0.41	0.0052

Kondo-Ichikawa

Off Axis Beam

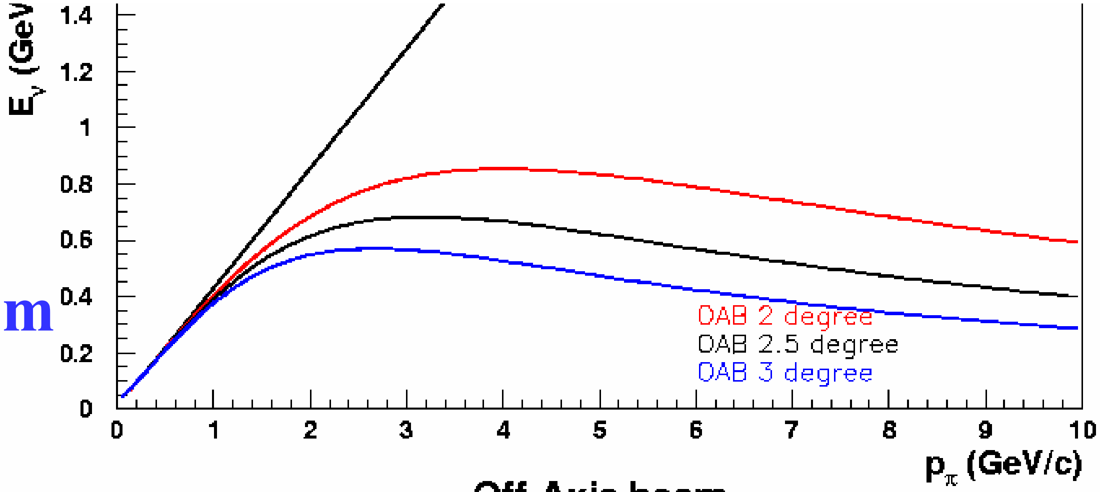


(ref.: BNL-E889 Proposal)

- **Quasi Monochromatic Beam**
- **x2~3 intense than NBB**

Tuned at oscillation maximum

~0.7 GeV



Off-Axis beam

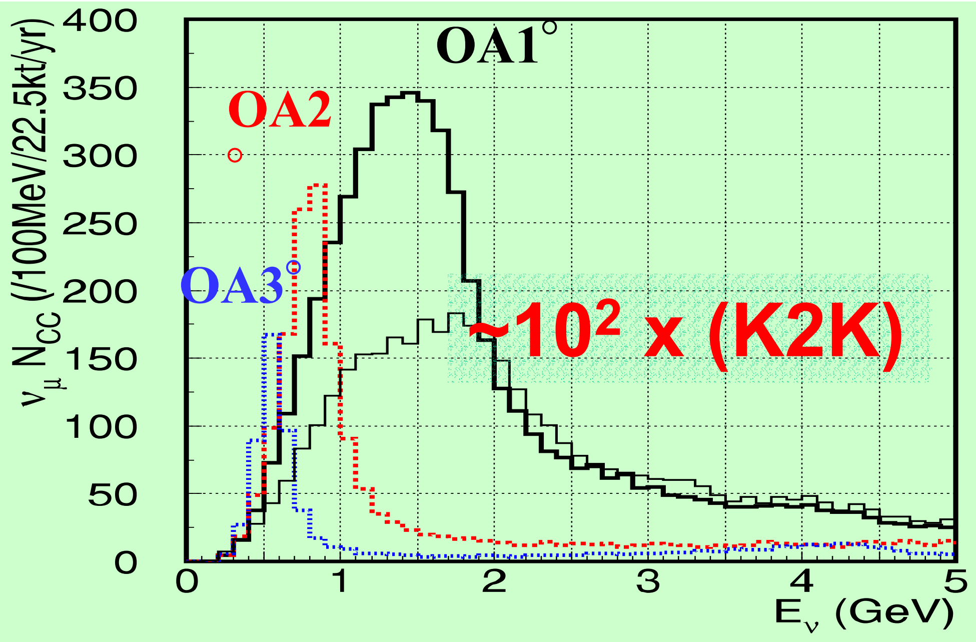
Statistics at SK

(OAB2deg,1yr,22.5kt)

~4500 ν_μ tot

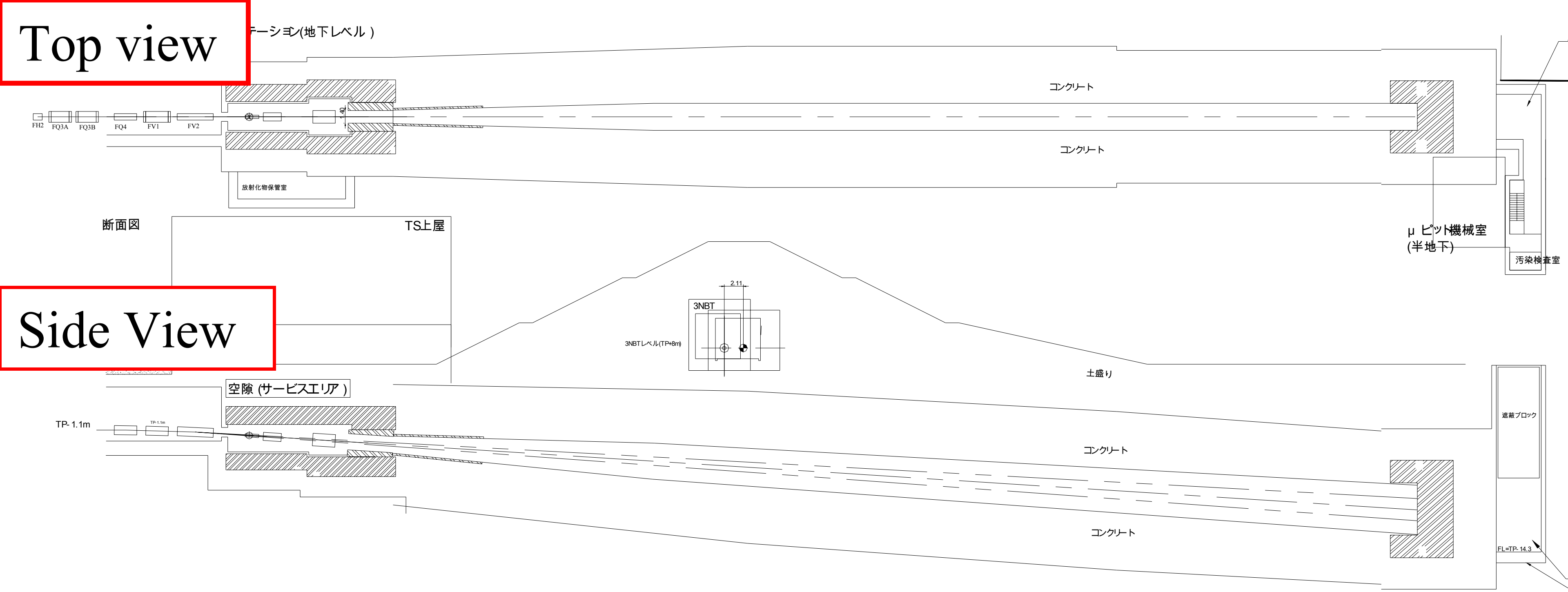
~3000 ν_μ CC

ν_e ~0.2% at ν_μ peak



~10^2 x (K2K)

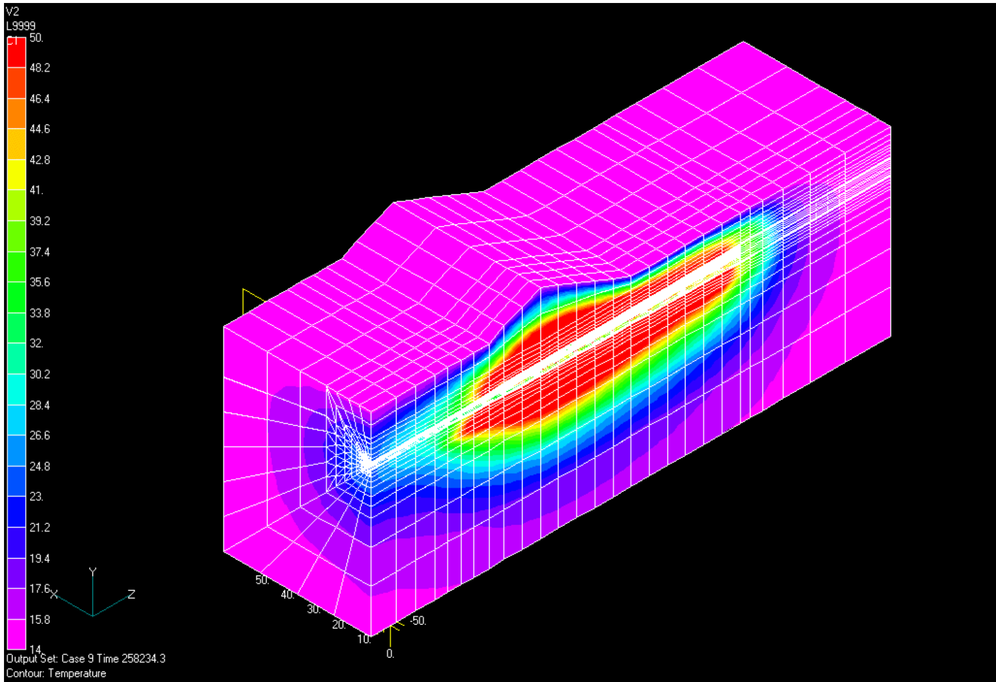
Kondo-Ichikawa


Top view

Side View

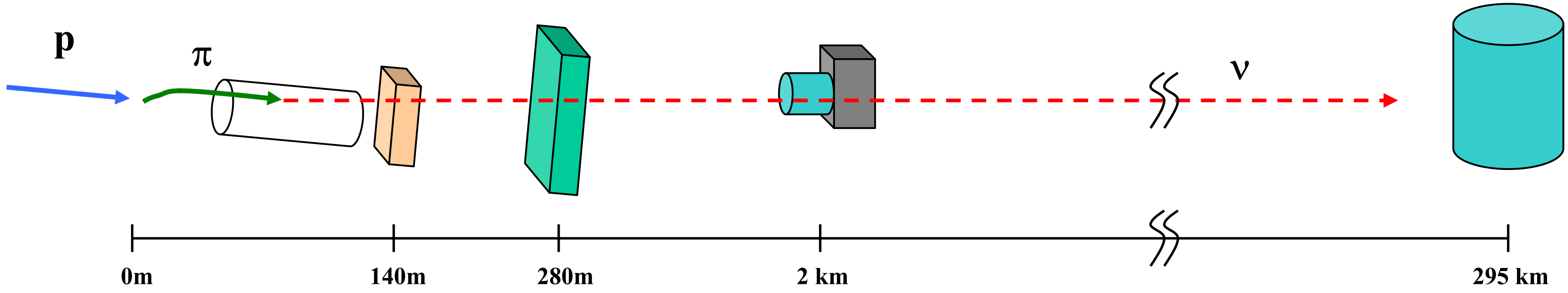
Decay Volume

4MW beam can be accepted.



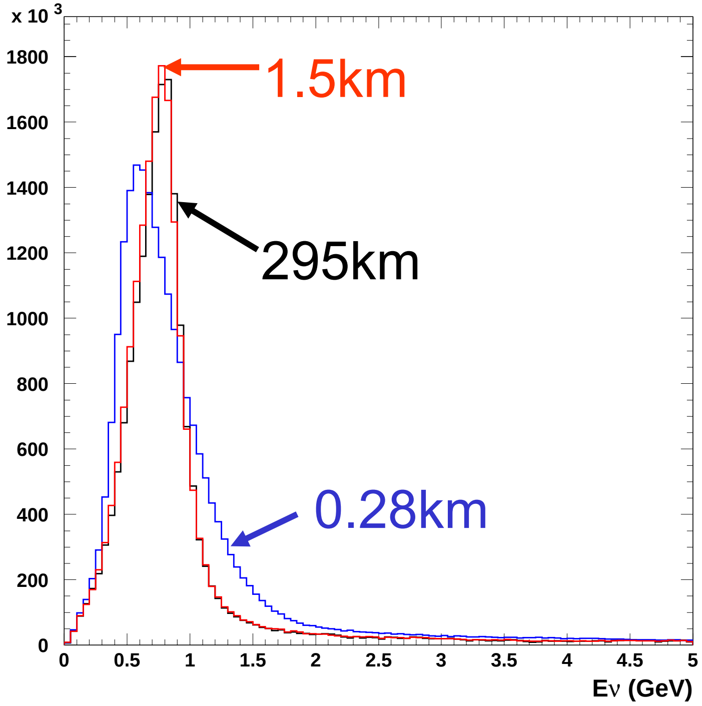
Kondo-Ichikawa

Detectors



- **Muon monitors @ ~140m**
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- **First Near detector @280m**
  - Neutrino intensity/spectrum/direction
- **Second Near Detector @ ~2km**
  - Almost same E_ν spectrum as for SK
  - Water Cherenkov can work
- **Far detector @ 295km**
  - **Super-Kamiokande (50kt)**

Neutrino spectra at diff. dist



dominant syst. in K2K

Kondo-Ichikawa

Measurement of $\sin^2 2\theta_{23}$, Δm^2_{23}

Based on 5 years running with full 0.75 MW Jaeri Beam

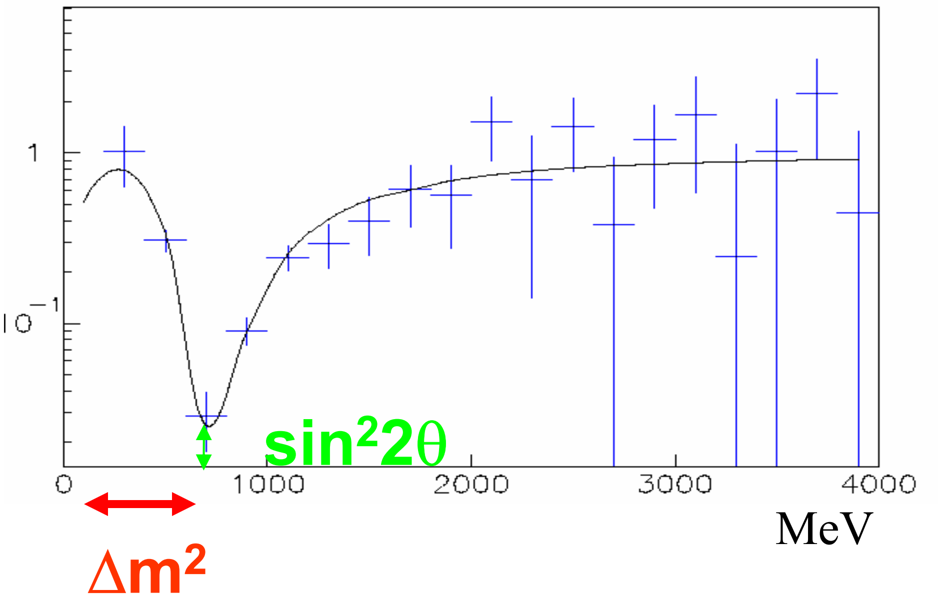
ν_μ disappearance

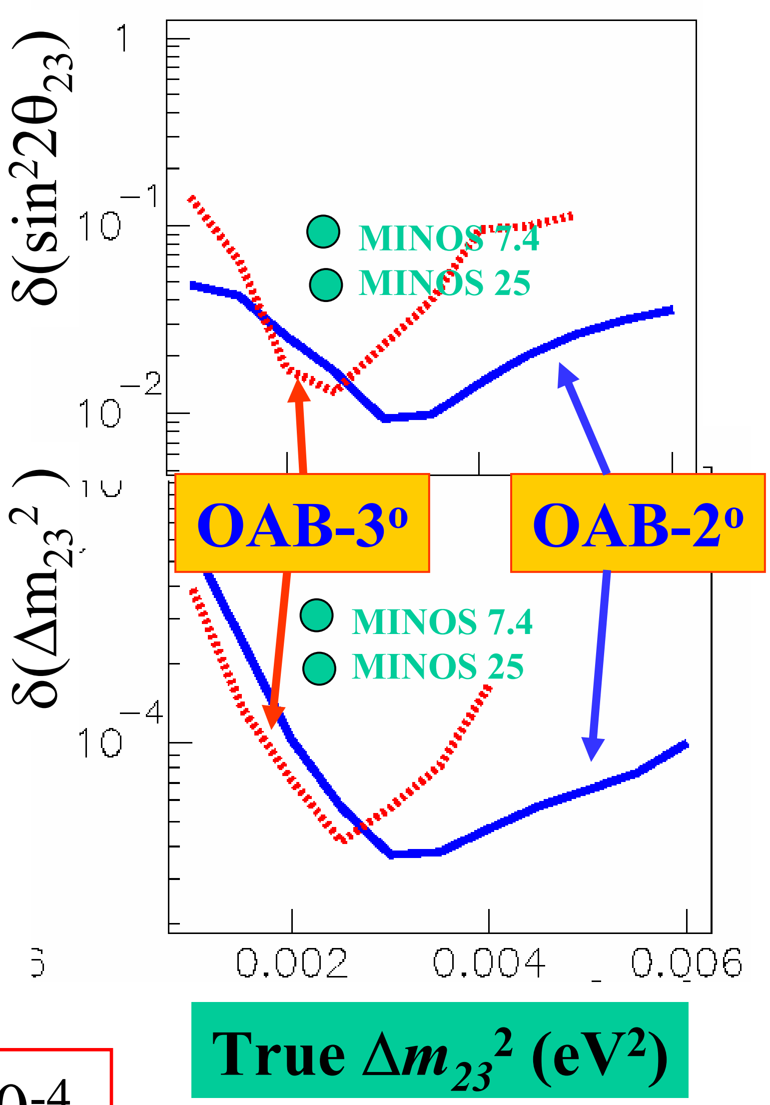
FC, 1-ring, μ-like events

Sys. error 10% for near/far

4% energy scale

20% non-QE B.G.

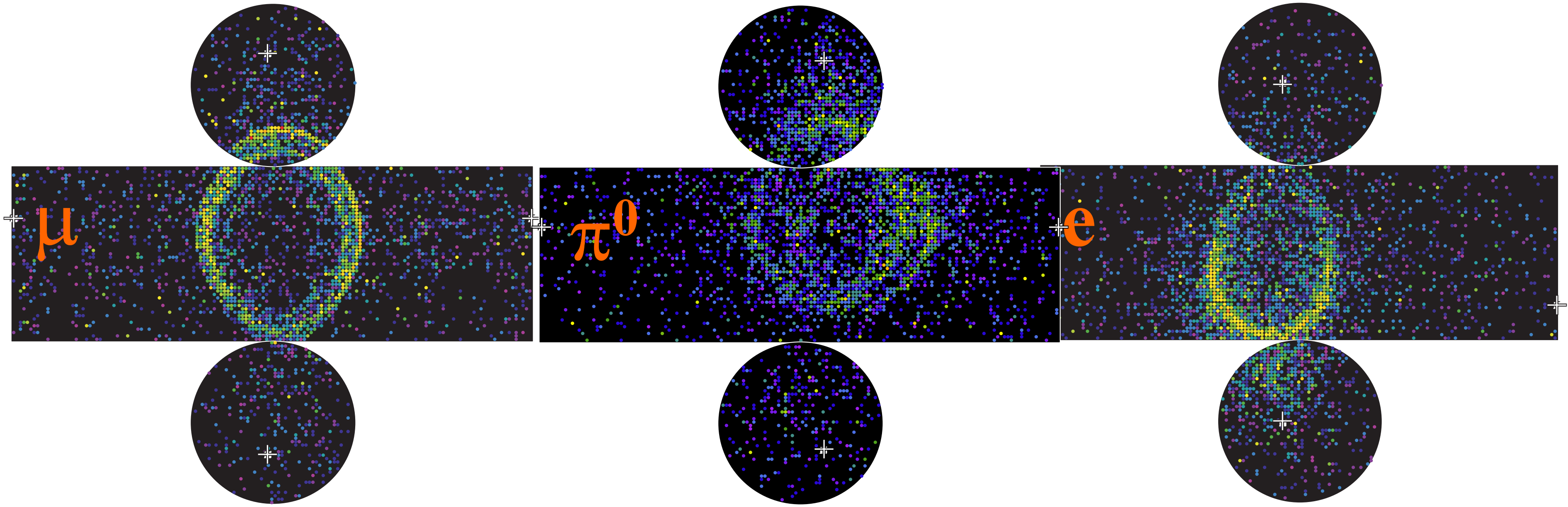




$\delta(\sin^2 2\theta) \sim 0.01$ $\quad \delta(\Delta m^2) \sim< 1 \times 10^{-4}$

Kondo-Ichikawa

ν_e appearance in JHF-Kamioka



Back ground for ν_e appearance search

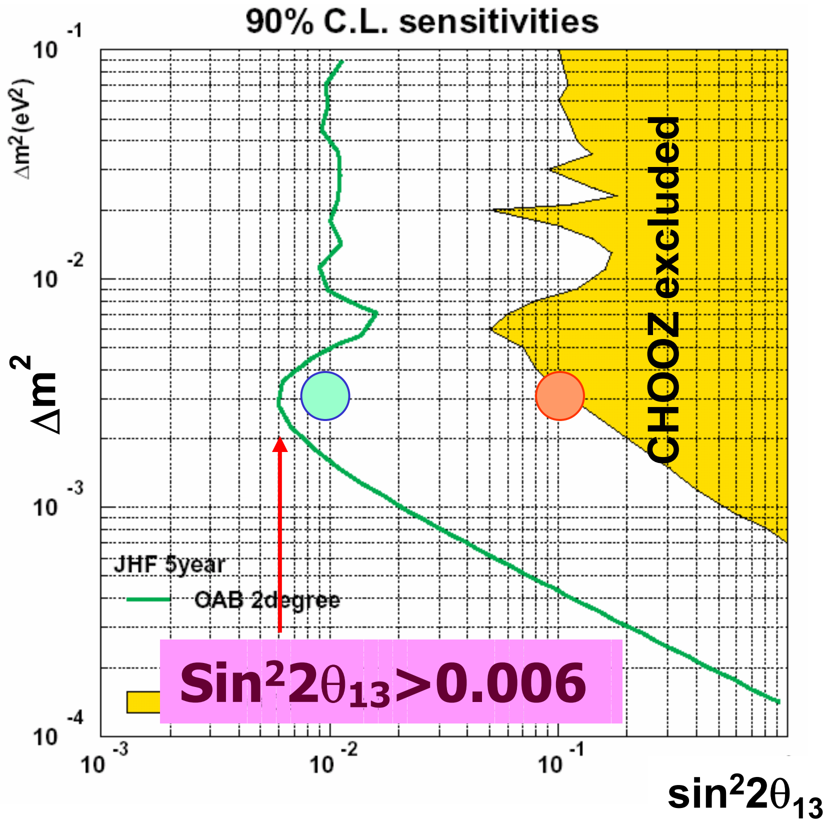
- Intrinsic ν_e component in initial beam
- Merged π^0 ring from ν_μ interactions

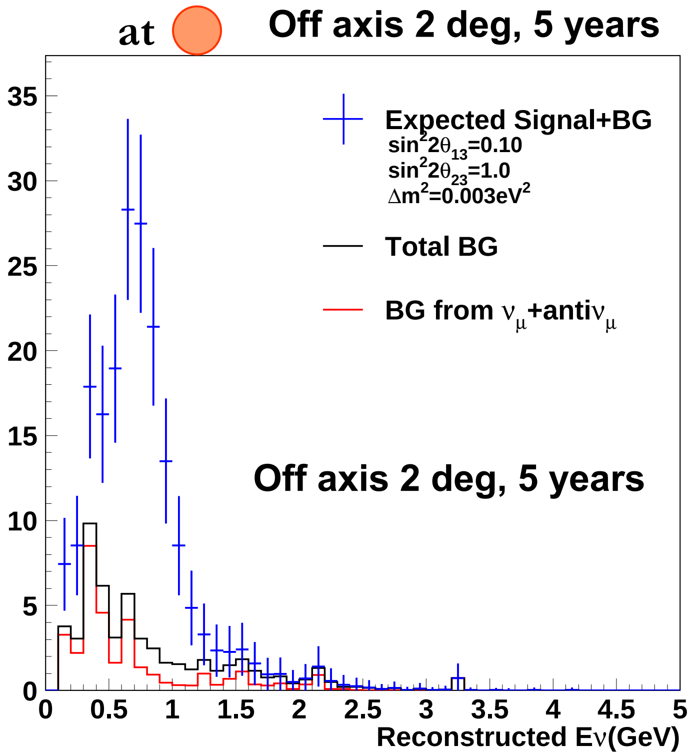
Requirement ⇨ 10% uncertainty for BG estimation

The 1kt π^0 data will be studied for exercise

Kondo-Ichikawa

$\sin^2 2\theta_{13}$ from ν_e appearance

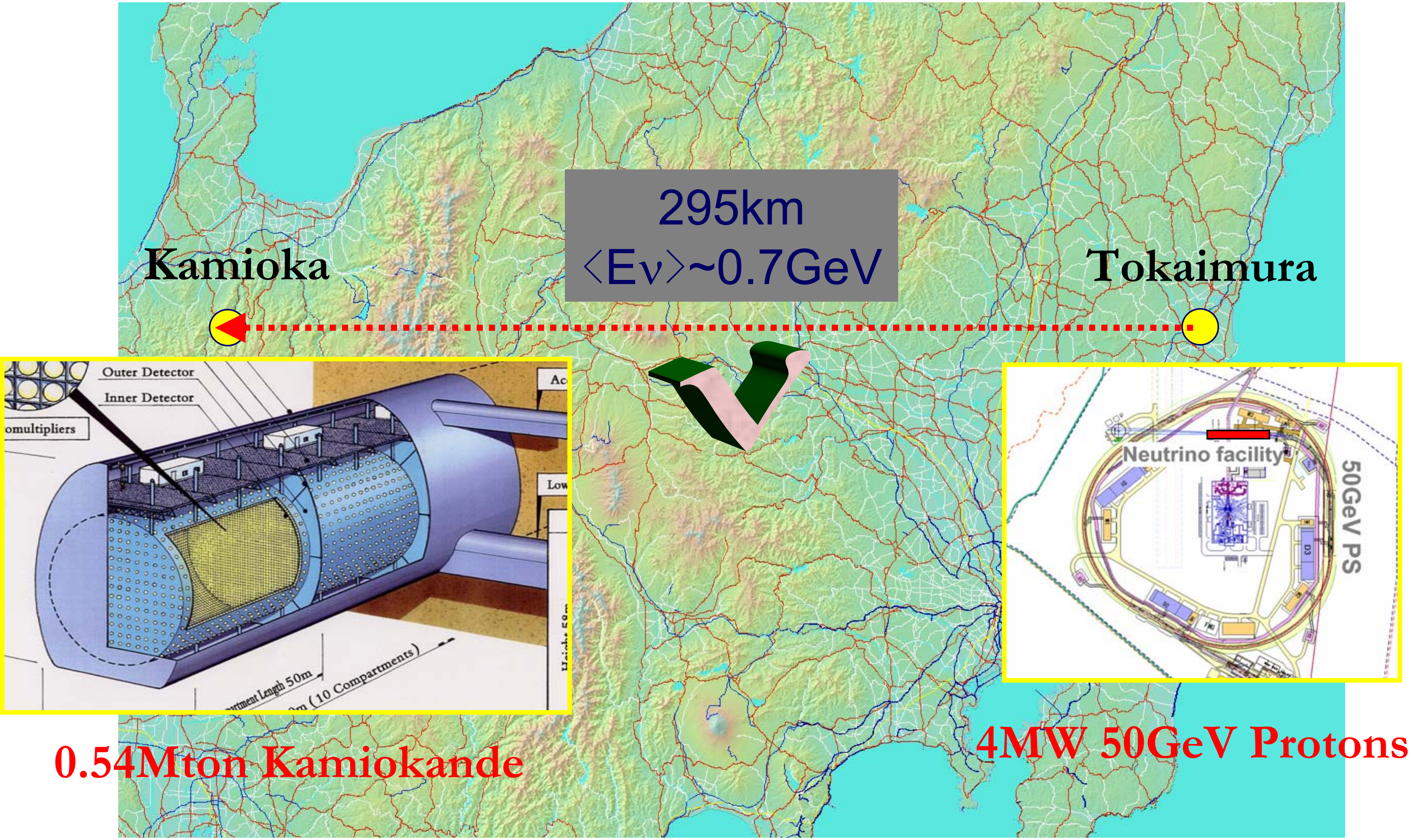




$\sin^2 2\theta_{13}$	Background in Super-K (as of Oct 25, 2001)					Signal	Signal + BG
	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	total		
● 0.1	12.0	10.7	1.7	0.5	24.9	114.6	139.5
● 0.01	12.0	10.7	1.7	0.5	24.9	11.5	36.4

Kondo-Ichikawa

3. JHF ν experiment -CPV



295km
⟨Eν⟩~0.7GeV

Kamioka

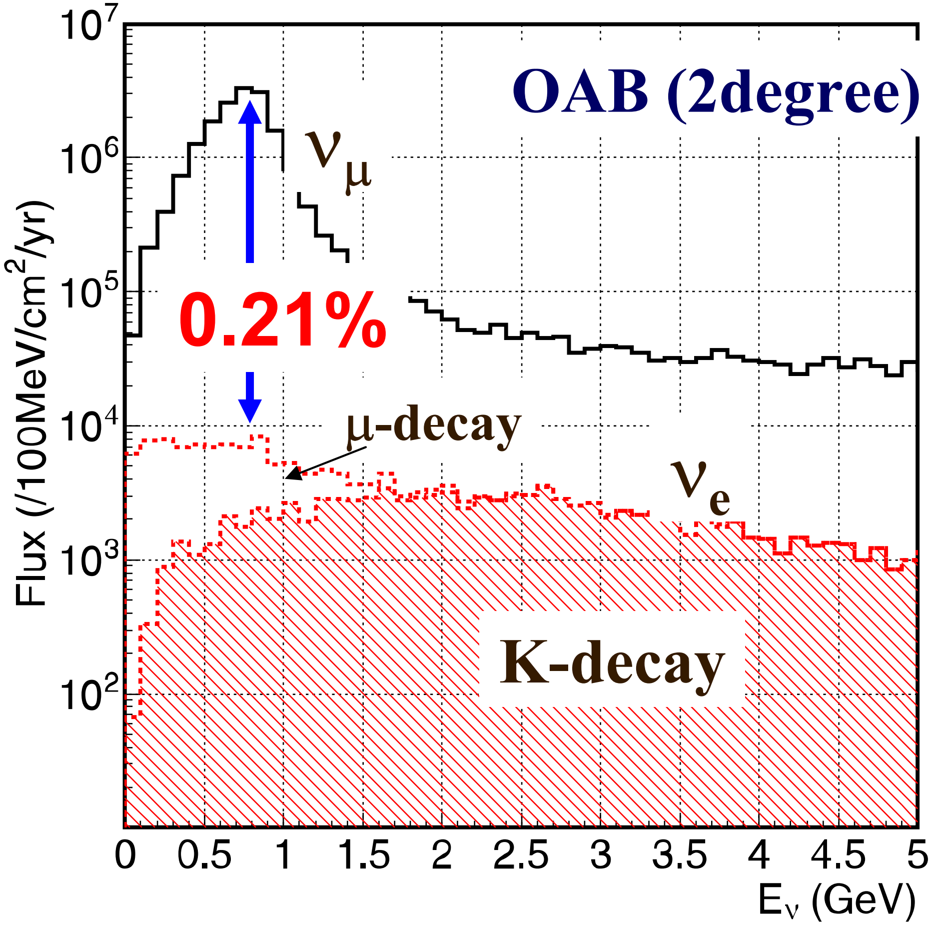
Tokaimura

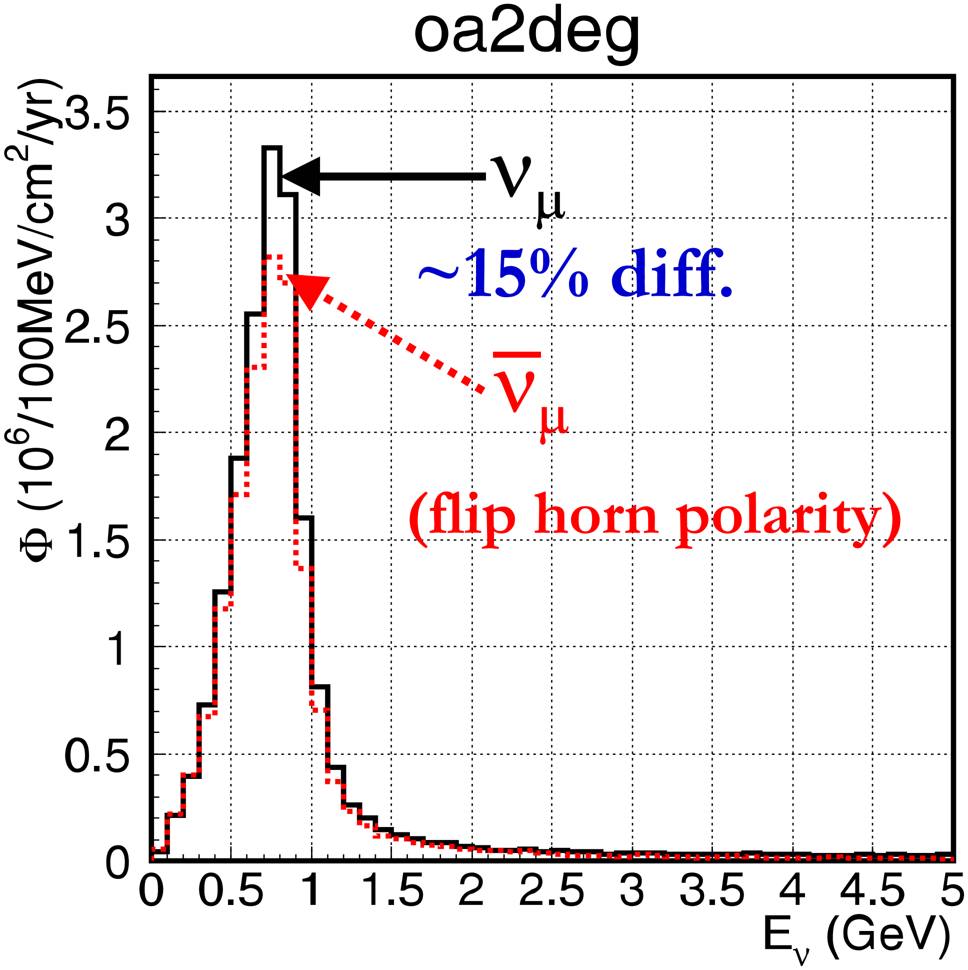
0.54Mton Kamiokande

4MW 50GeV Protons

Nakaya

ν / $\bar{\nu}$ beam flux

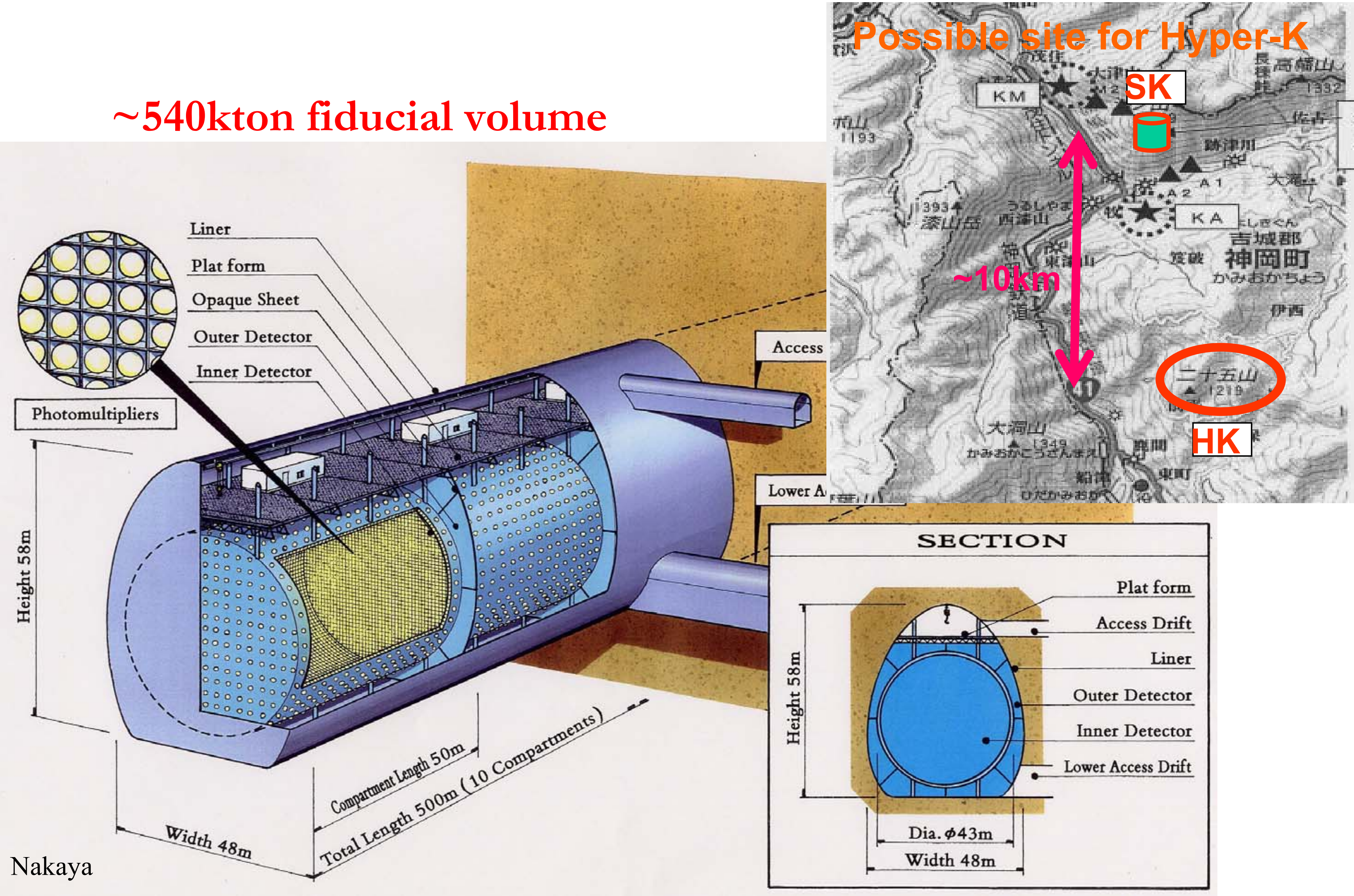




Nakaya

Hyper-Kamiokande

~540kton fiducial volume


Possible site for Hyper-K

Nakaya

Expected signal and Background

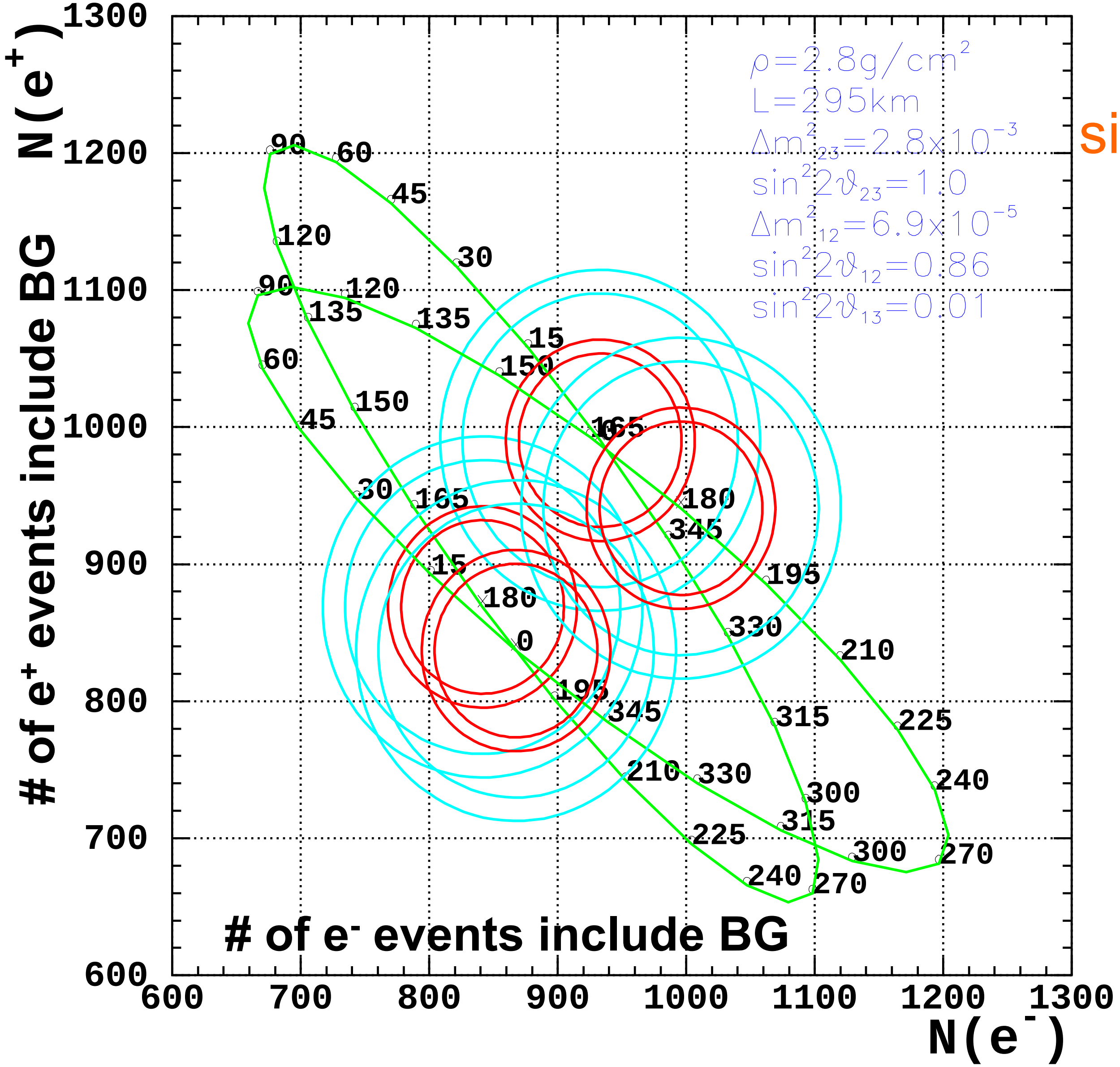
ν_μ:2yr, $\bar{\nu}_\mu$:6.8yr
4MW
0.54Mt

$\Delta m_{21}^2=6.9\times10^{-5}eV^2$
$\Delta m_{32}^2=2.8\times10^{-3}eV^2$
$\theta_{12}=0.594$
$\theta_{23}=\pi/4$
$\theta_{13}=0.05$ ($\sin^2 2\theta_{13}=0.01$)

	signal		background				
	$\delta=0$	$\delta=\pi/2$	total	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\nu_\mu\rightarrow\nu_e$	536	229	913	370	66	450	26
$\bar{\nu}_\mu\rightarrow\bar{\nu}_e$	536	790	1782	399	657	297	430

Nakaya

number of $\nu_e,\bar{\nu}_e$ appearance events

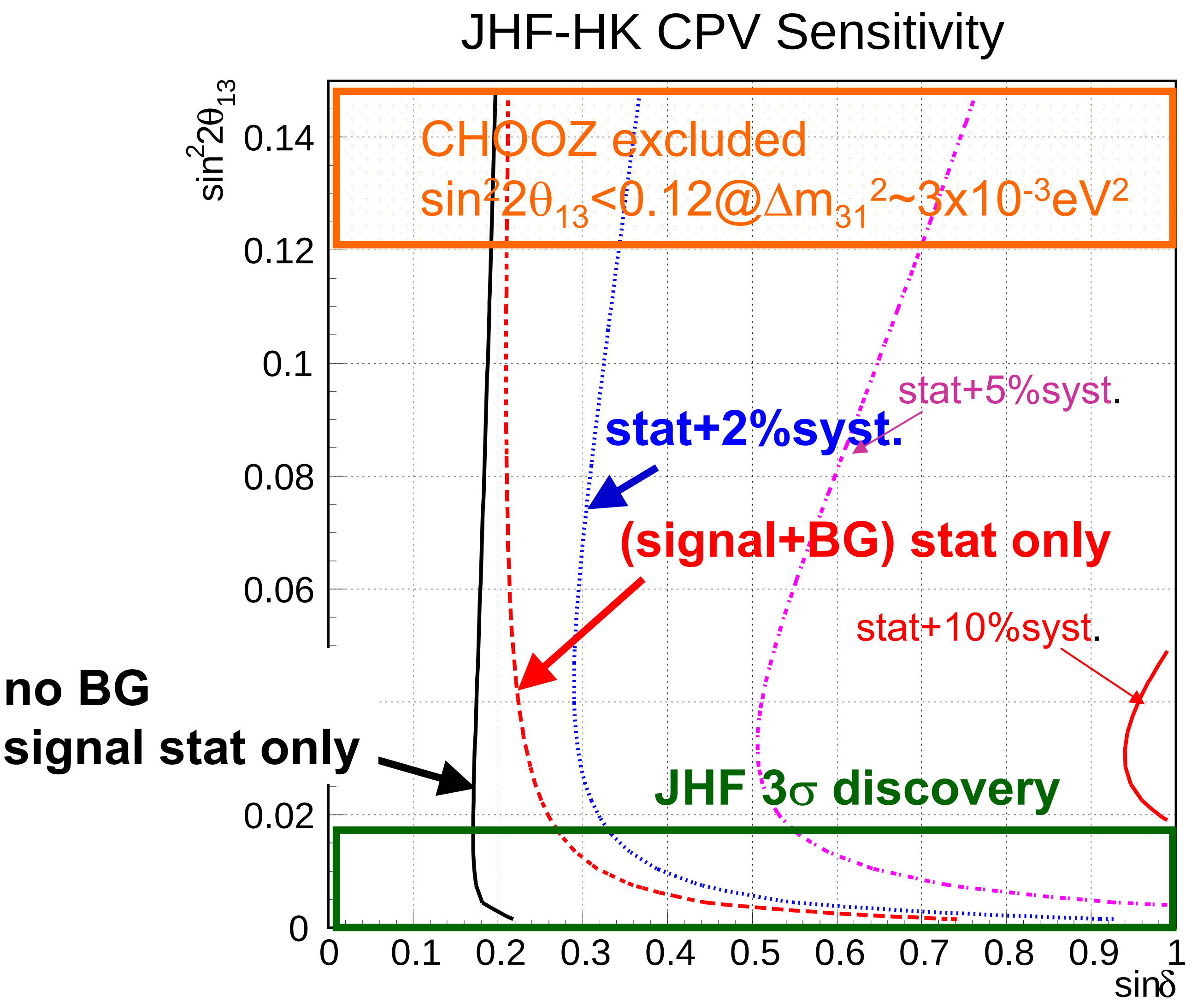


$\sin^2 2\theta_{13}=0.01$

3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13}=0.01$

Nakaya

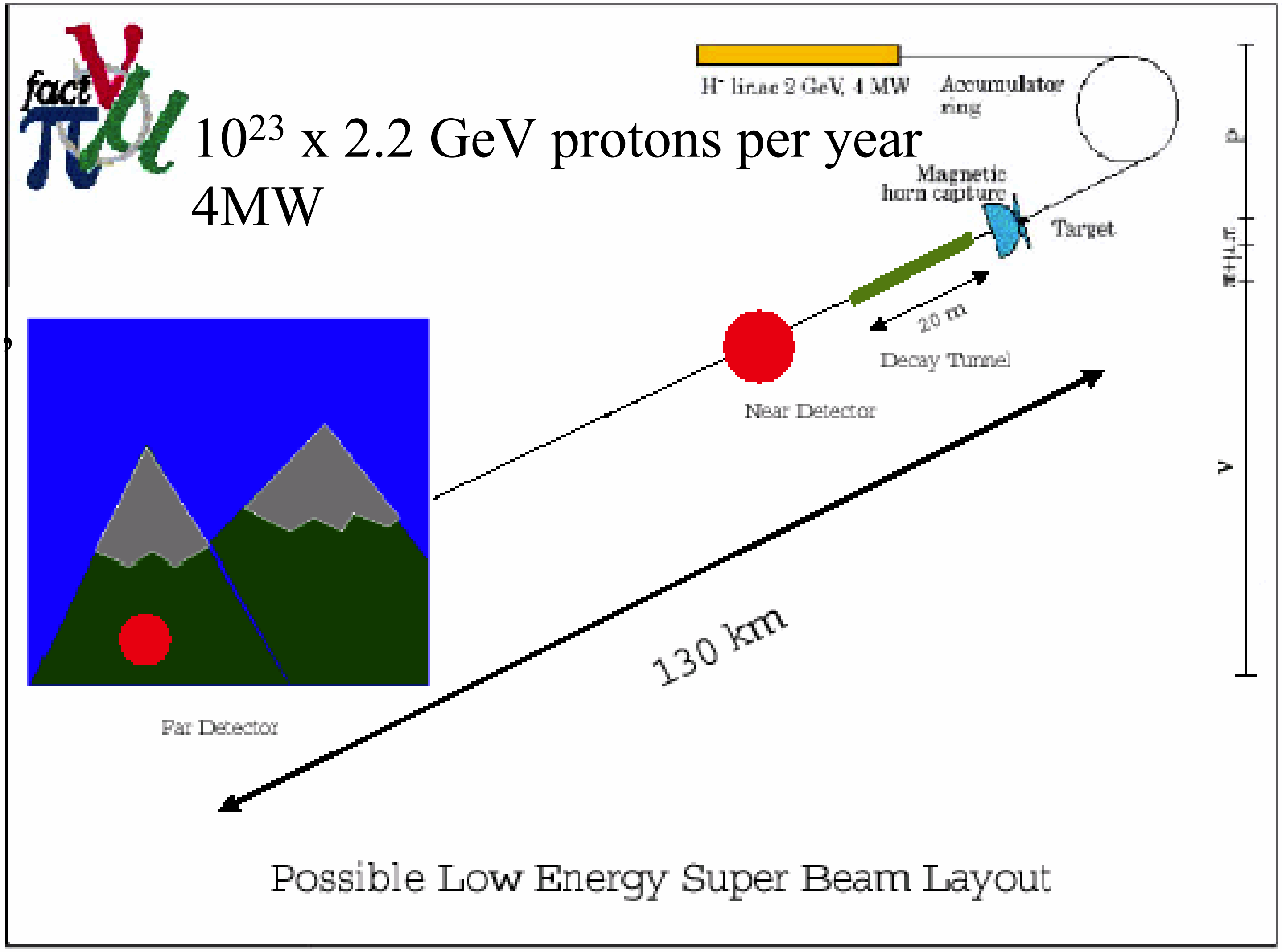
~~CP~~ sensitivity (3σ)



3σ CP sensitivity : |δ|>20° for $\sin^2 2\theta_{13} > 0.01$ with 2% syst.

Nakaya

CERN SPL to Frejus



Possible Low Energy Super Beam Layout

10^{23} x 2.2 GeV protons per year

4MW

“Super-K”
~50 kT
or

“UNO”
~500 kT
water

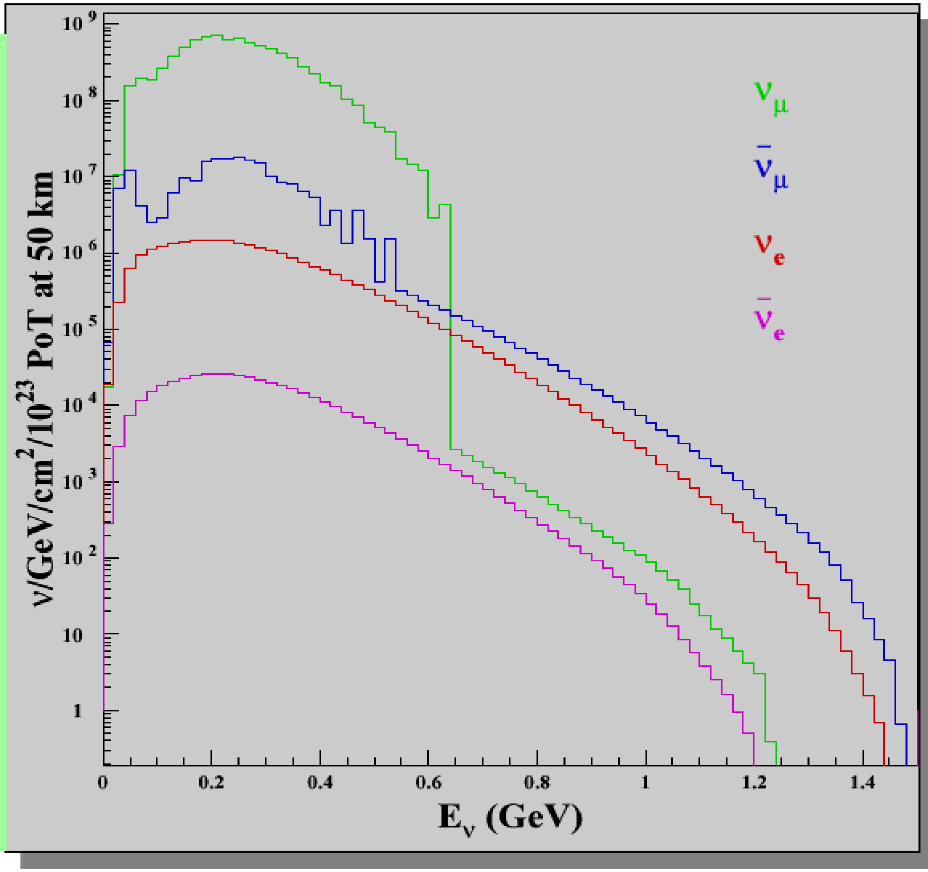
Mezzetto

M. Mezzetto, "SuperBeam studies at CERN", *Nufact 01*, Tsukuba, May 24-30, 2001

Fluxes for SPL Beam

Flux intensities at 50 km from the target

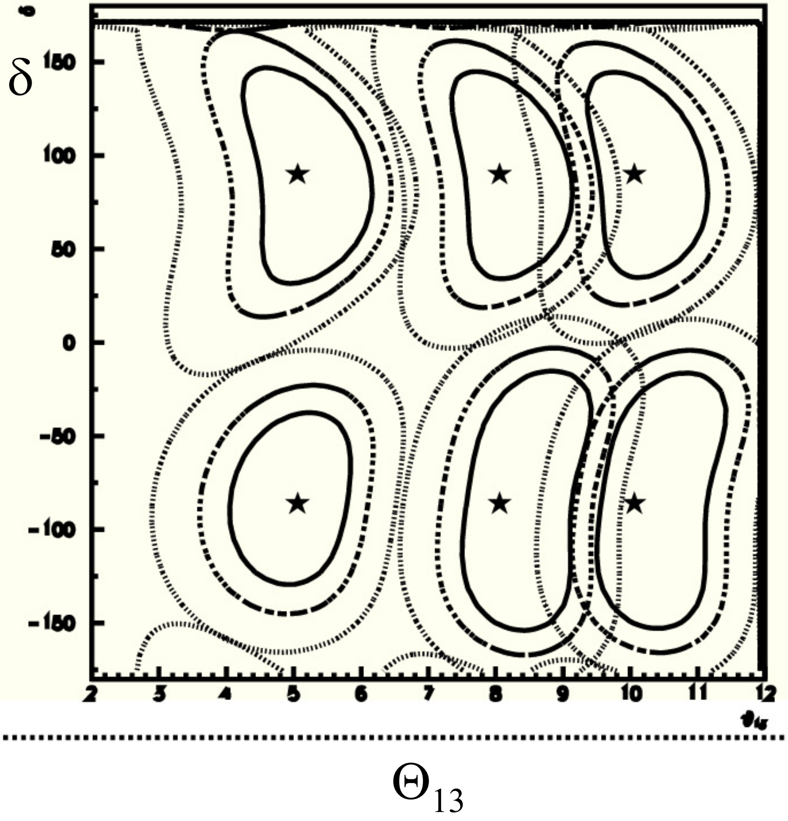
Flavour	Absolute Flux (/ 10^{23}pot / m^2)	Rel. Flux (%)	E (GeV)
μ	$3.2 \cdot 10^{12}$	100	0.27
— μ	$2.2 \cdot 10^{10}$	1.6	0.28
e	$5.2 \cdot 10^{9}$	0.67	0.32
— e	$1.2 \cdot 10^{8}$	0.004	0.29



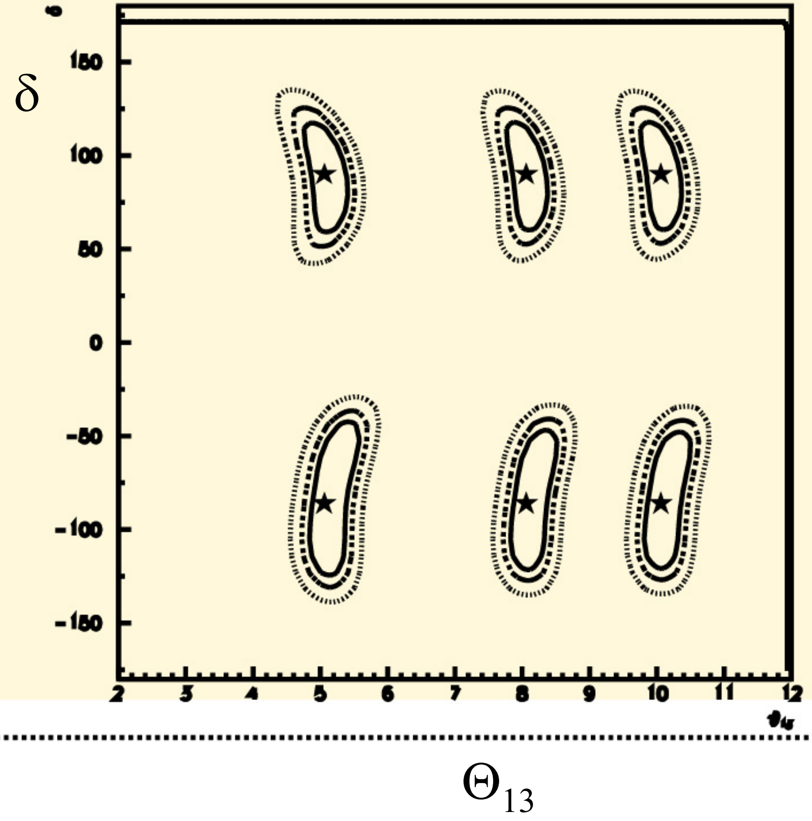
Mezzetto

Preliminary CP sensitivity

40 kton water detector 1 , 90%CL, 99%CL lines



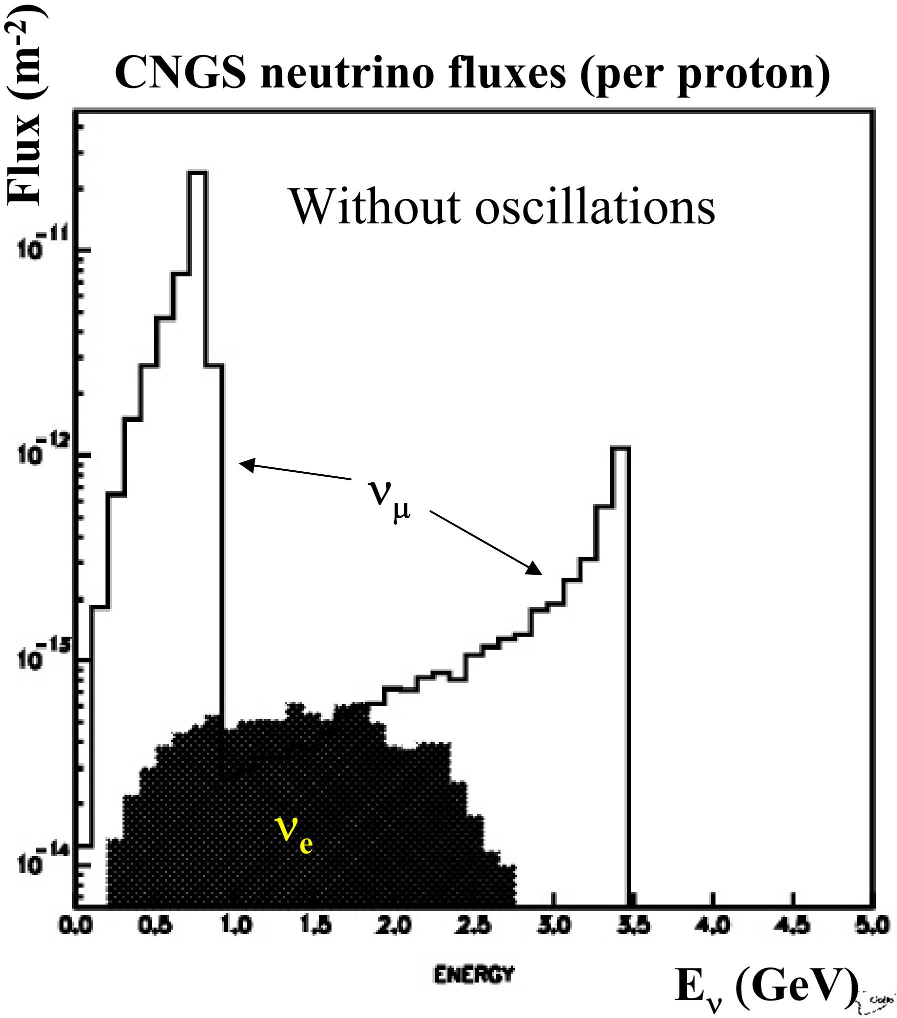
400 kton water detector 1 , 90%CL, 99%CL lines

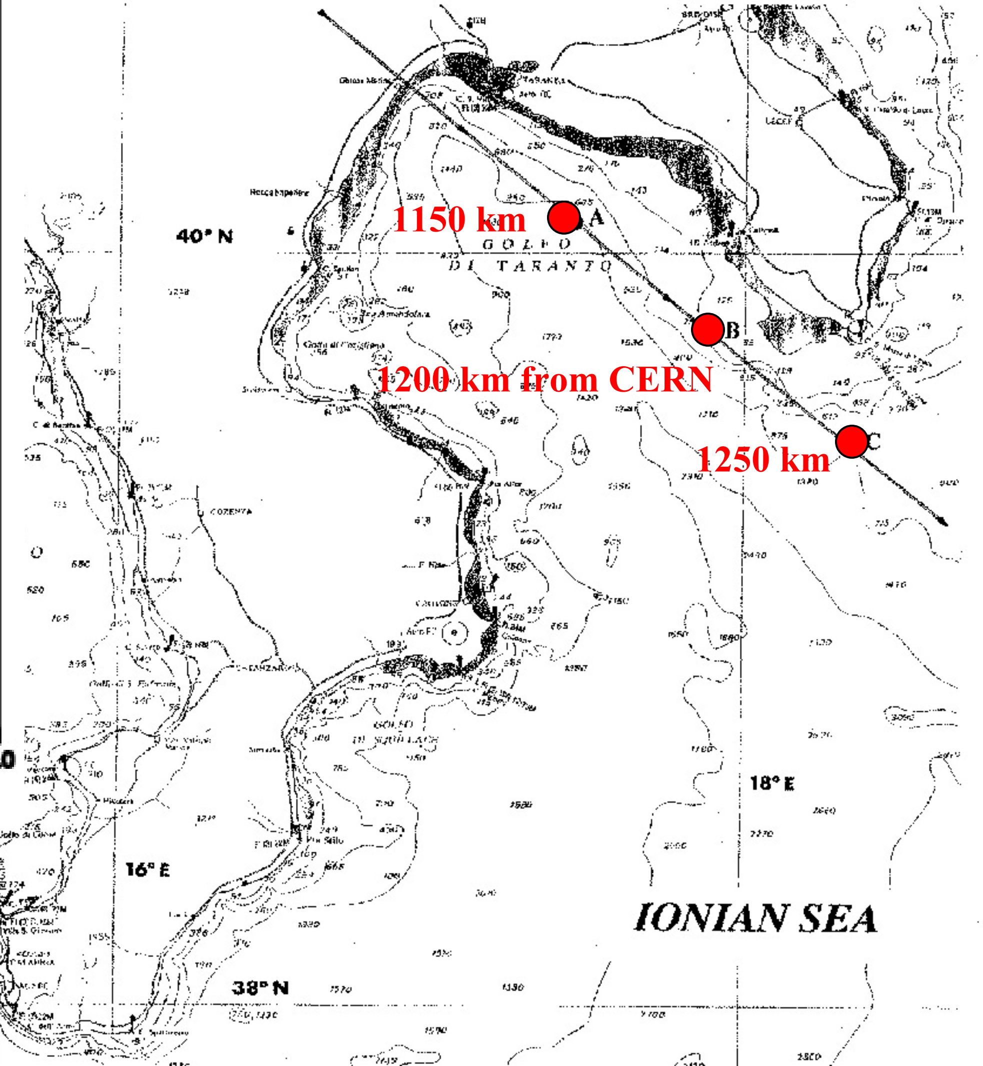


Mezzetto

M. Mezzetto, "Future Neutrino Oscillations ", Moriond, March 17, 2003. .

Off-Axis CNGS to Gulf of Taranto





Dydak

Gulf of Taranto Detector

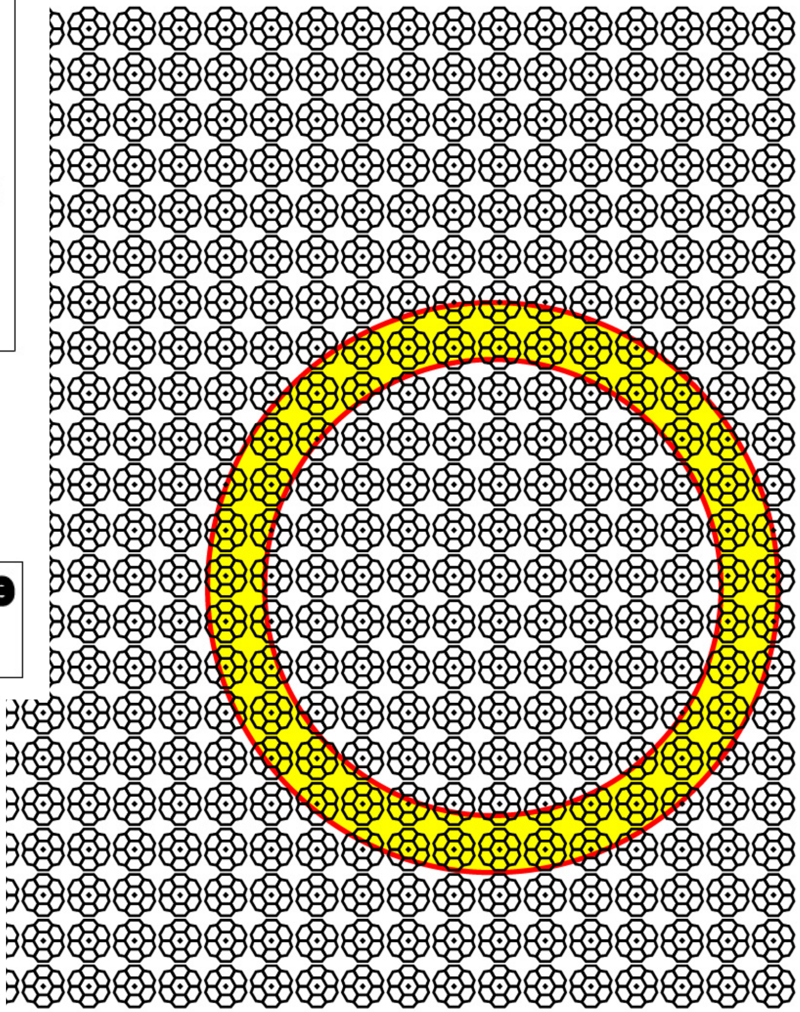
Detector wall in Gulf of Taranto...

Depth	1000 m
Diameter	300 m
No. of PMT's	8000
Distance between PMT's	3.2 m
Area per PMT	8.9 m^2
Transverse dimension of mirror unit	1.2 m
Fraction of active coverage	14%

...later re-arranged as km^3 underwater array

Depth	as large as possible
Distance between PMT's	50 m

	No. of events
Reference: ν_μ^π CC events w/o oscillation	14700
NC background ($1\pi^0$) from ν_μ^π	50
NC background ($1\pi^0$) from ν_μ^K	30
Intrinsic ν_e ($\sim$ 0:1%)	20
Sum of all backgrounds	100
Error on background (stat. + syst.)	15
90% CL on $\sin^2\theta_{13}$	$\sim$ 0:002



2MT fiducial mass running for 3 years with 5x10^{19} protons/year

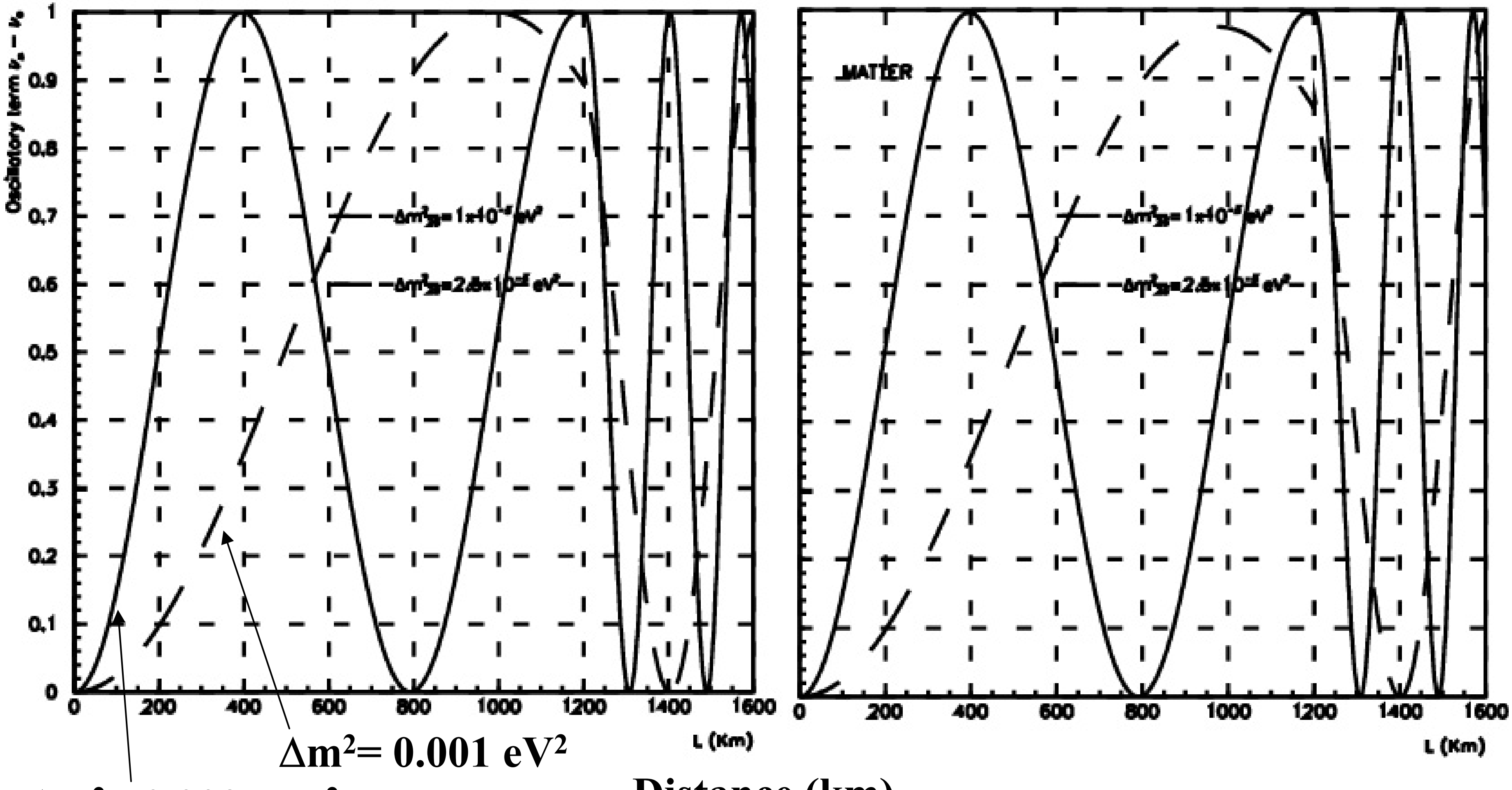
Dydak

Oscillation Amplitudes for 800 MeV Neutrinos

$\nu_\mu - \nu_e$

Vacuum Oscillation

Earth Crust Oscillation



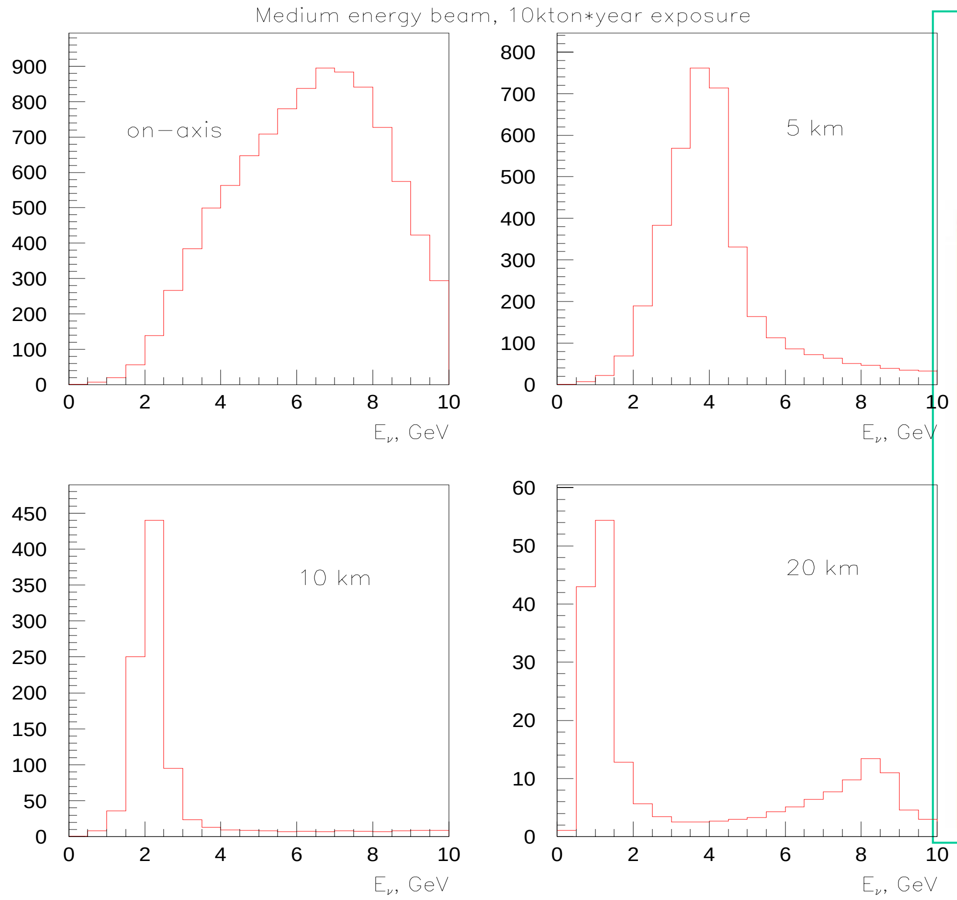
$\Delta m^2 = 0.001$ eV²

$\Delta m^2 = 0.0025$ eV²

Distance (km)

Dydak

Off-Axis Numi Beams


Medium energy beam, 10kton*year exposure

- •~ 2 GeV energy :
  - Below t threshold
  - Relatively high rates per proton, especially for antineutrinos
- •Matter effects to differentiate mass hierarchies
- •Baselines 700 – 1000 km

Sources of the ν_e background

NuMI Off-axis Detector

Low Z imaging calorimeter:

- Glass RPC or
- Drift tubes or
- Liquid or solid scintillator

Electron ID efficiency ~ 40% while keeping NC background below intrinsic ν_e level

Well known and understood detector technologies

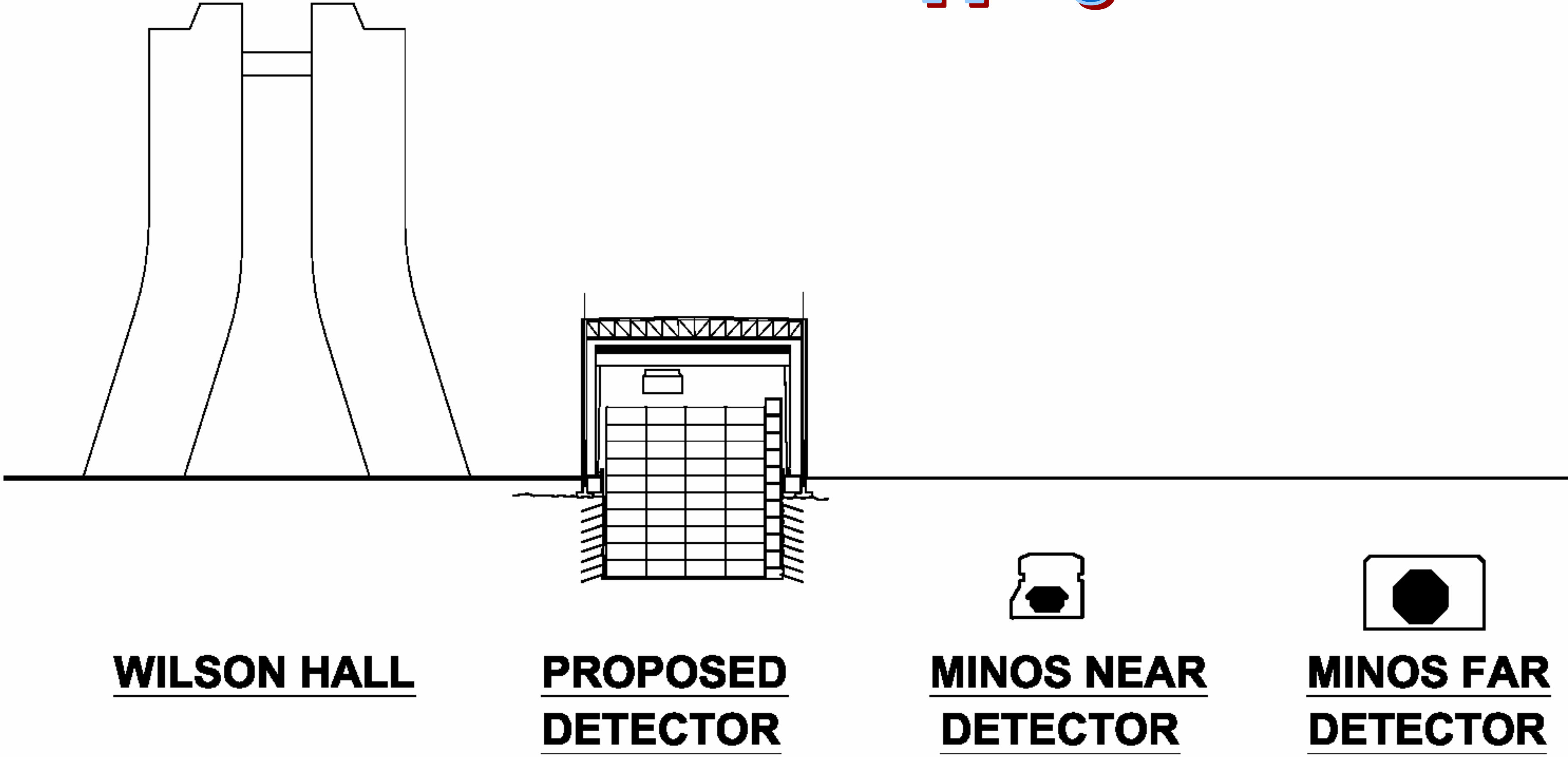
Primarily the engineering challenge of (cheaply) constructing a very massive detector

How massive??

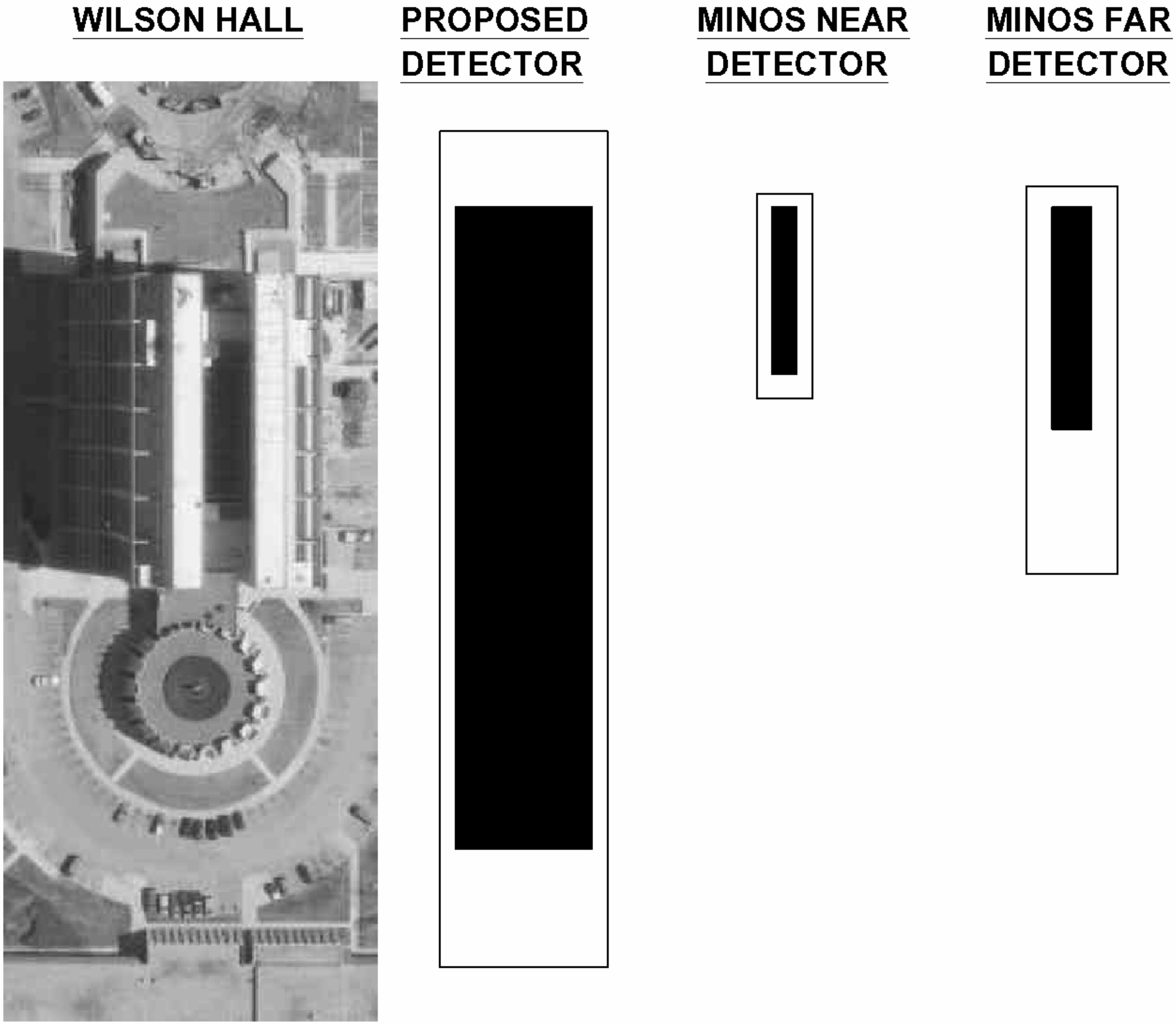
50 kton detector, 5 years run =>

- 10% measurement if $\sin^2 2\theta_{13}$ at the CHOOZ limit, or
- 3σ evidence if $\sin^2 2\theta_{13}$ factor 10 below the CHOOZ limit (normal hierarchy, $\delta=0$), or
- Factor 20 improvement of the limit

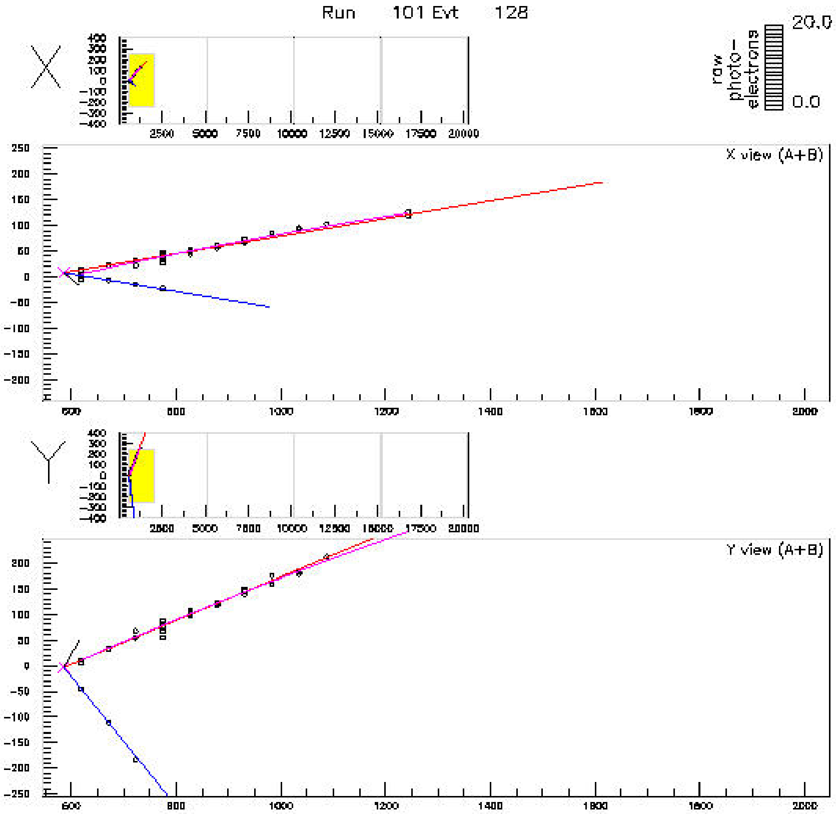
A Modular Detector
Built in Shipping Containers?



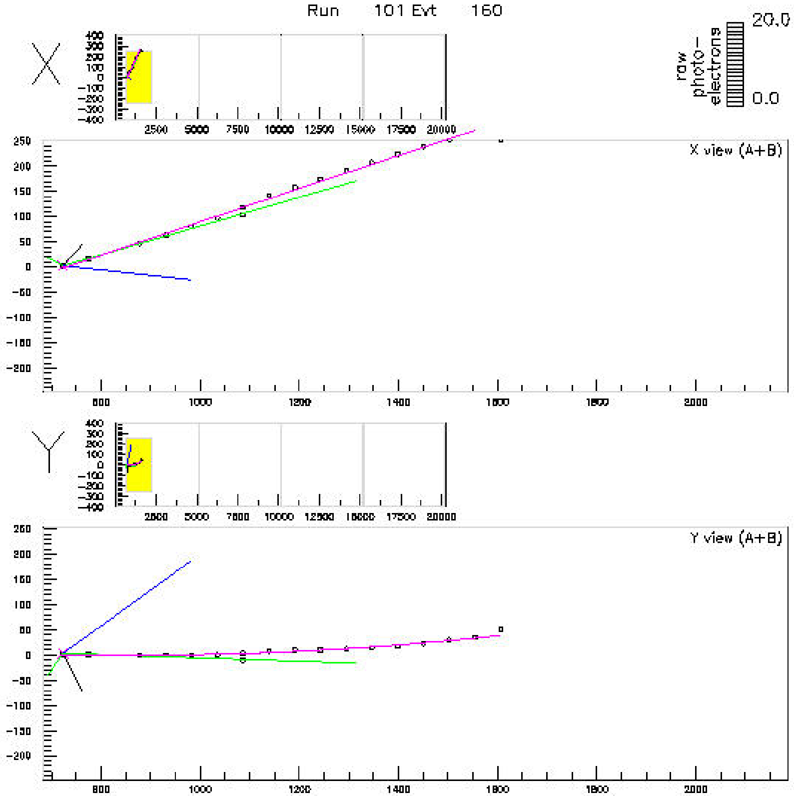
Cooper


WILSON HALL
PROPOSED DETECTOR
MINOS NEAR DETECTOR
MINOS FAR DETECTOR

Signal and background



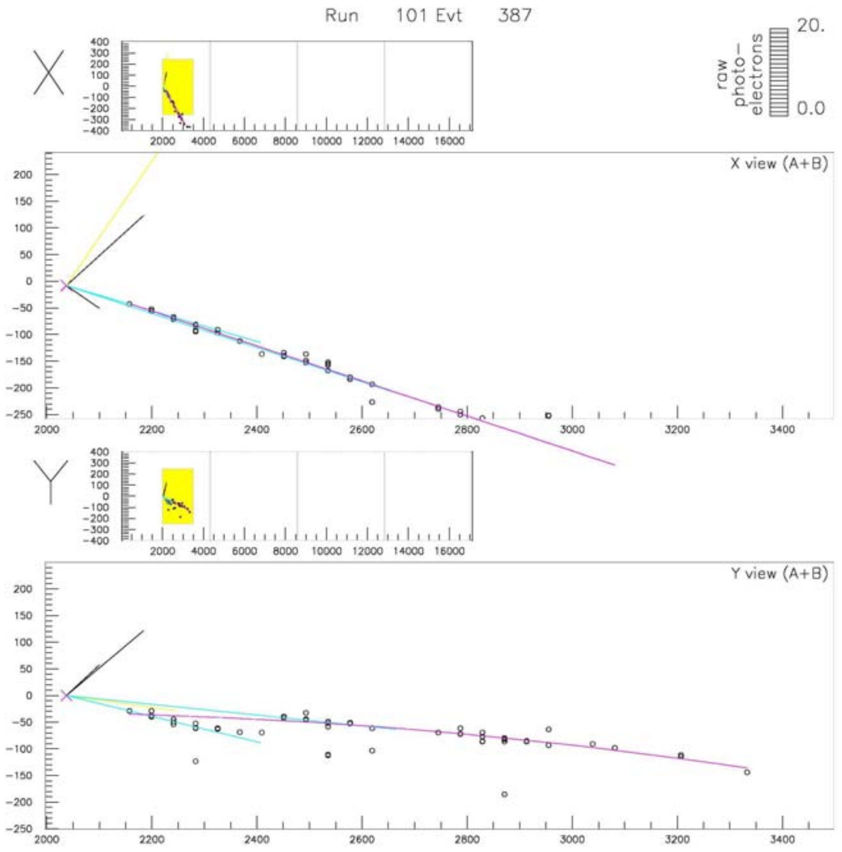
Fuzzy track = electron



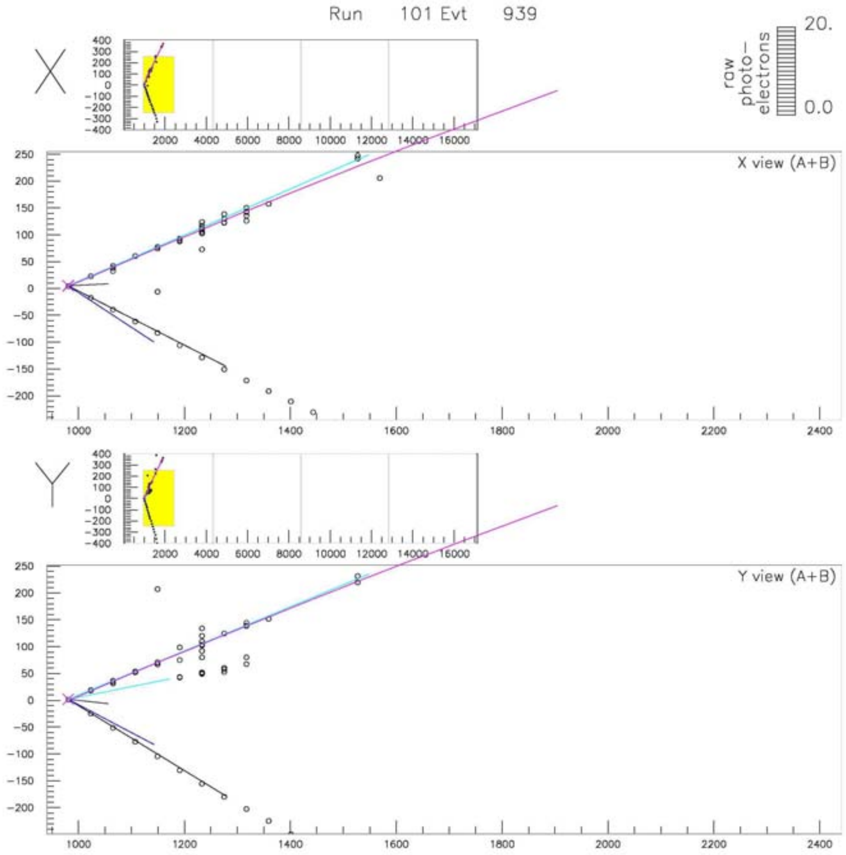
Clean track = muon (pion)

Wojcicki

Background examples



NC - π^0 - 2 tracks



ν_μ CC - with π^0 - muon

Two phase program?

Phase I? (~ $100-200 M, running 2008 – 2014)

- 50 kton (fiducial) detector with ε~35-40%
- 4x10^{20} protons per year (Nominal NuMI design plan… conservative? 6-8?)
- 1.5 years neutrino (6000 ν_μ CC, 70-80% ‘oscillated’)
- 5 years antineutrino (6500 ν_μ CC, 70-80% ‘oscillated’)

Phase II? (running 2014-2020)

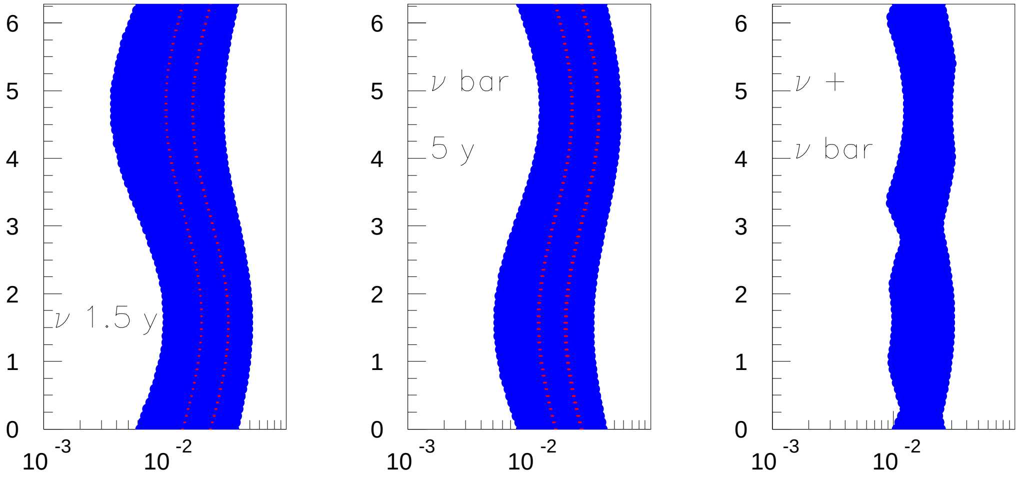
- 200 kton (fiducial) detector with ε~35-40%
- 20x10^{20} protons per year (needs new proton source)
- 1.5 years neutrino (120000 ν_μ CC, 70-80% ‘oscillated’)
- 5 years antineutrino (130000 ν_μ CC, 70-80% ‘oscillated’)

NuMI Off-Axis Sensitivity for Phases I and II

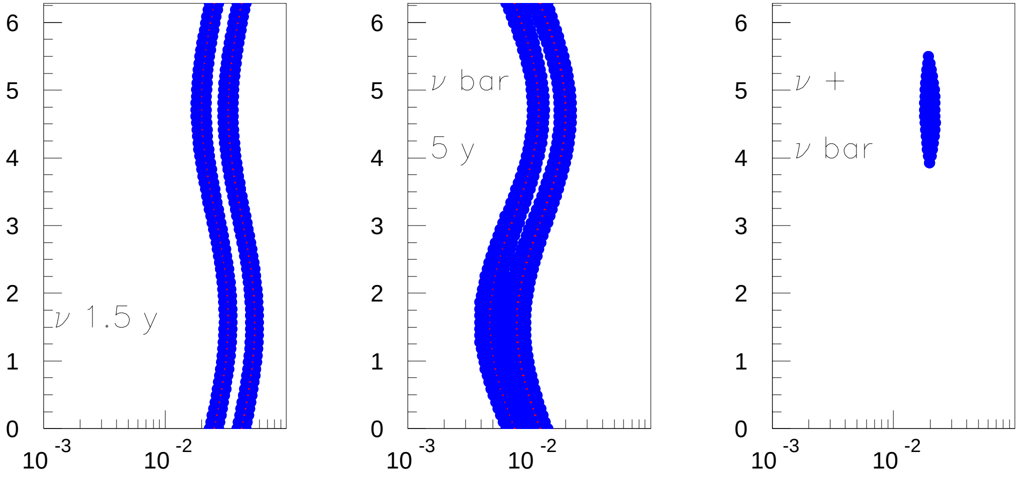
We take the Phase II to have 25 times higher POT x Detector mass

Neutrino energy and detector distance remain the same

$\delta-\sin^2 2\vartheta_{13}$ correlation, $\sin^2 2\vartheta_{13}=0.02$, $\delta=3\pi/2$, Phase I



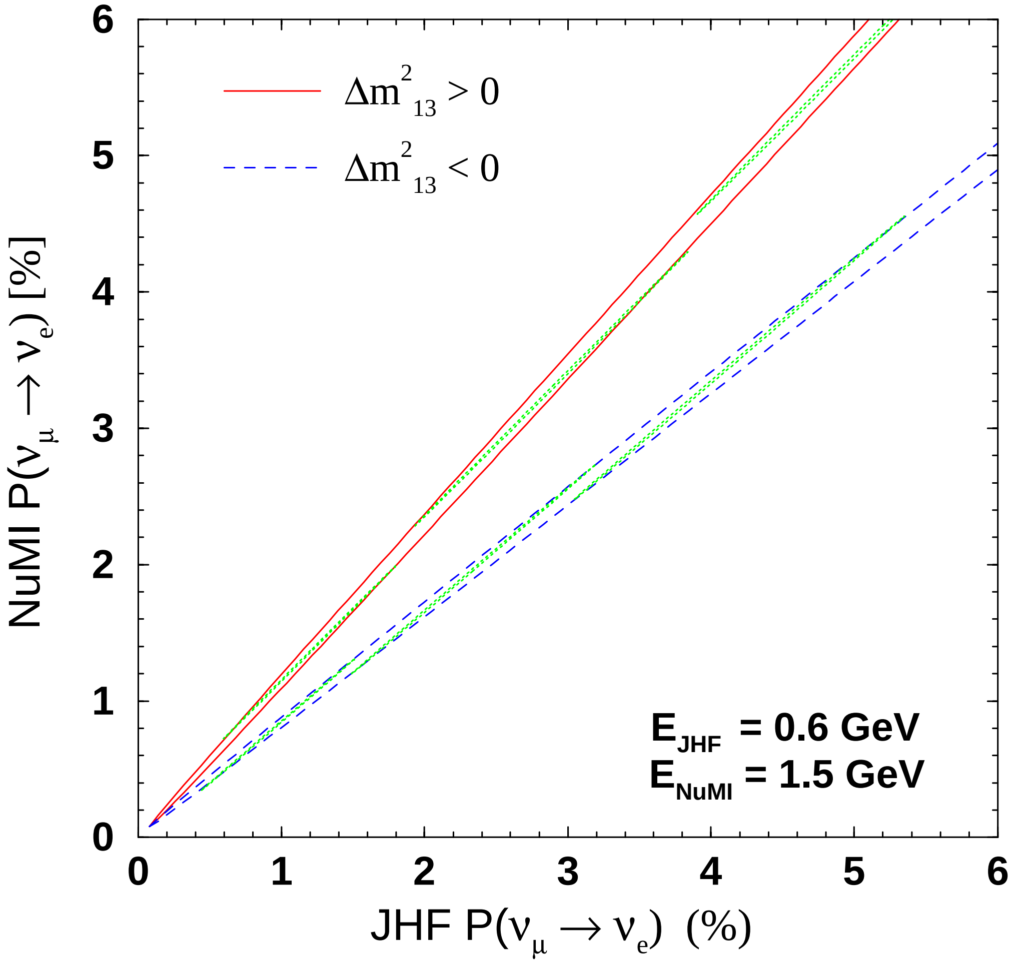
$\delta-\sin^2 2\vartheta_{13}$ correlation, $\sin^2 2\vartheta_{13}=0.02$, $\delta=3\pi/2$, Phase II



	NuMI Off-axis 50 kton, 85% eff, 5 years, 4x10^{20} pot/y		JHF to SK Phase I, 5 years	
	all	After cuts	all	After cuts
ν_μ CC (no osc)	28348	6.8	10714	1.8
NC	8650	19.4	4080	9.3
Beam ν_e	604	31.2	292	11
Signal (Δm^2_{23}=2.8/3 x 10^{-3}, NuMI/JHF)	867.3	307.9	302	123
FOM (signal/√bckg)		40.7		26.2

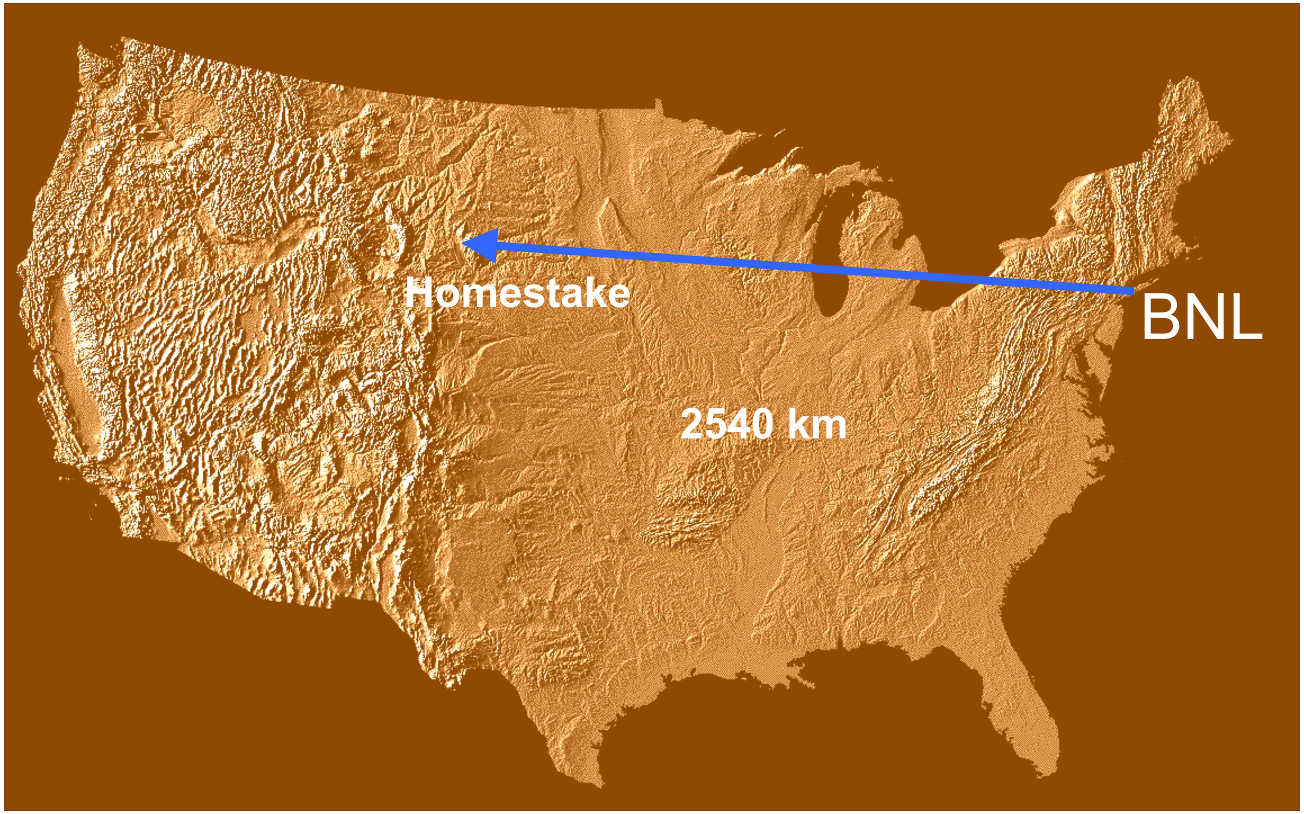
Determination of mass hierarchy: complementarity of JHF and NuMI

Combination of different baselines: NuMI + JHF extends the range of hierarchy discrimination to much lower mixing angles



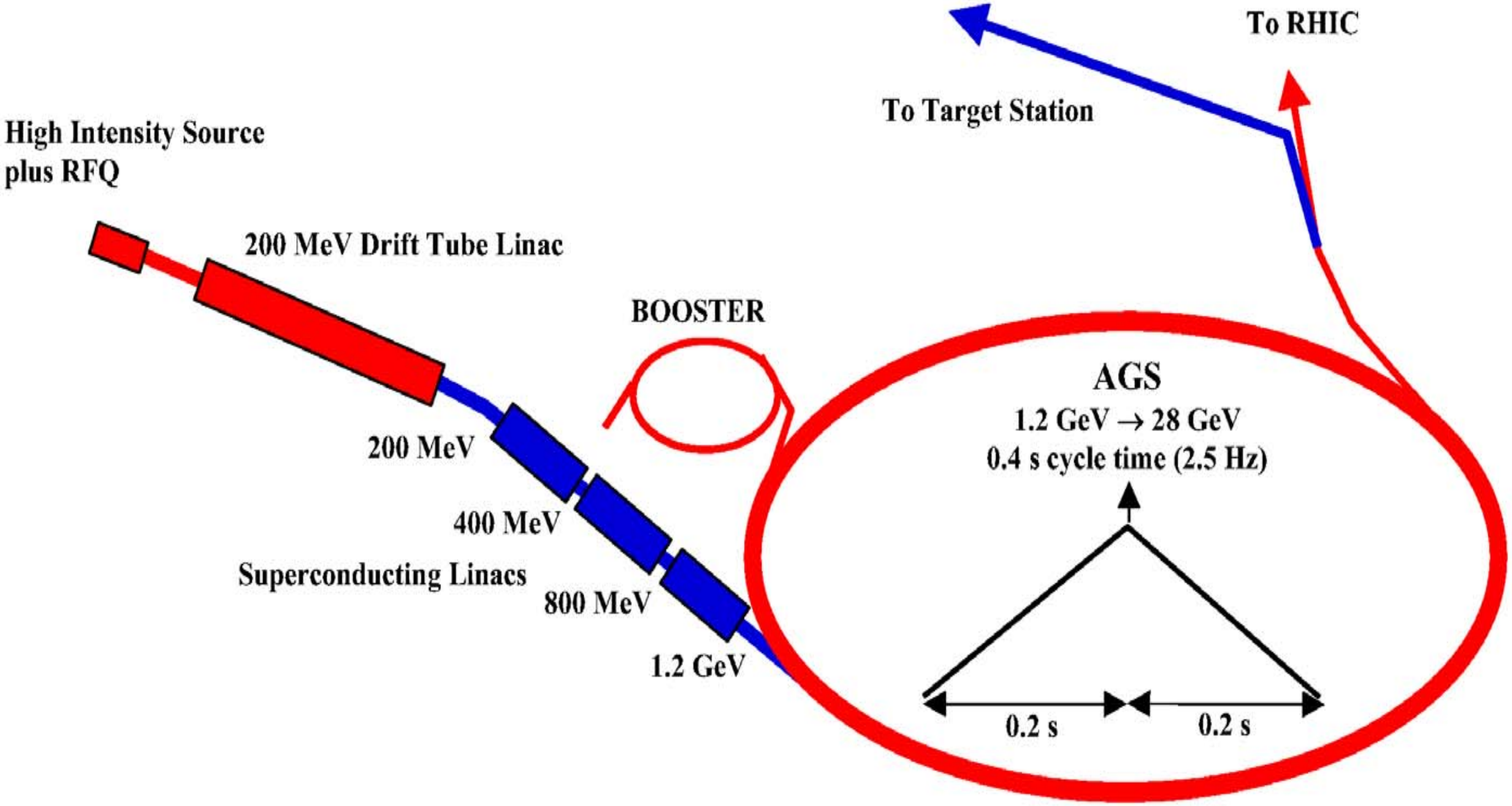
Minakata,Nunokawa, Parke

BNL → Homestake Super Neutrino Beam



28 GeV protons, 1 MW beam power
500 kT Water Cherenkov detector
5e7 sec of running, Conventional Horn based beam

AGS Target Power Upgrade to 1 MW



- the *AGS Upgrade* to provide a source for the 1.0 MW Super Neutrino Beam will cost $265M FY03 (TEC) dollars

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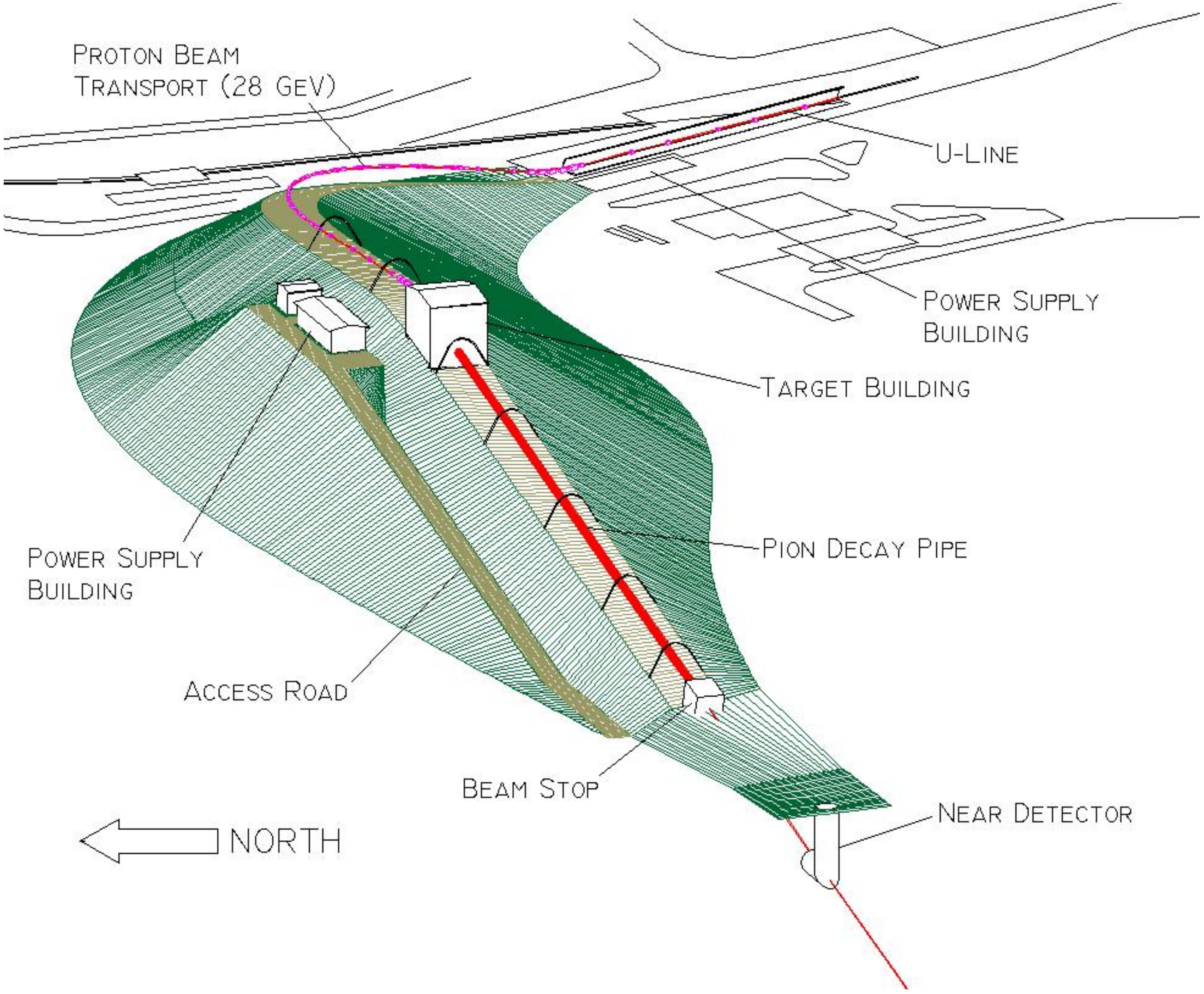
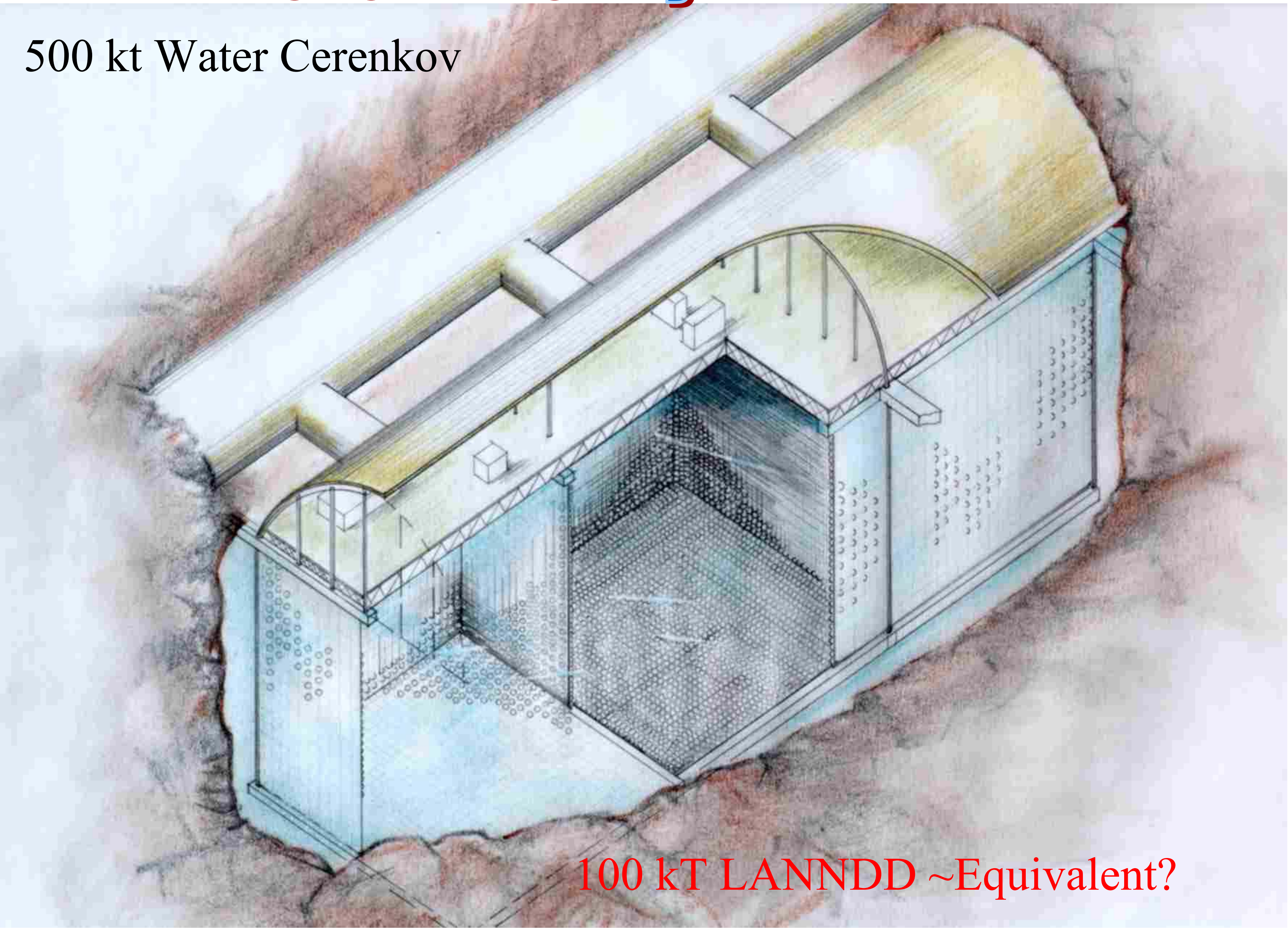
3-D Neutrino Super Beam Perspective



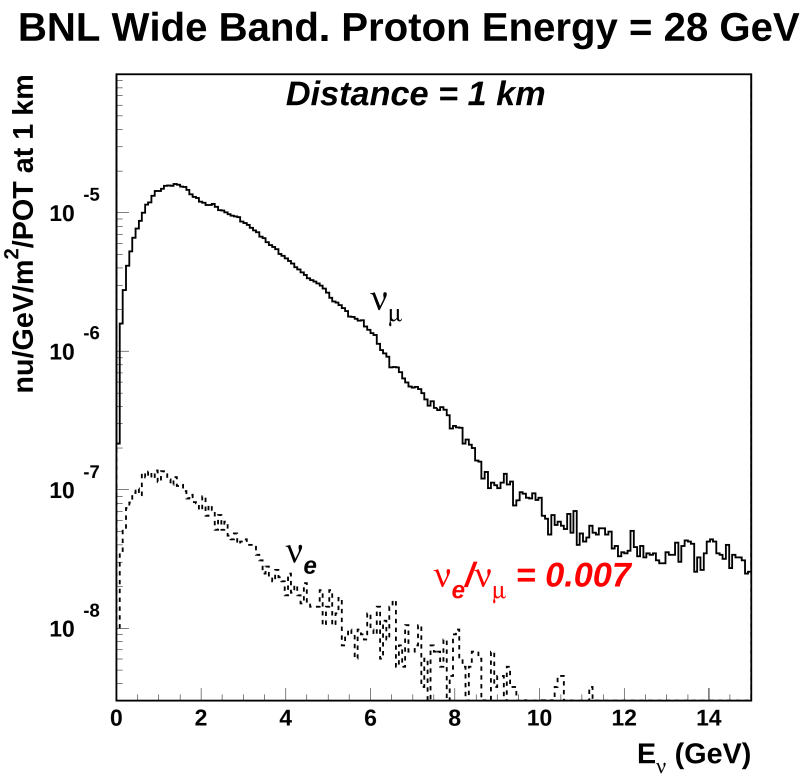
UNO: The Study Baseline



500 kt Water Cerenkov

100 kT LANNDD ~Equivalent?

Neutrino spectrum from AGS



- Proton energy 28 GeV
- 1 MW total power
- ~10^{14} proton per pulse
- Cycle 2.5 Hz
- Pulse width 2.5 mu-s
- Horn focused beam with graphite target
- 5×10^{-5} ν/m^2/POT @ 1km

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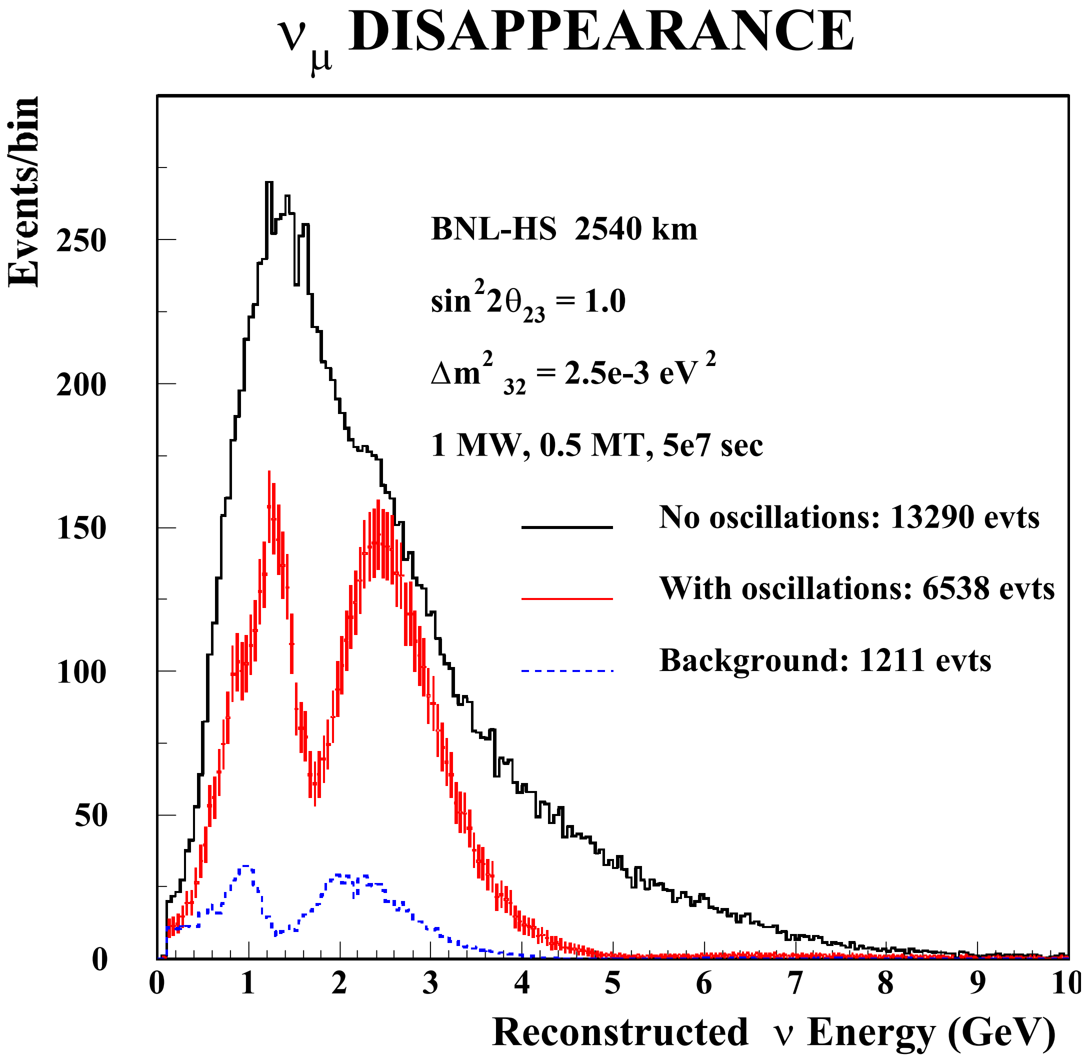
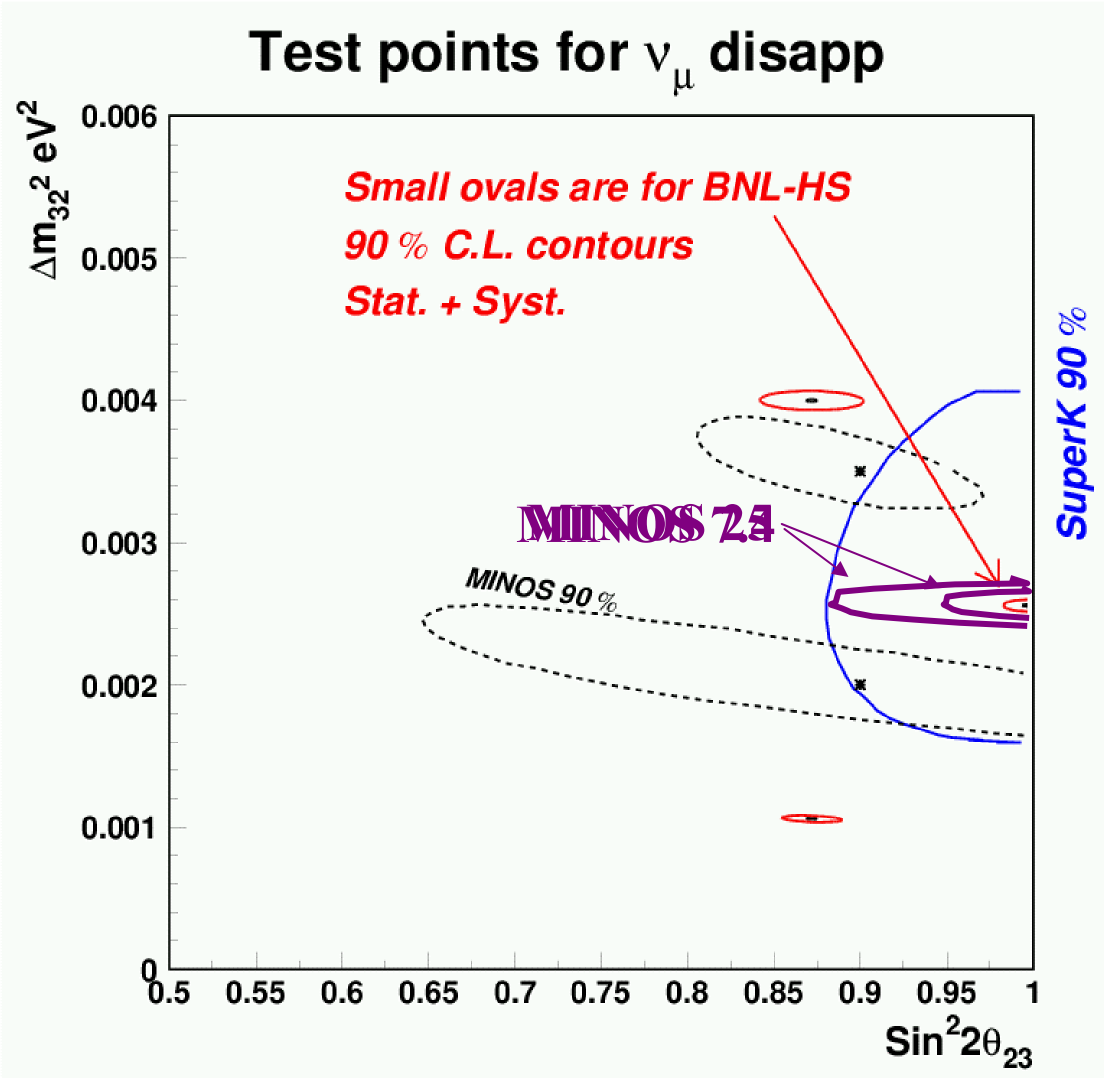
Advantages of a Very Long Baseline


ν_μ DISAPPEARANCE

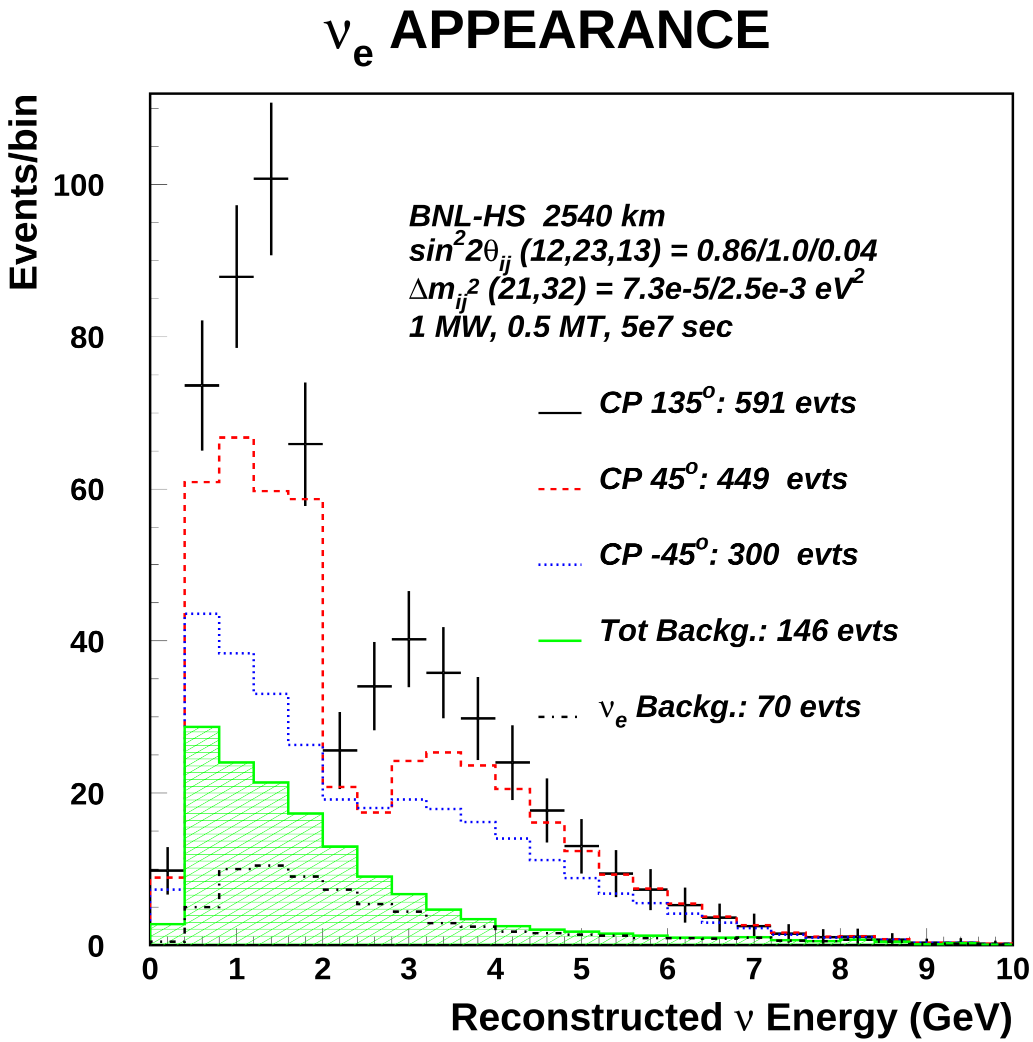
- neutrino oscillations result from the factor $\sin^2(\Delta m_{32}^2 L / 4E)$ modulating the ν flux for each flavor (here ν_μ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a *very long baseline* actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the Δm_{32}^2 to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

VLB Application to Measurement of Δm_{32}^2



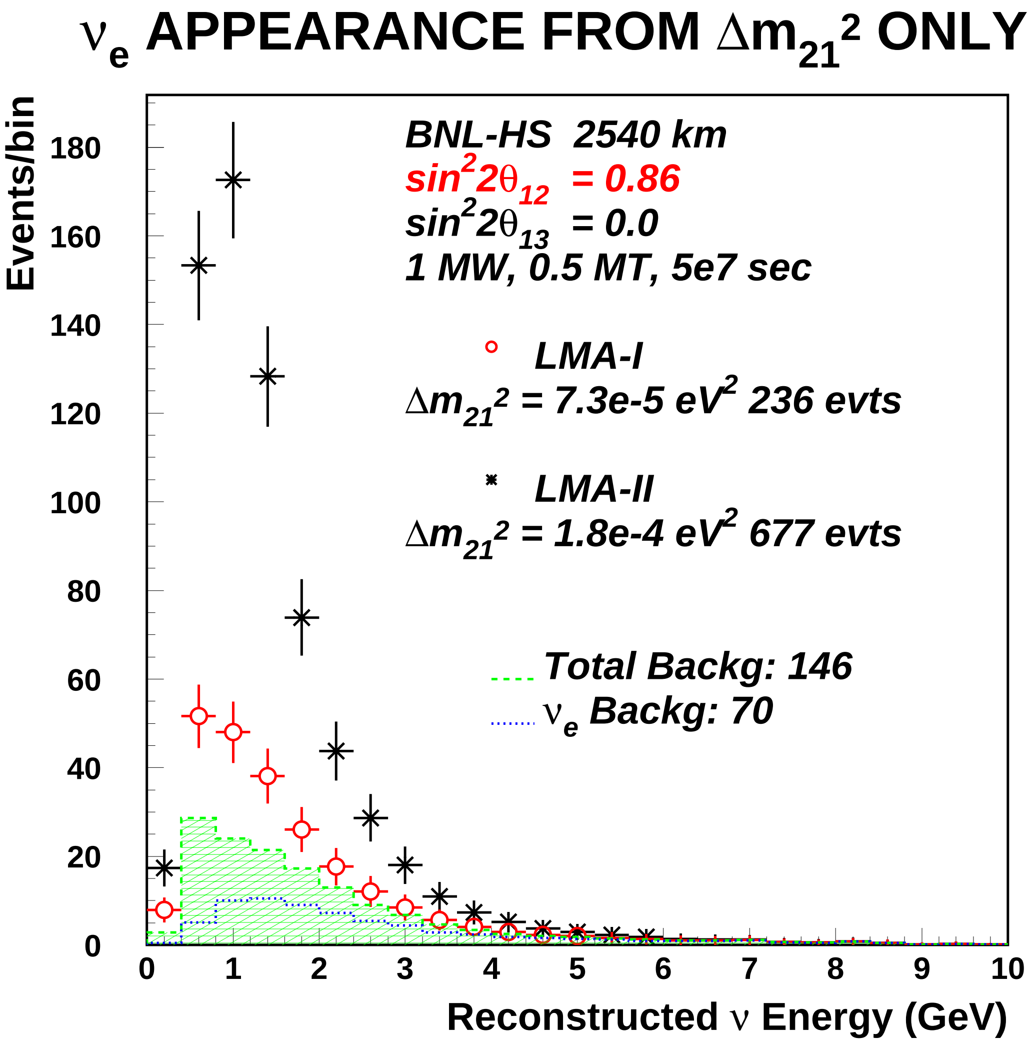
- the multiple node method of the VLB measurement is illustrated by comparing the BNL 5-year measurement precision with the present Kamiokande results and the projected MINOS 3-year measurement precision; all projected data include both statistical and systematic errors
- there is no other plan, worldwide, to employ the VLB method (a combination of target power and geographical circumstances limit other potential competitors)
- other planned experiments can’t achieve the VLB precision

ν_e Appearance Measurements



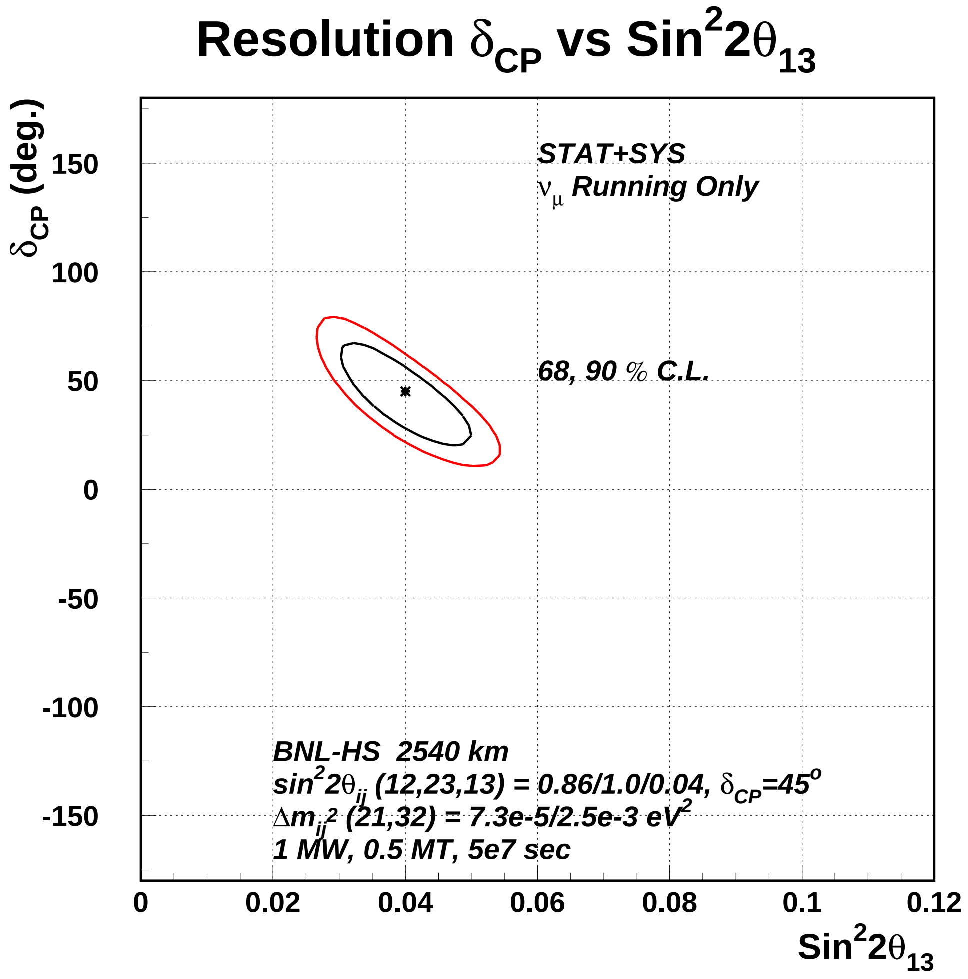
- a direct measurement of the appearance of $\nu_\mu \rightarrow \nu_e$ is important; the VLB method competes well with any proposed super beam concept
- for values > 0.01, a measurement of $\sin^2 2\theta_{13}$ can be made (the current experimental limit is 0.12)
- for most of the possible range of $\sin^2 2\theta_{13}$, a good measurement of θ_{13} and the CP-violation parameter δ_{CP} can be made by the VLB experimental method

ν_e Appearance Measurements (Cont.)



- even if $\sin^2 2\theta_{13} = 0$, the current best-fit value of $\Delta m_{21}^2 = 7.3\text{x}10^{-5}$ induces a ν_e appearance signal
- the size of the ν_e appearance signal above background depends on the value of Δm_{21}^2; the figure left indicates the range of possible measured values for the ν_e yields above background for various assumptions of the final value of Δm_{21}^2

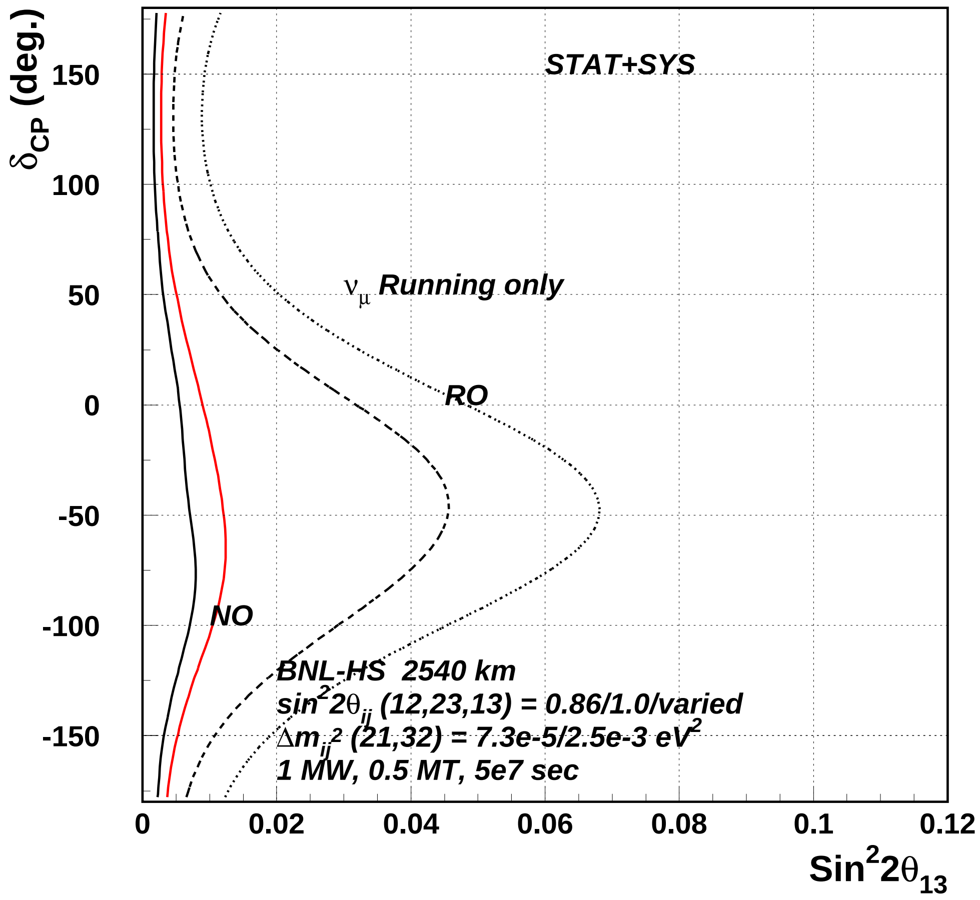
Mass -ordering and CP-violation Parameter δ_{CP}



- the CP-violation parameter δ_{CP} can be measured in the VLB exp. And is relatively insensitive to the value of $\sin^2 2\theta_{13}$
- the mass-ordering of the neutrinos is determined in the VLB exp; $\nu_1 < \nu_2 < \nu_3$ is the natural order but $\nu_1 < \nu_3 < \nu_2$ is still possible experimentally; VLB determines this, using the effects of matter on the higher-energy neutrinos

Possible limits on $\sin^2 2\theta_{13}$ versus δ_{CP}

90, 99.7 % CL signal, δ_{CP} vs $\sin^2 2\theta_{13}$



- **For normal mass ordering limit on $\sin^2 2\theta_{13}$ will be 0.005 for no CP**

If reversed mass ordering then need to run antineutrinos

Comparison of Some Experiments

		F2S	C2GT	JHF2K	JHF2K-II	C2F	C2F+BB	νF	MINOS25	BNL-NUSEL
$< E_\nu >$ [GeV]		2	0.8	1	1	0.3	0.3	10	1-5	1-10
Fiducial mass	Water Cherenkov		1 Mt	22.5 kt	1 Mt	40 kt	1Mt			500 kT
	Iron/scintillator	20 kt						40 kt	5kT	100kt LA?
	Plastic/RPCs	20 kt								
Physics reach	$\sigma(\Delta m^2_{23})$ [eV^2]	1×10^{-4}	3×10^{-5}	1×10^{-4}		1×10^{-4}			2x10^{-4}	1x10^{-4}
	$\sigma(\sin^2 2\theta_{23})$	0.01	0.01	0.01		0.01			0.05	0.01
	$\sin^2\theta_{13}$ [90% CL]	1.5×10^{-3}		1.5×10^{-3}	2.5×10^{-4}	1.5×10^{-3}		2.5×10^{-5}	~0.03	~0.003
	θ_{13} [deg: 90% CL]	2.2		2.2	0.9	2.2		0.3		
	sgn Δm^2_{23}	?	No	No	?	No	No	Yes	?	Yes…
	CP-violation	No	No	No	?	No	?	Yes	No	Yes… But may Need nubar.
Incremental material cost (facility + detector [10^9 US \$])		0.1-0.2	0.1	0.2	1.0	0.7	2.0	2.0	0-0.05	1.0
Year of earliest operation		2008	2008		2015		2020		Done 2010	2010-2012?

From NuMI Off-Axis LOI

Conclusions

- Although no option provides a “fast path” to the future of oscillation measurements, there do appear to be several paths which will provide a rich variety of data on these measurements.
- It is likely that more than one will be essential to completely answer all of the questions available in a reasonable period of time.
- Take care for discovery potential beyond what we think we are after now!
- Which ones to undertake? The attraction of incremental investments certainly appears seductive… But taking a bolder step should be seriously considered and debated.