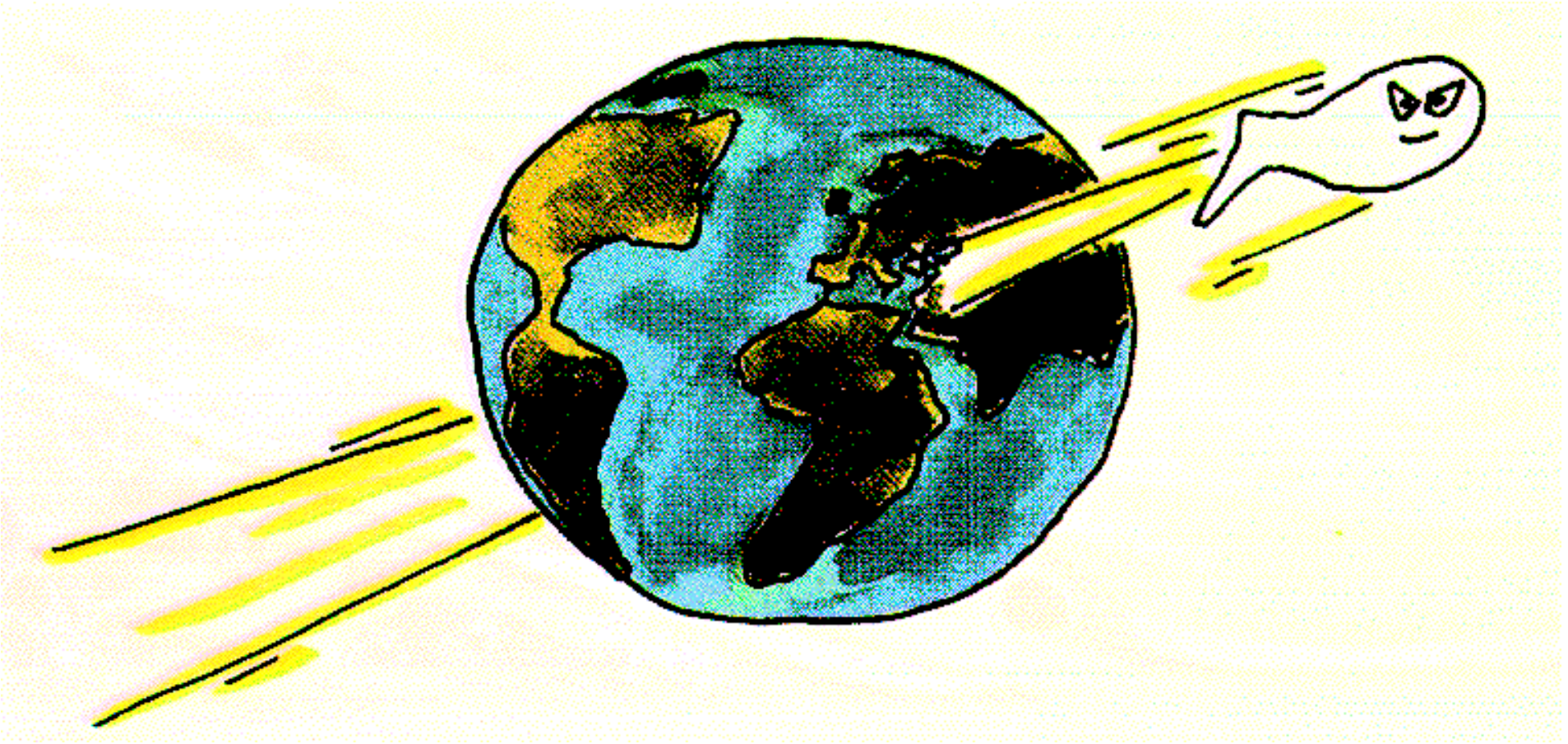
Super-Kamiokande Physics II: Long Baseline Beams



Neutrino Oscillations

Assume

FLAVOR STATES $|\nu_f\rangle$ **are superpositions of** **MASS STATES** $|\nu_m\rangle$

weakly interacting

unitary mixing matrix

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi} |\nu_i\rangle$$

If mixing matrix is not diagonal,
get *flavor oscillations*
as neutrinos propagate

Simple two-flavor case

$$|\nu_f> = \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

$$|\nu_g> = -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

Propagate a distance L:

$$|\nu_i(t)> = e^{-iE_i t}|\nu_i(0)> \sim e^{-im_i^2 L/2p}|\nu_i(0)>$$

Probability of detecting flavor g at L:

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

E in GeV
L in km
Δm^2 in eV^2

Parameters of nature to measure: θ, $\Delta m^2 = m_1^2 - m_2^2$

The Experimental Game

- Start with some neutrinos (natural or artificial)
- Measure (or calculate) flavor composition and energy spectrum
- Let them propagate
- Measure flavor and energies again

Have the flavors and energies changed?

If so, does the change follow $P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$ **?**

Disappearance: ν's oscillate into 'invisible' flavor

e.g. $\nu_e \rightarrow \nu_\mu$ at ~MeV energies

Appearance: directly see new flavor

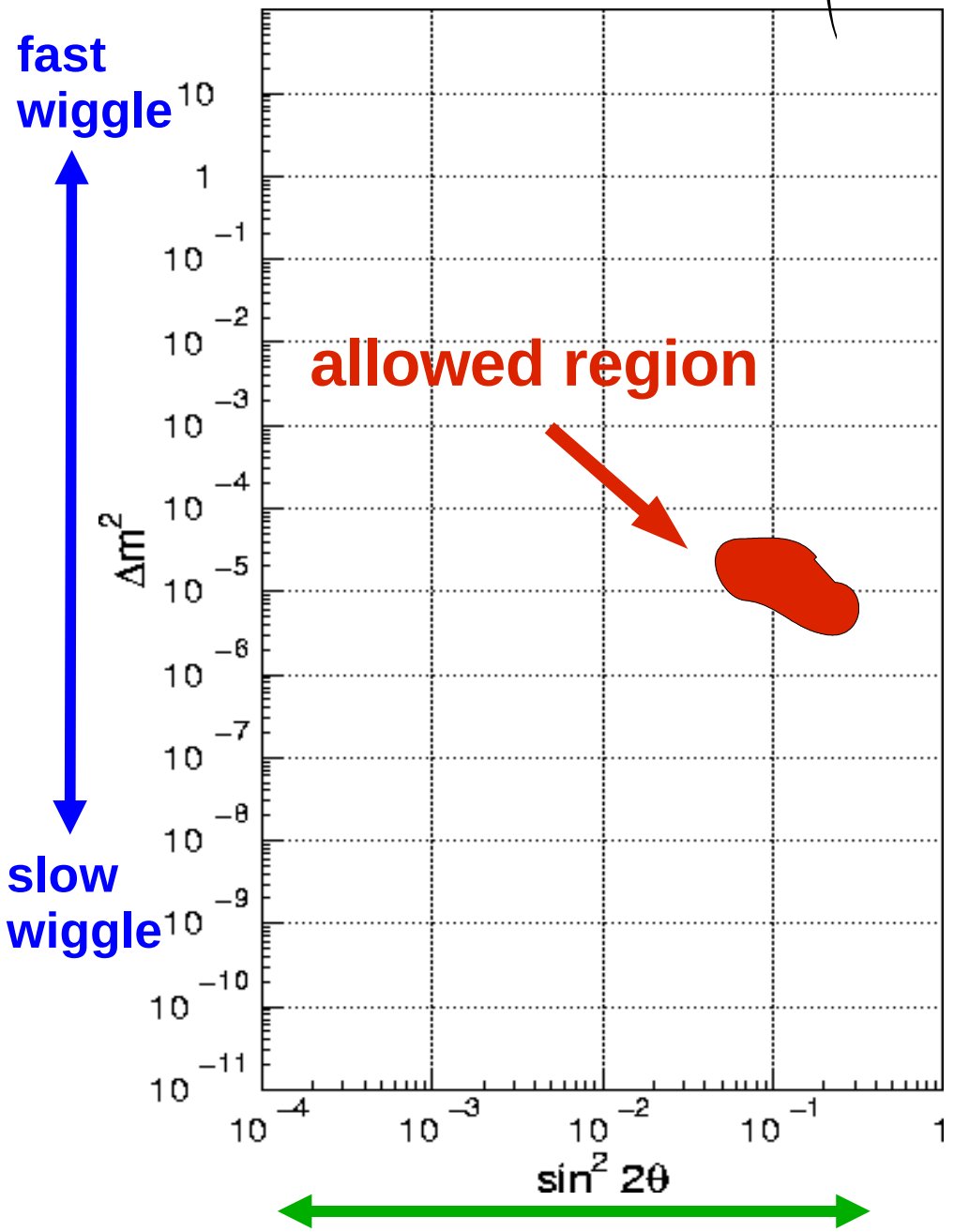
e.g. $\nu_\mu \rightarrow \nu_\tau$ at ~GeV energies

Oscillation Parameter Space

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

Twiddle L/E

Frequency ∝ $\Delta m^2 L/E$

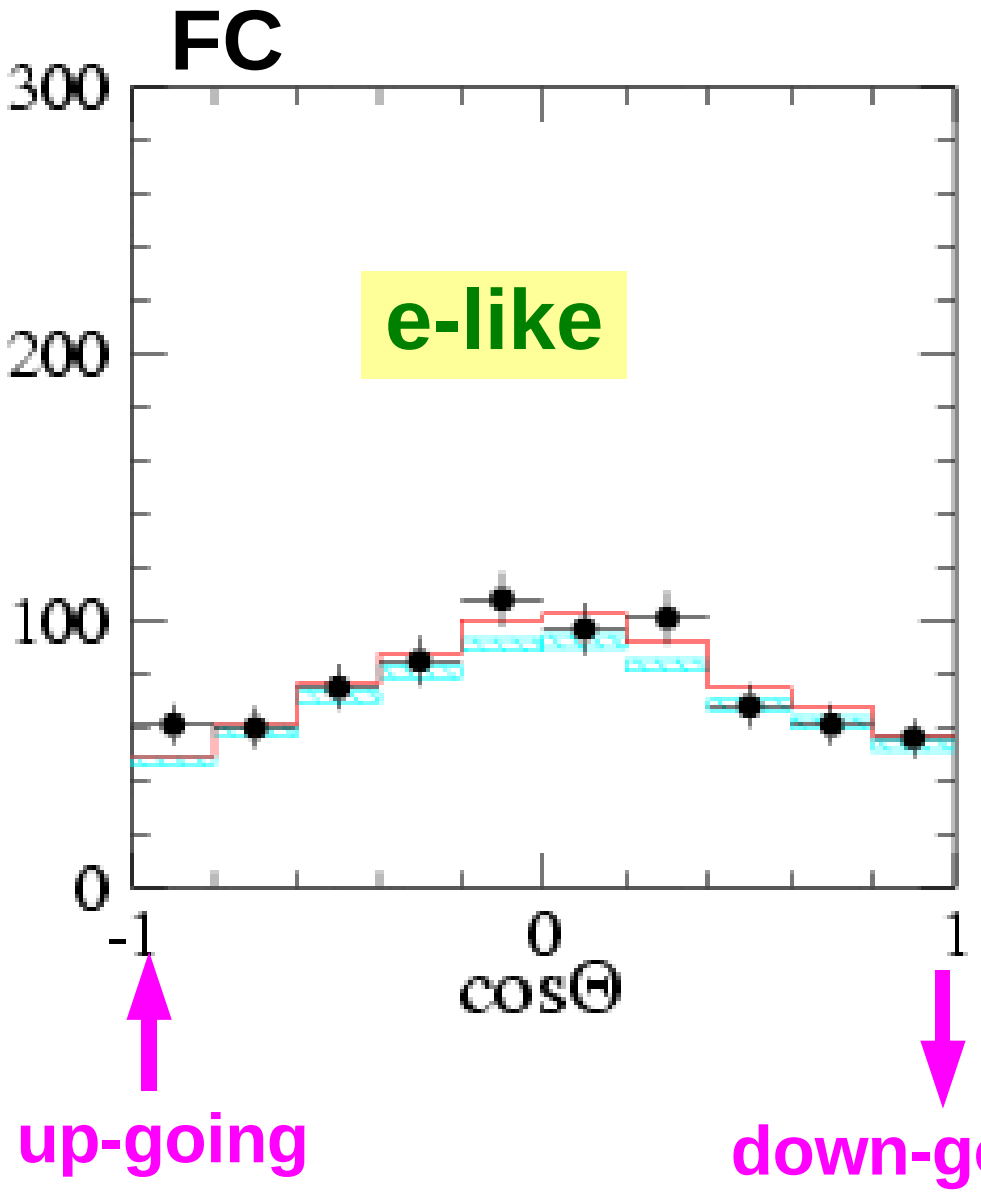


Amplitude ∝ $\sin^2 2\theta$

Experimental statistics

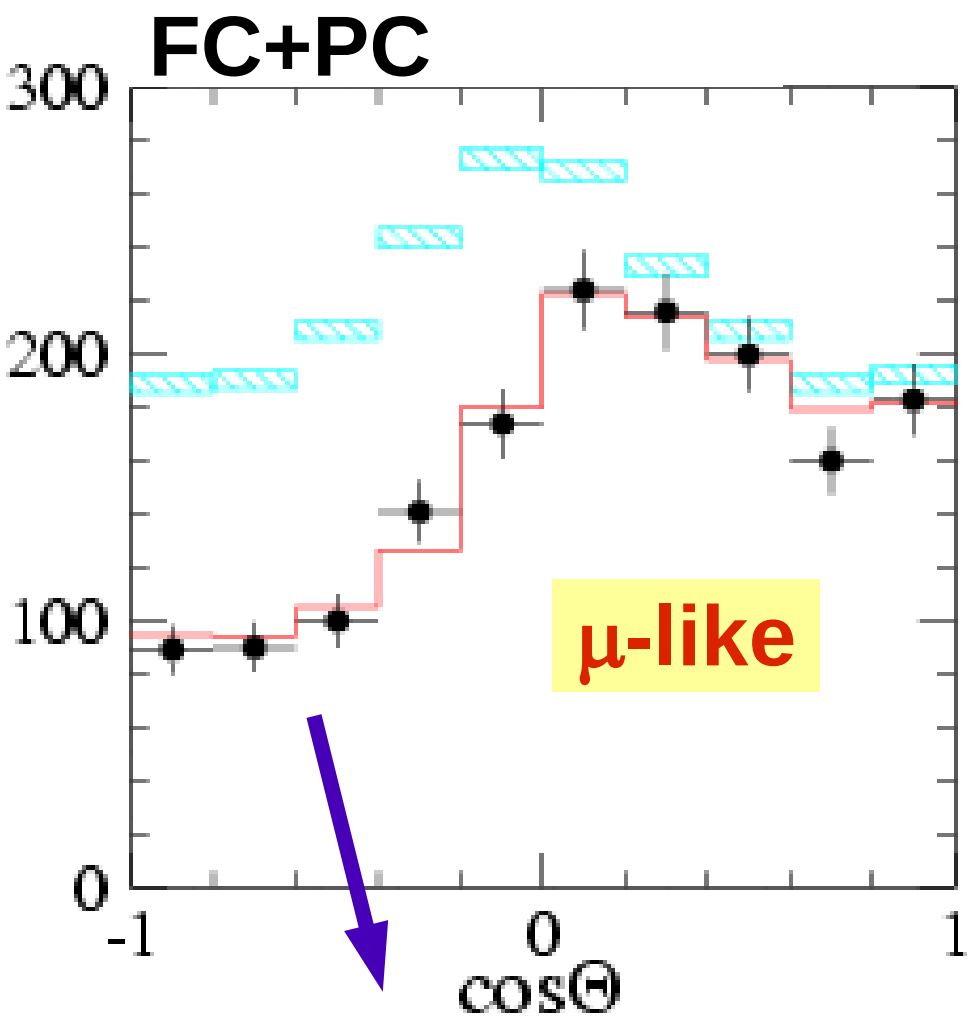
Zenith angle distribution

1489 days of SK data (SKI)



up-going

down-going



Deficit of ν_μ *from below* (long pathlength)

Next: INDEPENDENT TEST of atmospheric neutrino oscillations using a well-understood ν beam

E_ν ~ GeV, L~ 100's of km for same L/E

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

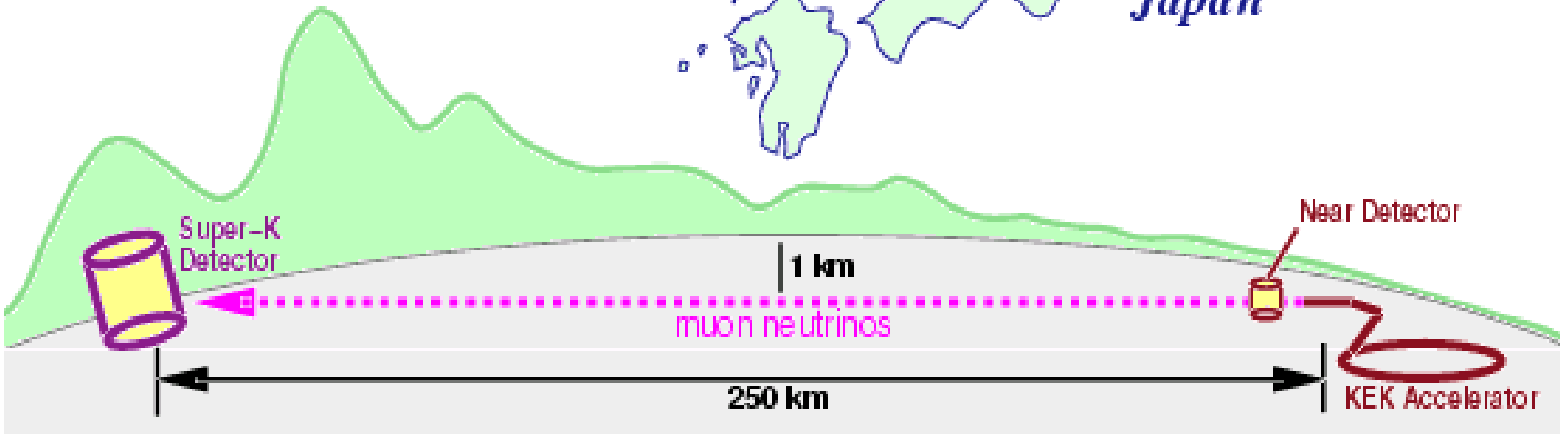
LONG BASELINE EXPERIMENTS

Compare flux, flavor and energy spectrum at near and far detectors

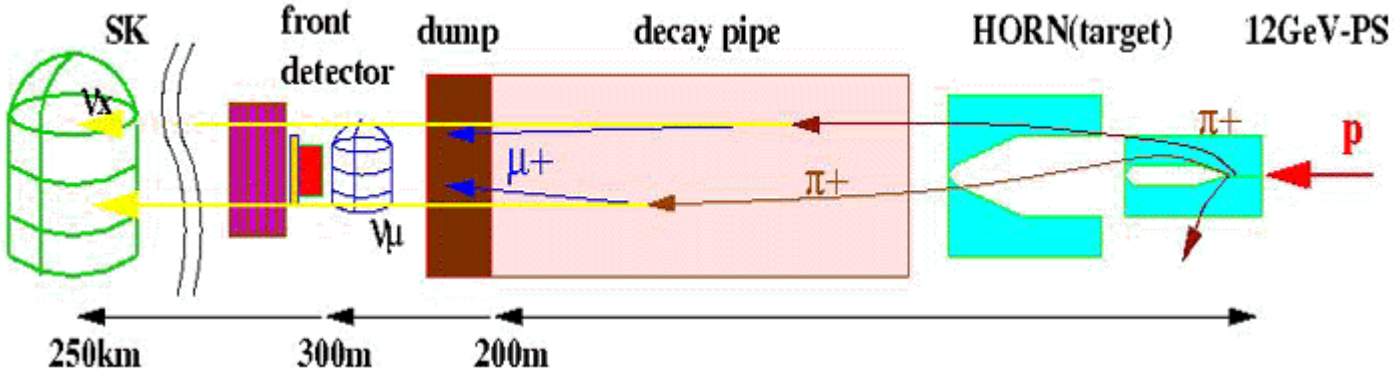
K2K (KEK to Kamioka) Long Baseline Experiment

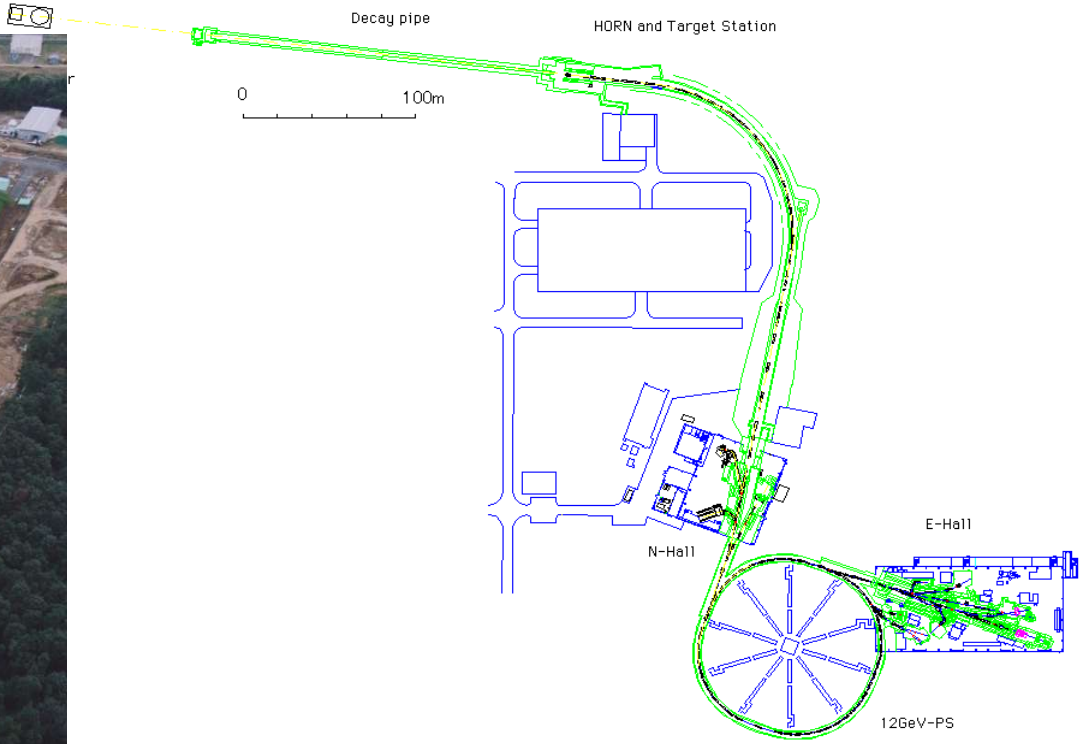
~ 1 GeV muon neutrinos

12 GeV protons on Al target
+ π focusing horn
+ decay pipe for pions
Events matched w/GPS

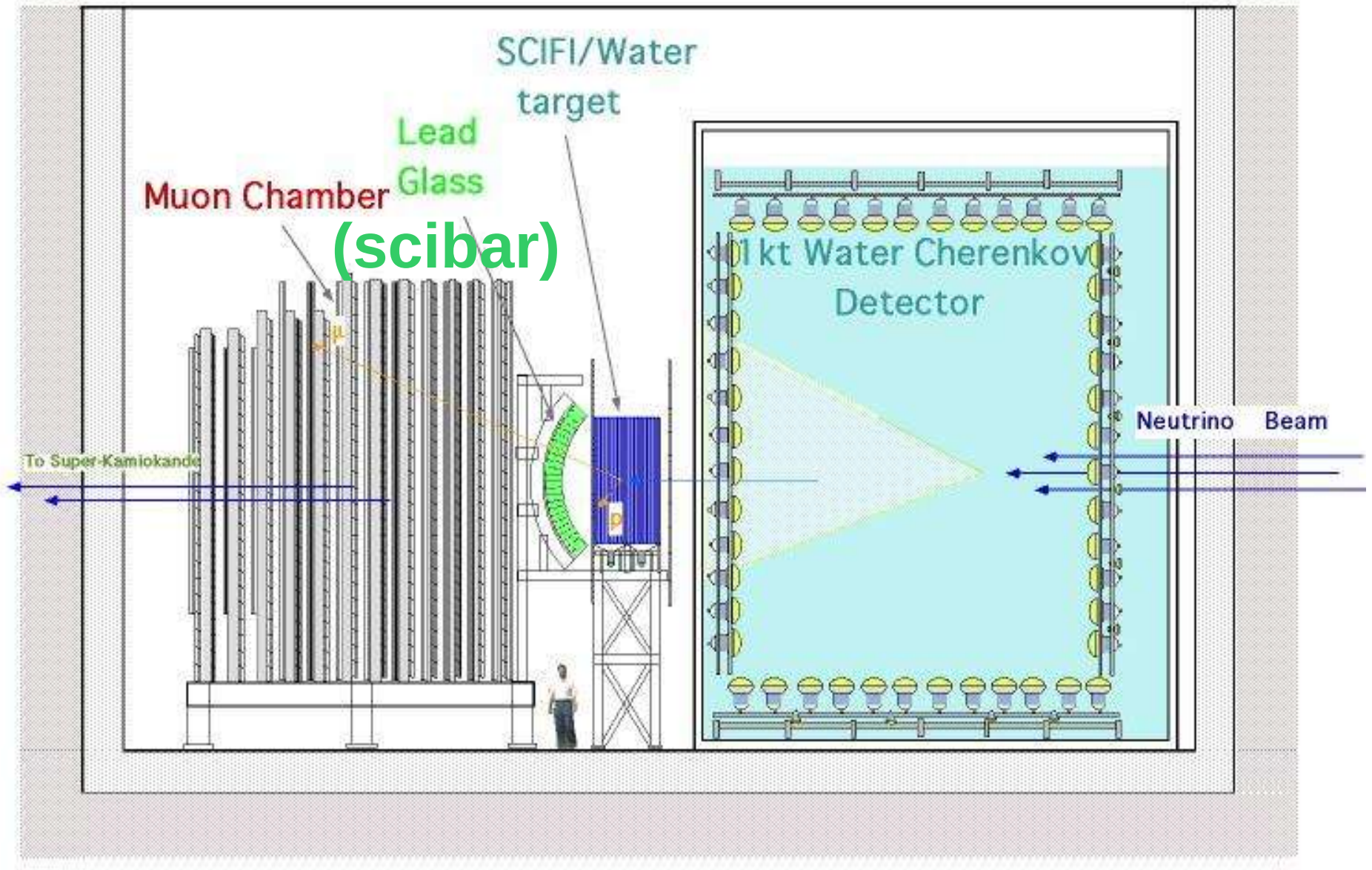


The Neutrino Beamline at KEK



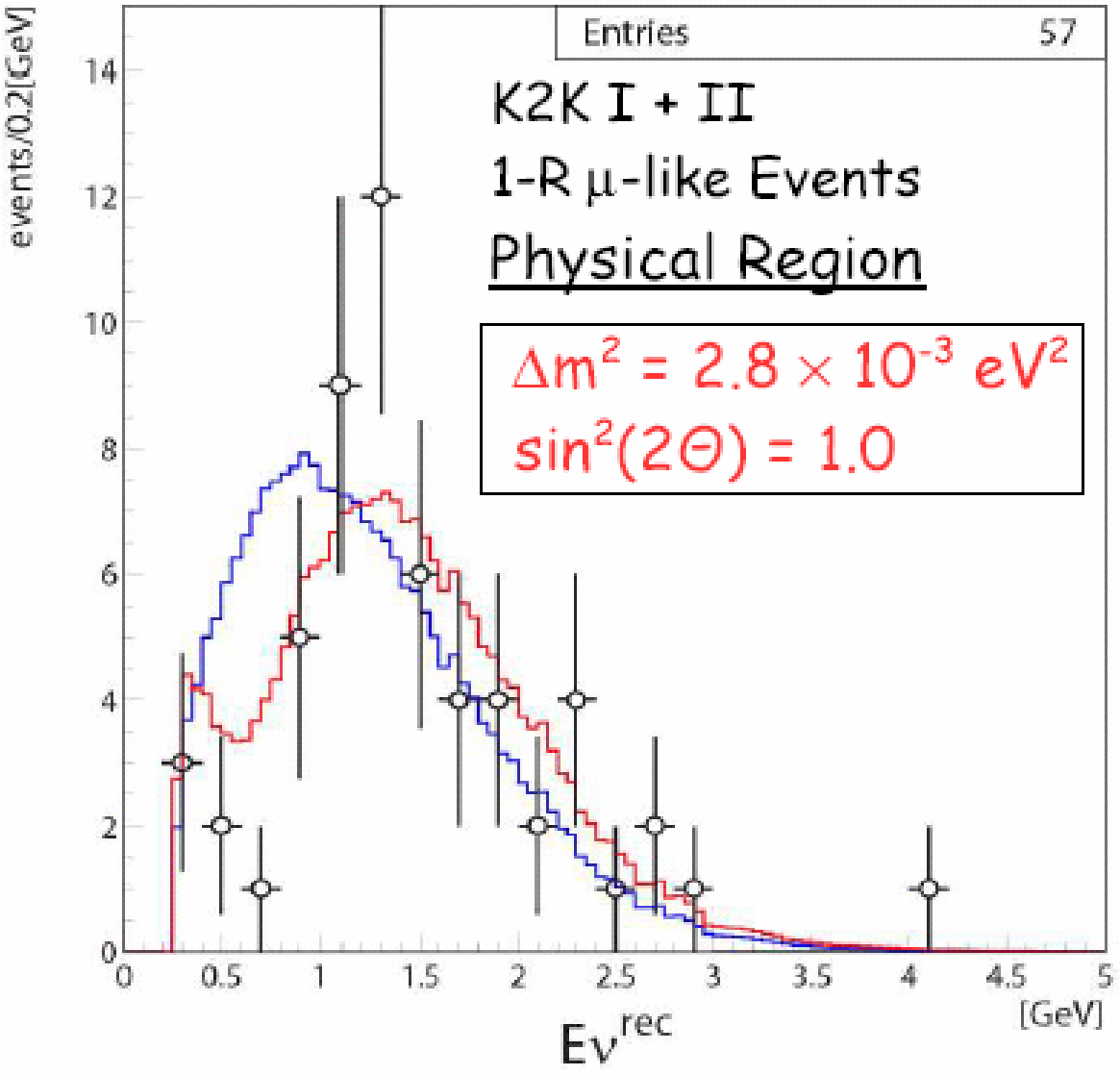


The Near Detector (300 m away)



Characterize the ν beam for extrapolation to SK

Results from K2K

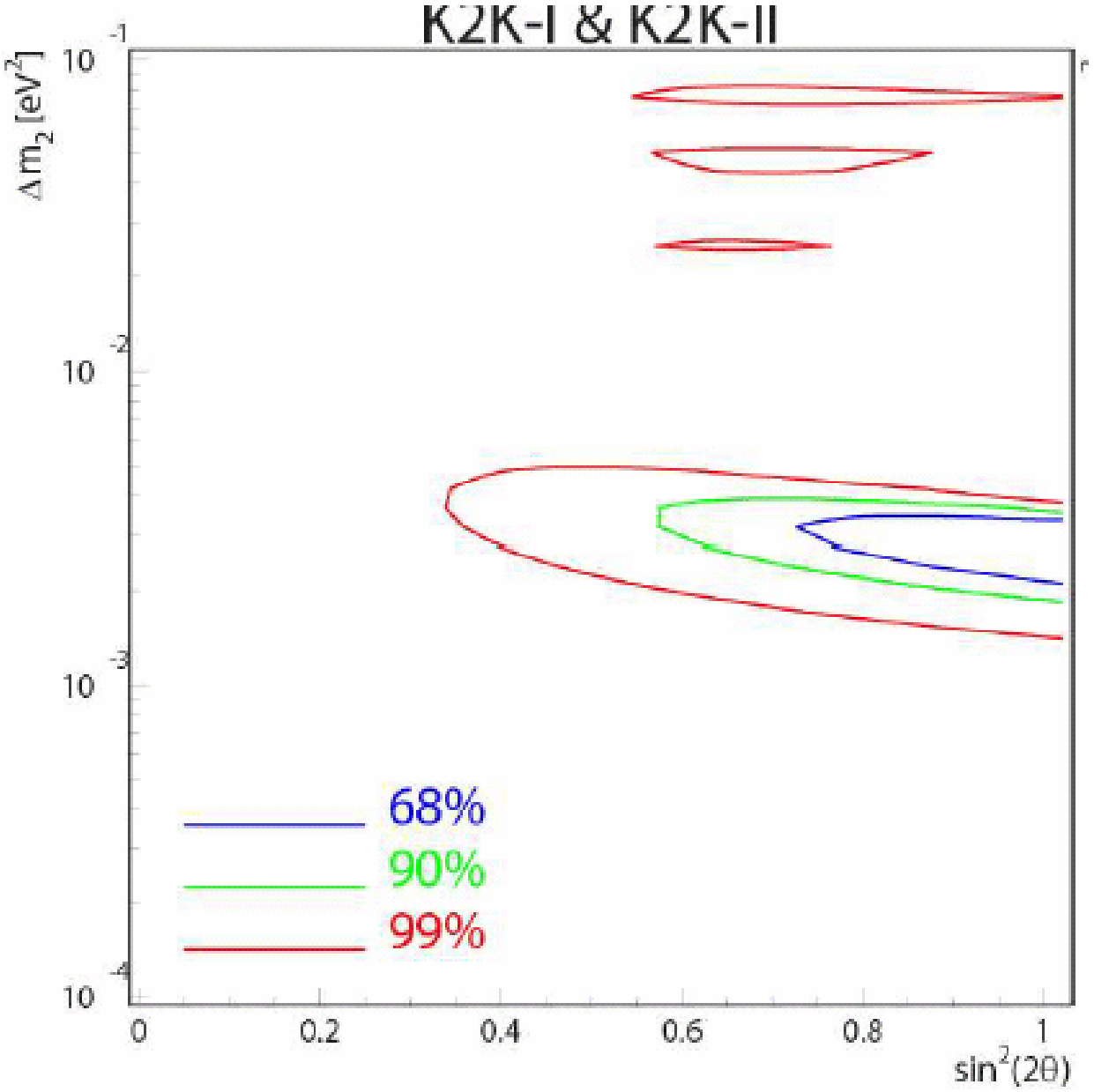


Single-ring μ-like events

Total 107 beam events observed; expect 149.7

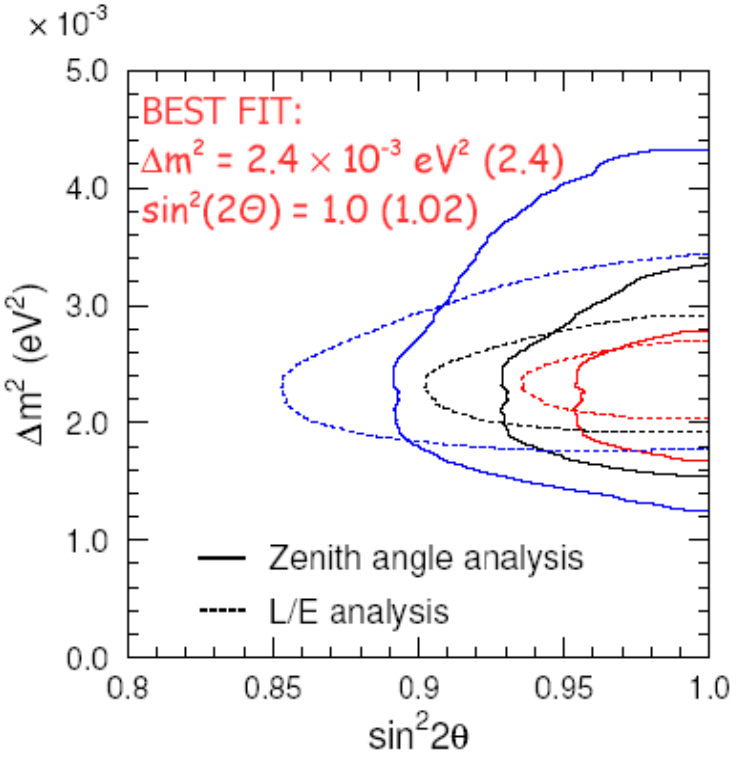
Suppression observed, spectral distortion consistent with oscillations

K2K Allowed Oscillation Parameters



Best Fit Results:
$\Delta m^2 = 2.8 \times 10^{-3}$ eV^2
$\sin^2(2\theta) = 1.0$
(constrained to physical region)

Consistent with SK atmospheric

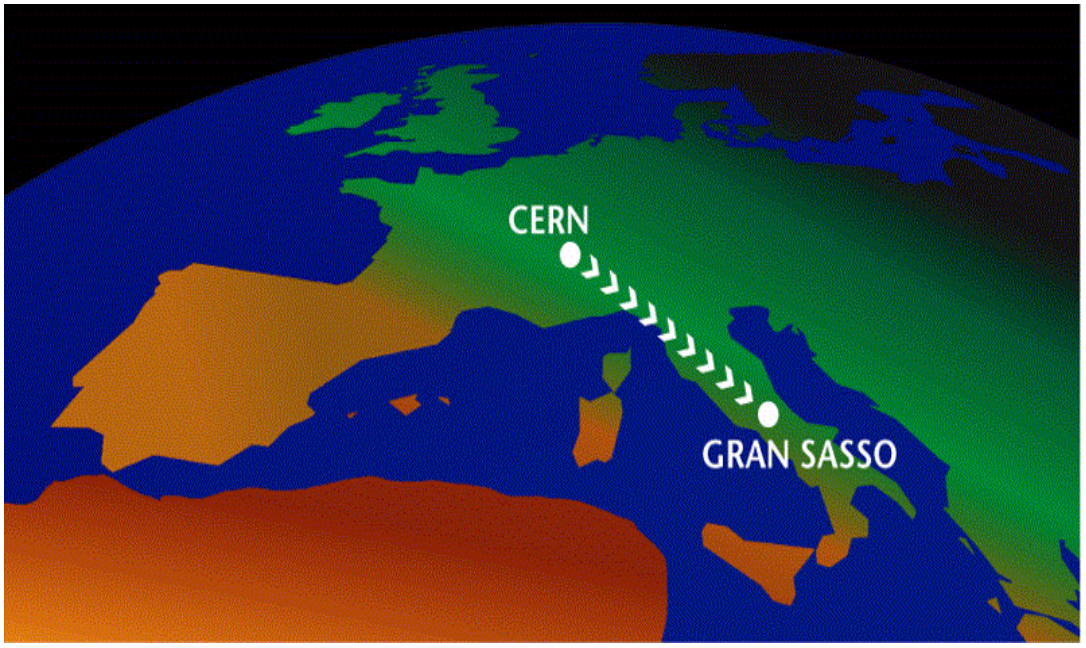


Future Long Baseline Experiments

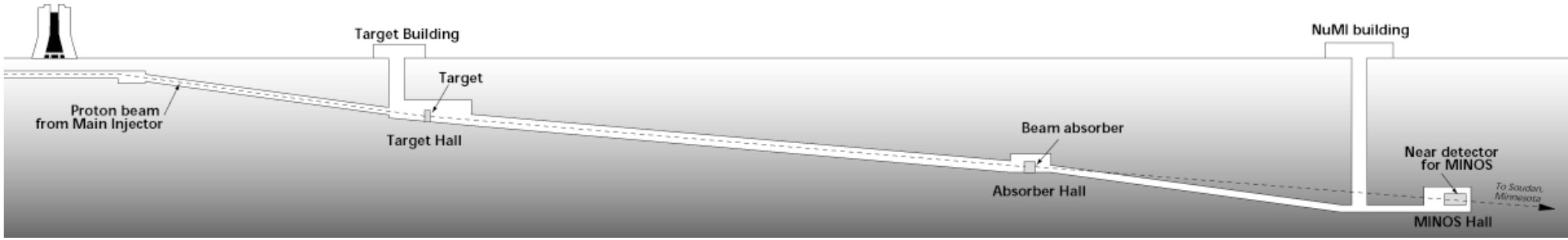
start 2005-6, 730 km distance

MINOS: Fermilab to Soudan

CNGS: CERN to Gran Sasso

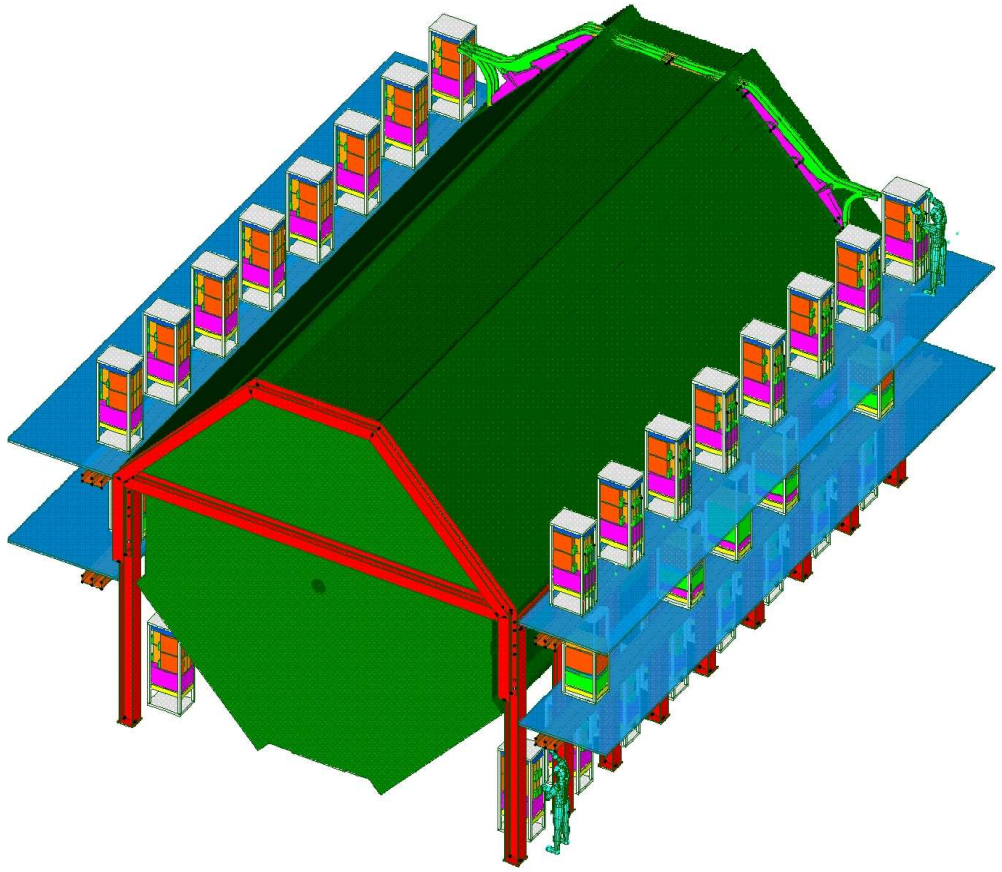


NuMI Beamline at Fermilab



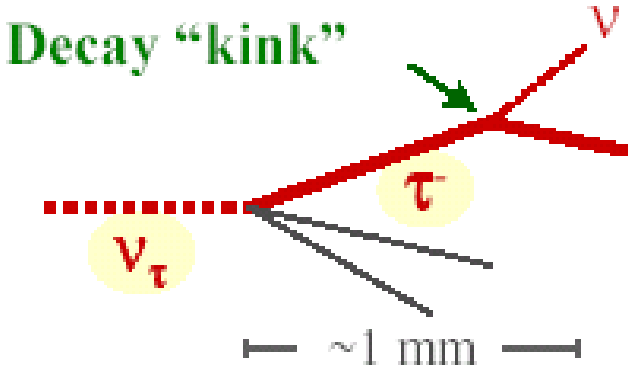
MINOS Detector at the Soudan mine

iron plates
+ scintillating fibers
w/ magnetic field

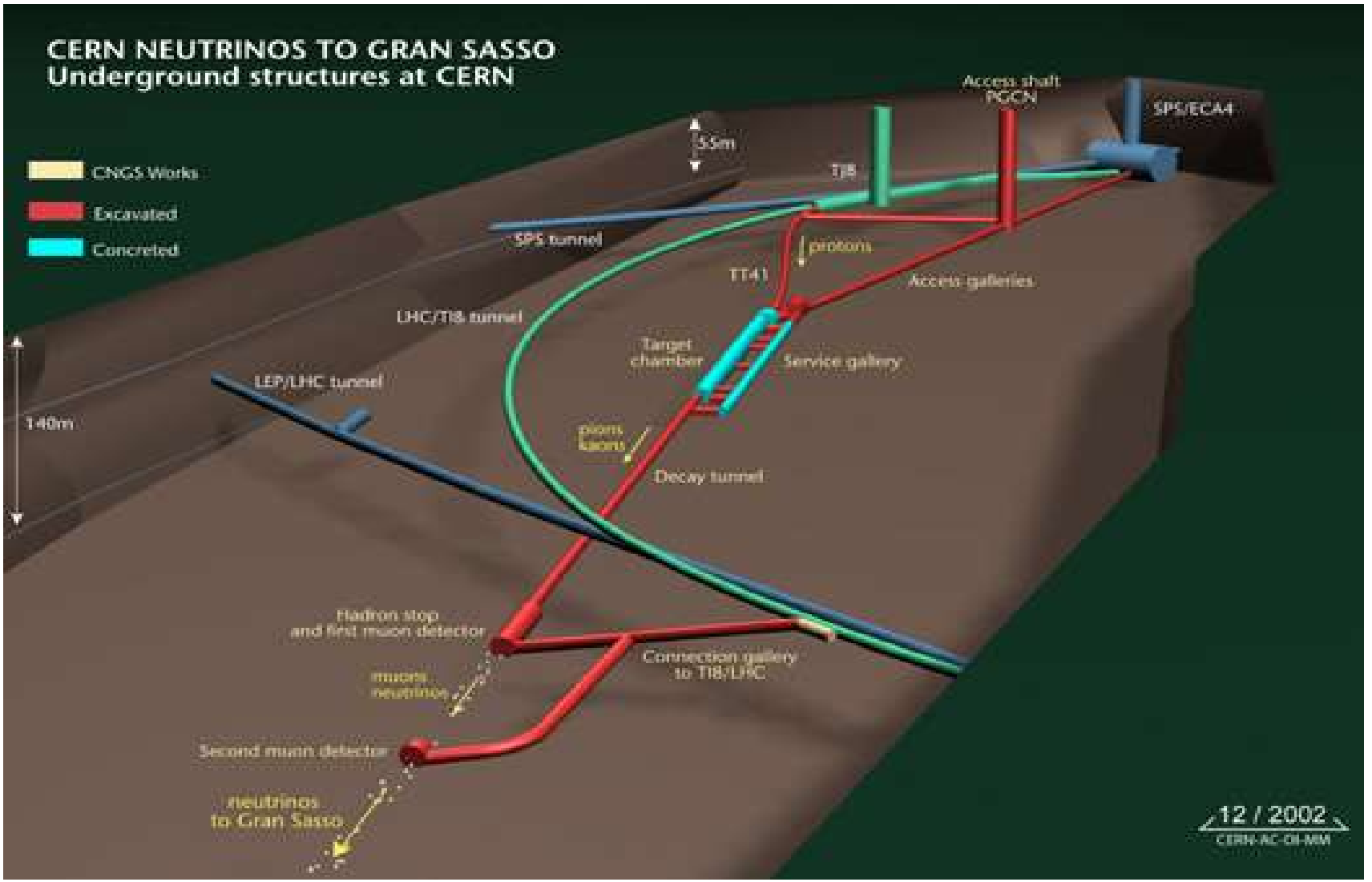


CNGS

CERN Neutrinos to Gran Sasso

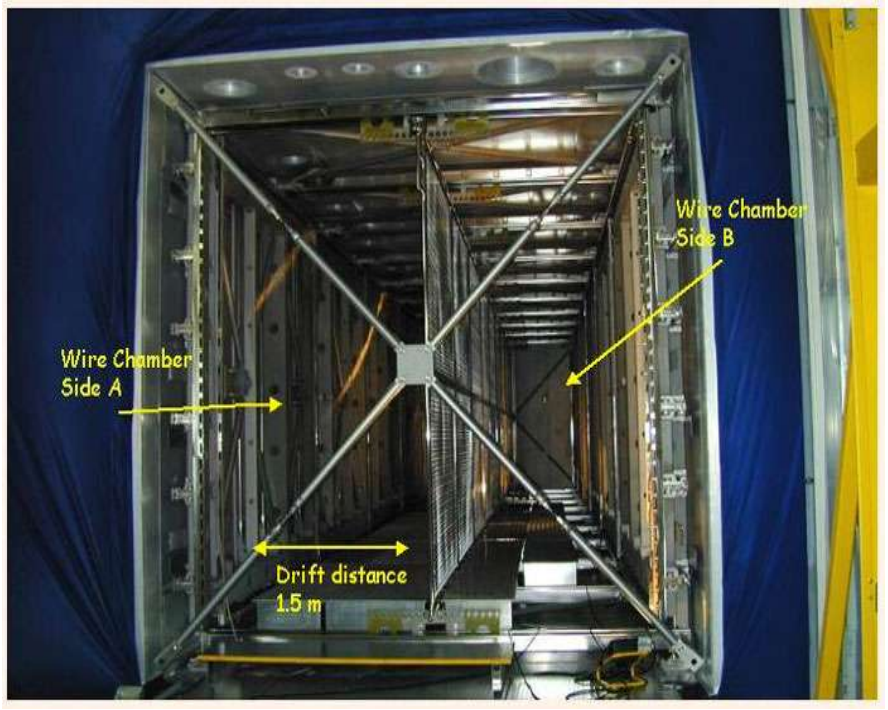


Look for τ neutrinos explicitly

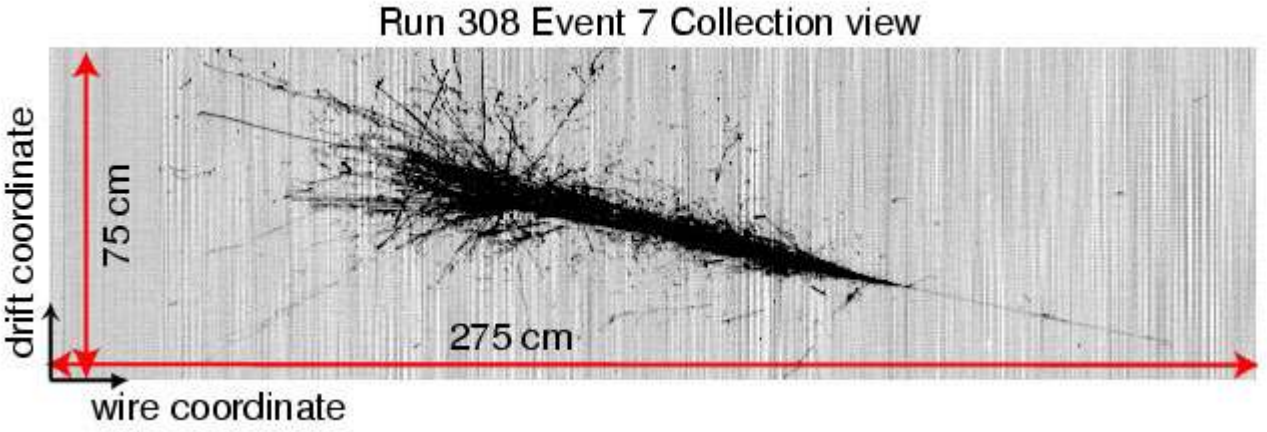


ICARUS

Liquid Argon Time Projection Chamber

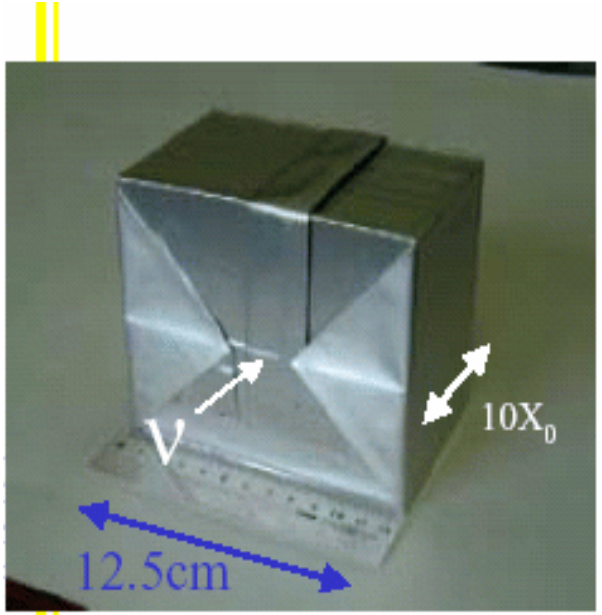


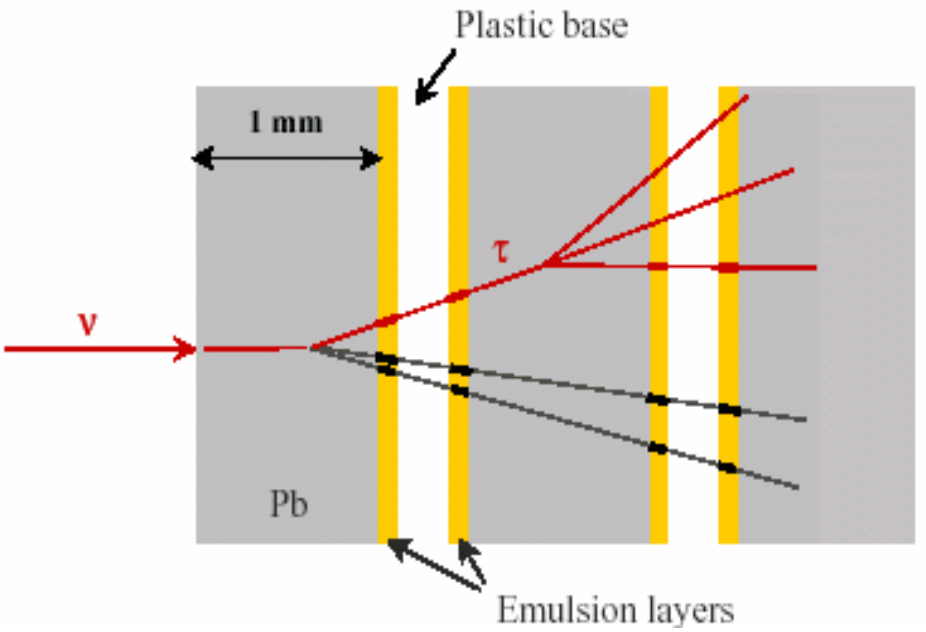
"Digital Bubble Chamber"

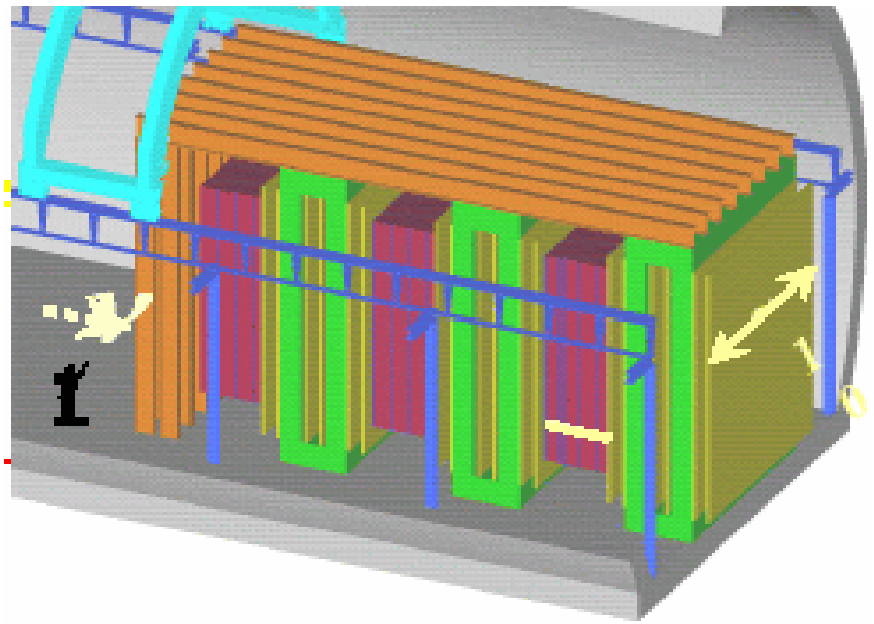


OPERA

lead/emulsion sandwich + scintillator planes





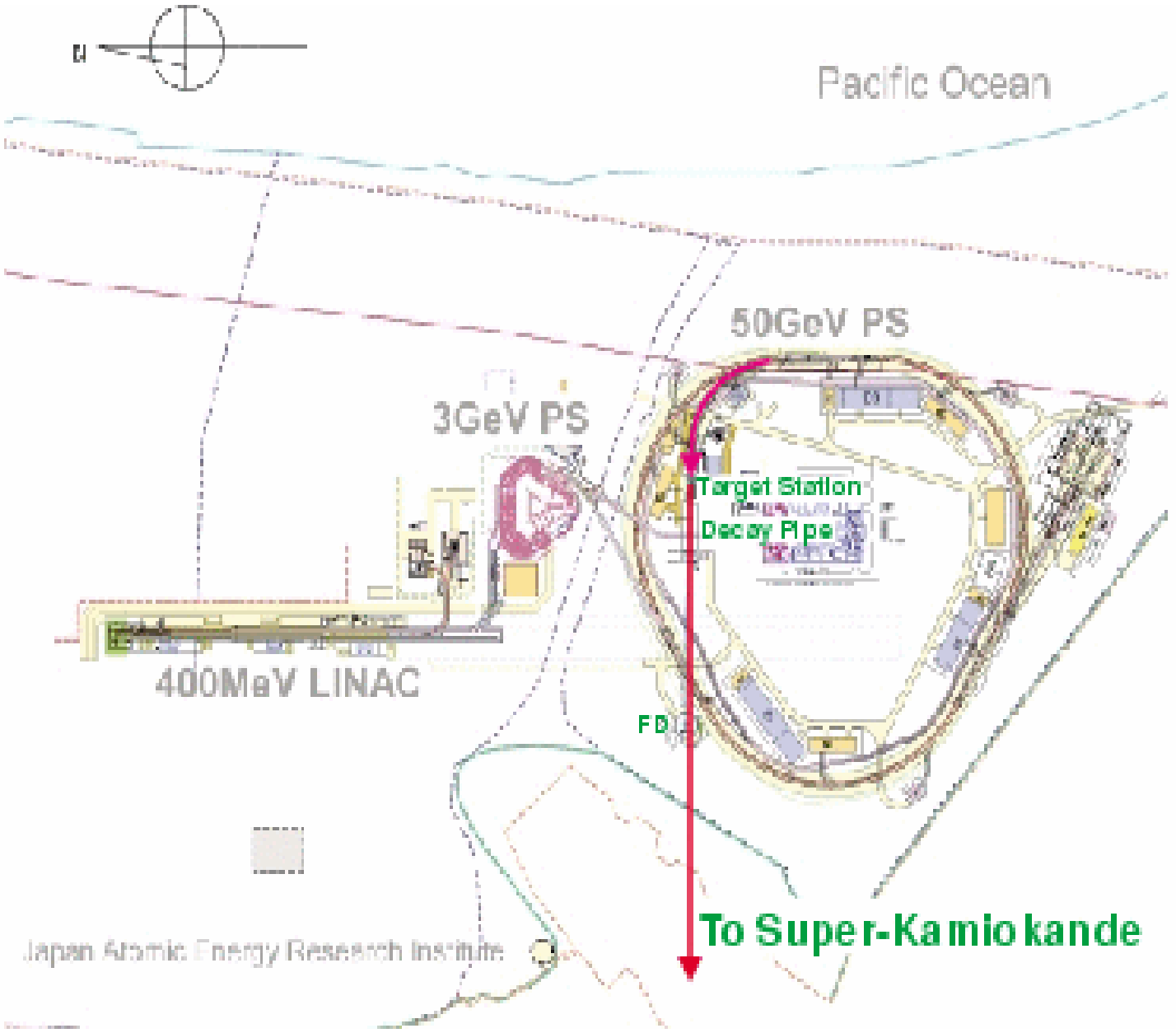


Extract bricks for scanning if electronic detector indicates τ-like event

T2K: "Tokai to Kamioka"

Existing detector: Super-K
295 km, about 30 times K2K flux
2.5 deg. off axis

T2K ("Tokai to Kamioka") 2° off-axis



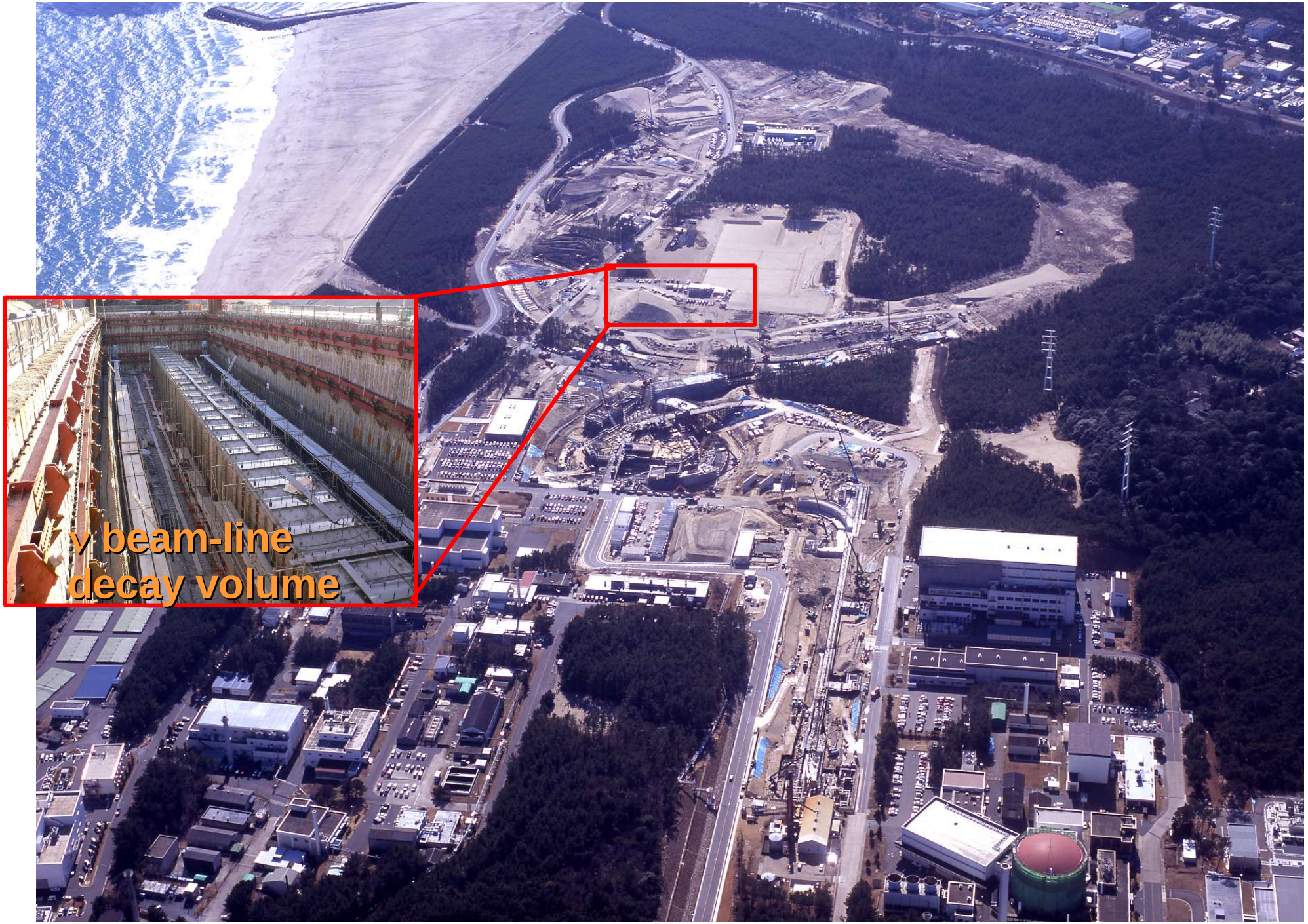
Near + 2 km detectors,

Super-K refurbished by 2006

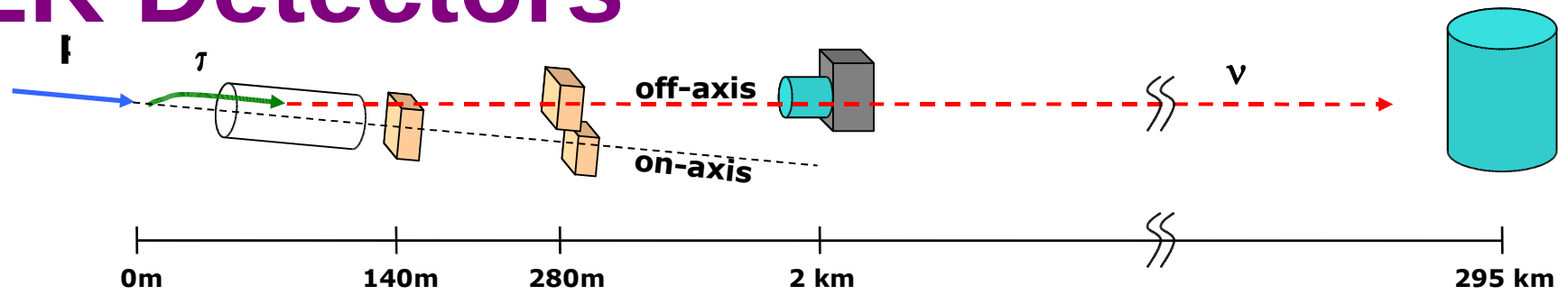
Start 2009

Beam neutrino energy tuned to oscillation minimum

J-PARC beamline under construction now



T2K Detectors

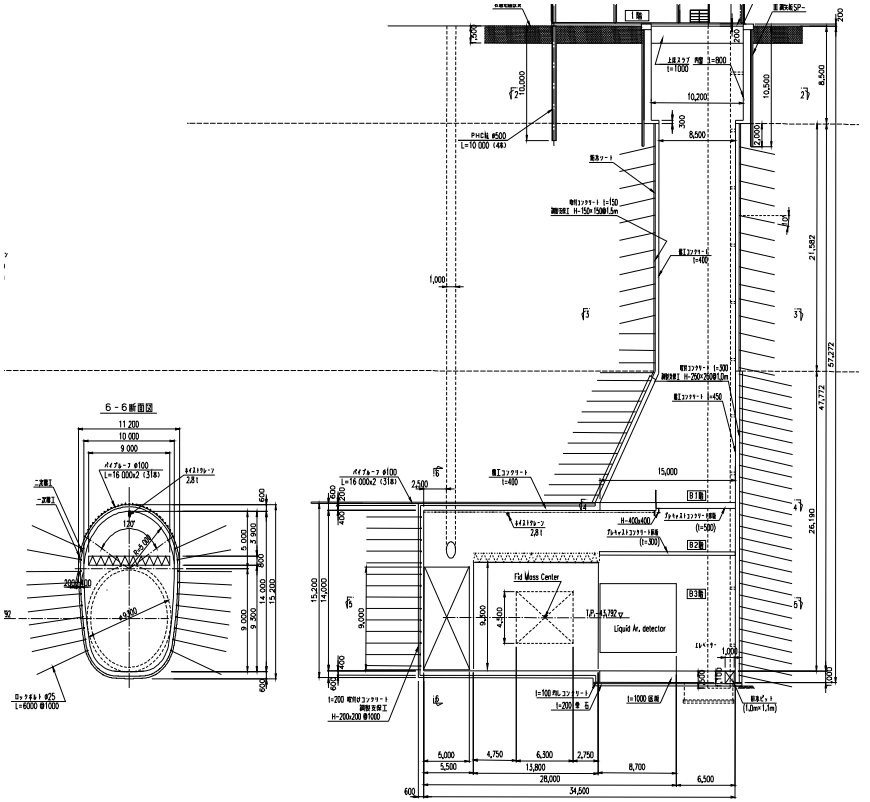


1. Near detector at 280 m: fine-grained tracker

2. Intermediate detector at 2 km

Water Cherenkov +
fine-grain tracker (LAr) +
muon ranger

Beam spectrum looks more like beam at SK
⇒ *cancel systematics*



3. Super-K III at 295 km, fully refurbished

Summary

Atmospheric muon neutrinos are changing flavor ('disappearing') as they travel through the Earth:

This measurement in SK was the first clear indication of neutrino mass and oscillation

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

This oscillation disappearance has now been confirmed with a long-baseline beam of neutrinos: K2K results are consistent

Next generation: MINOS, CNGS, T2K