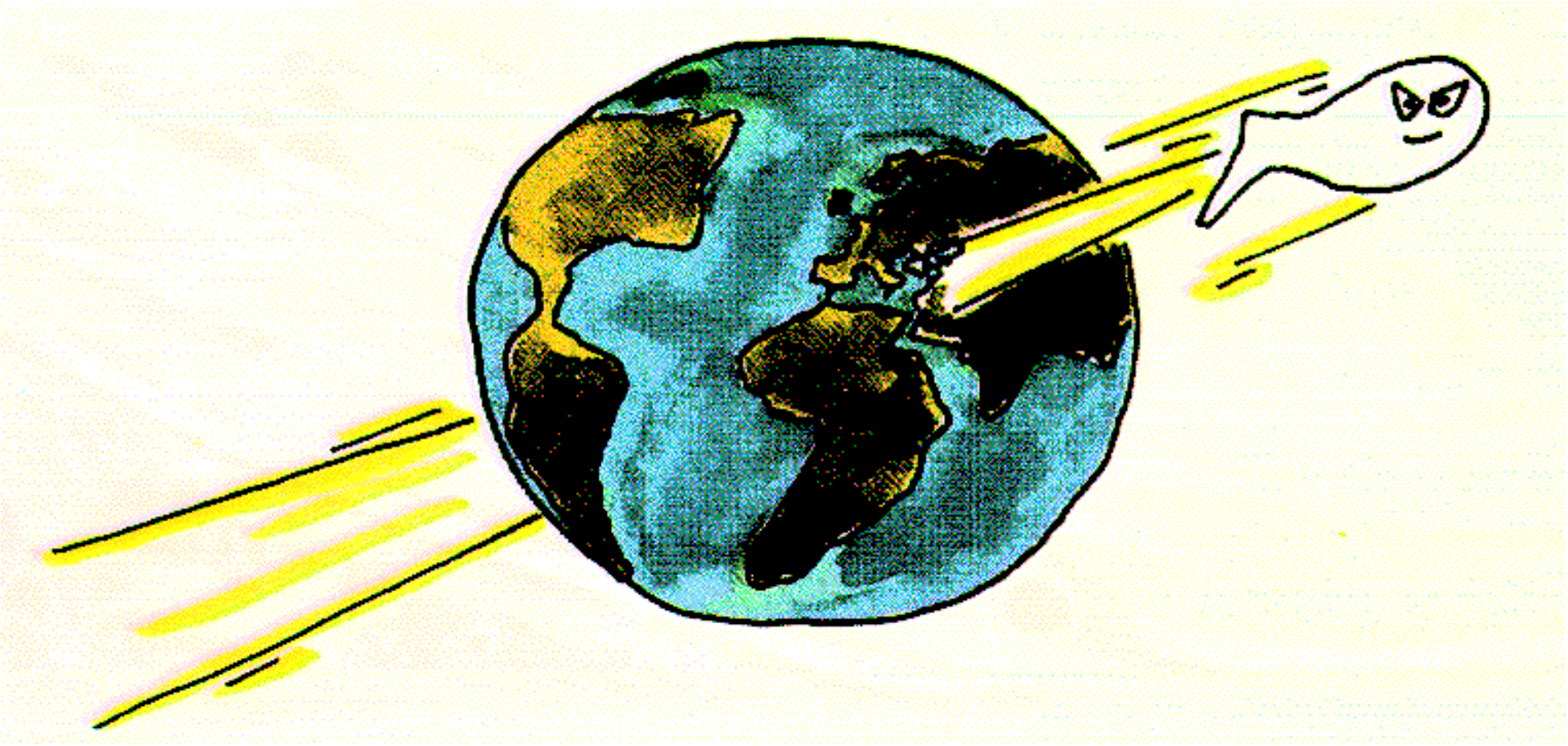
Today:

Part I: Neutrino oscillations:
beam experiments

Part II: Next tutorials:
making distributions with
histograms and ntuples

Super-Kamiokande Physics II: Long Baseline Beams



Neutrino Oscillations

Assume

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

weakly interacting

unitary mixing matrix

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

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

Simple two-flavor

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

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

Propagate a distance L:

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

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, $\Delta m^2 = m_1^2 -$

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

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

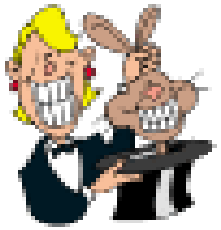
?

<u>Disappearance</u>: ν's oscillate into 'invisible' flavor

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

<u>Appearance</u>: directly see new flavor

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



Oscillation Parameter Space

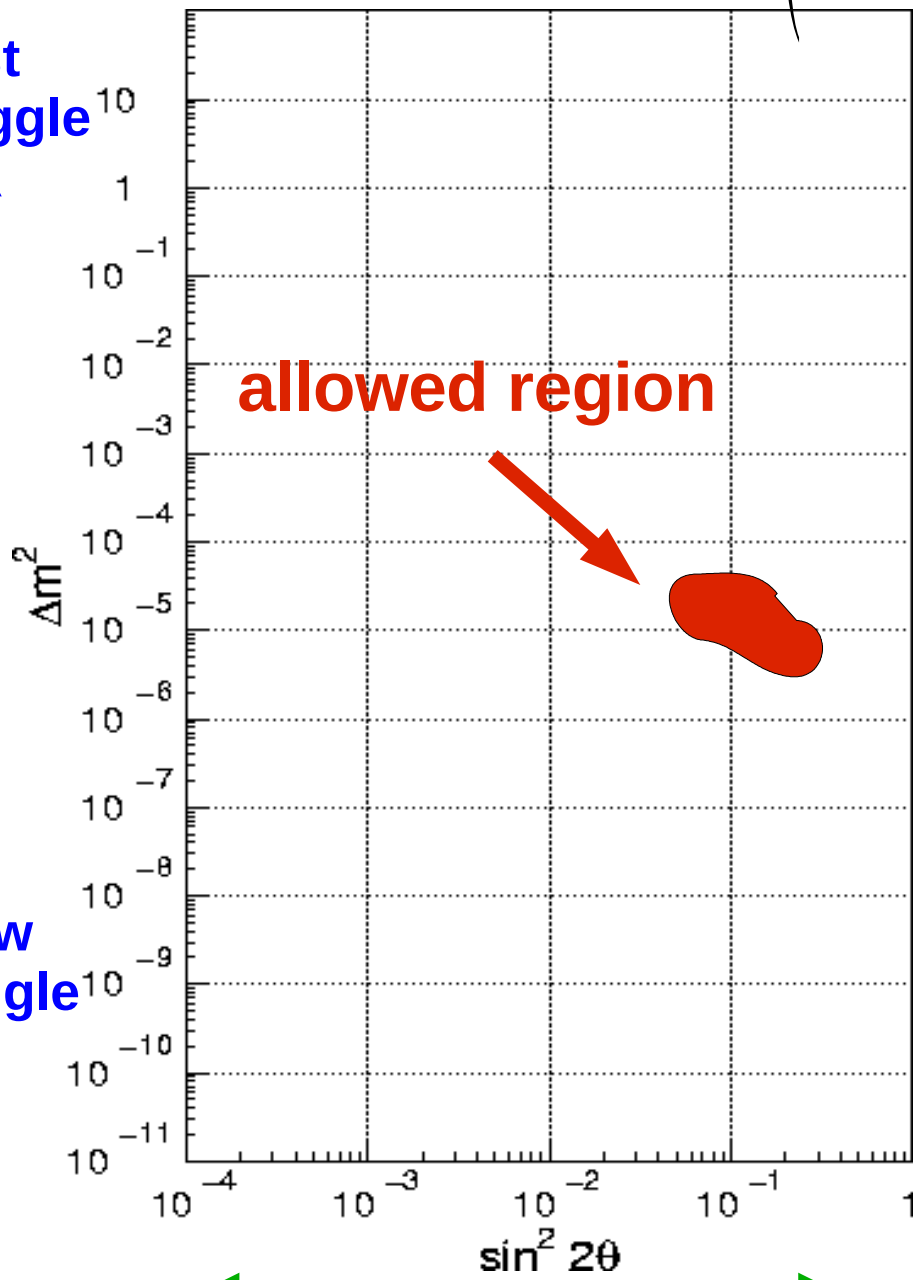
$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

Twiddle L/E

Frequency $\propto \Delta m^2 L/E$

fast wiggle

slow wiggle

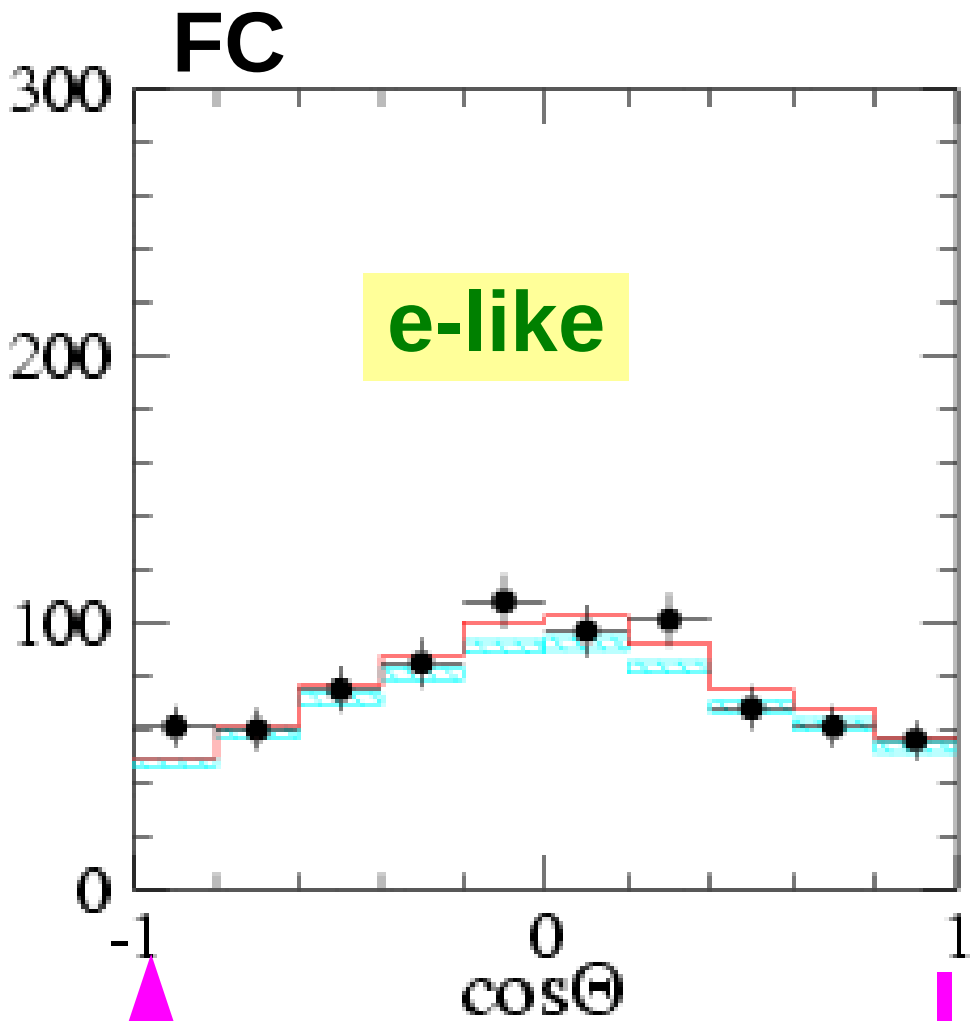


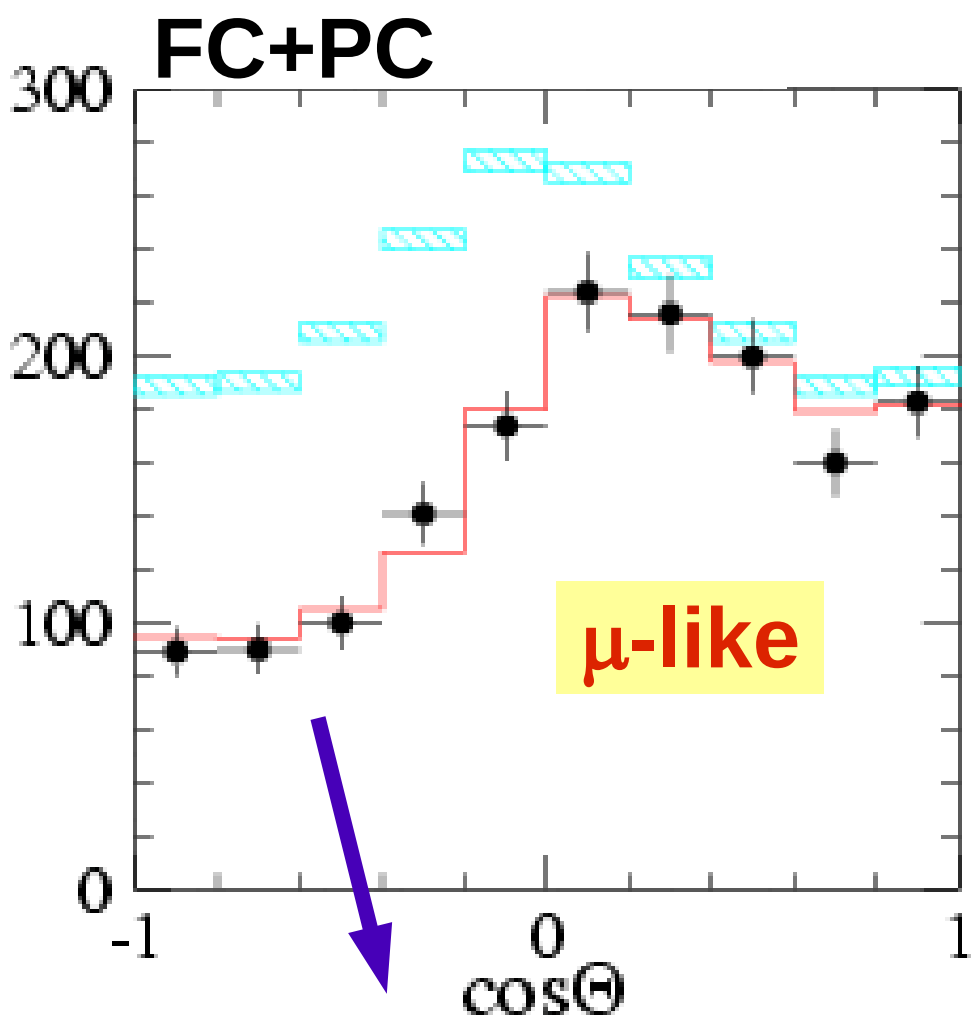
Amplitude $\propto \sin^2 2\theta$

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

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

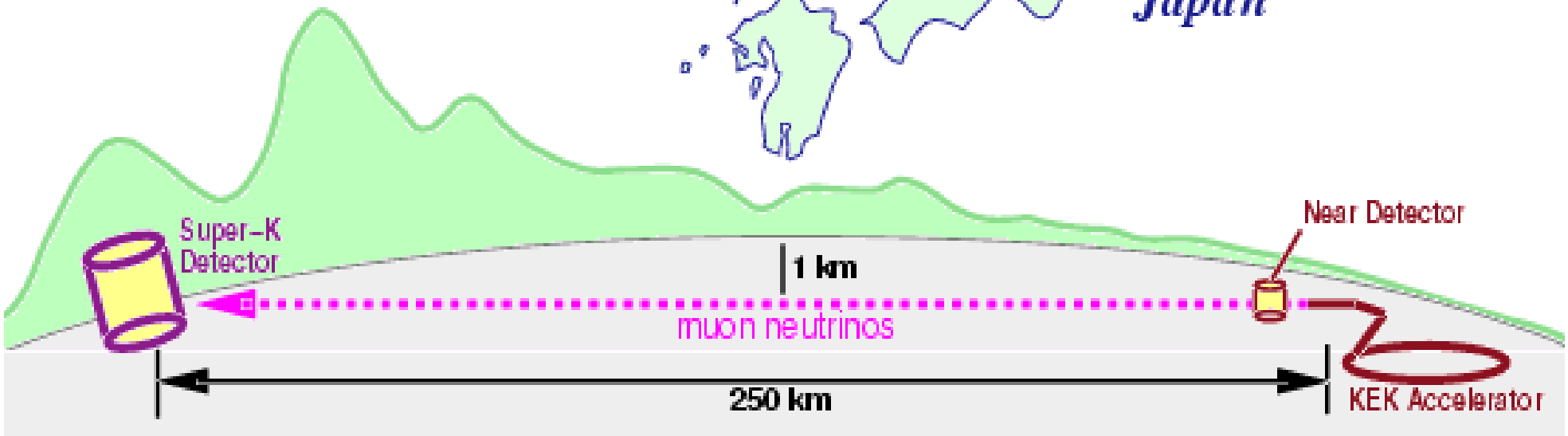
LONG BASELINE EXPERIMENTS

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

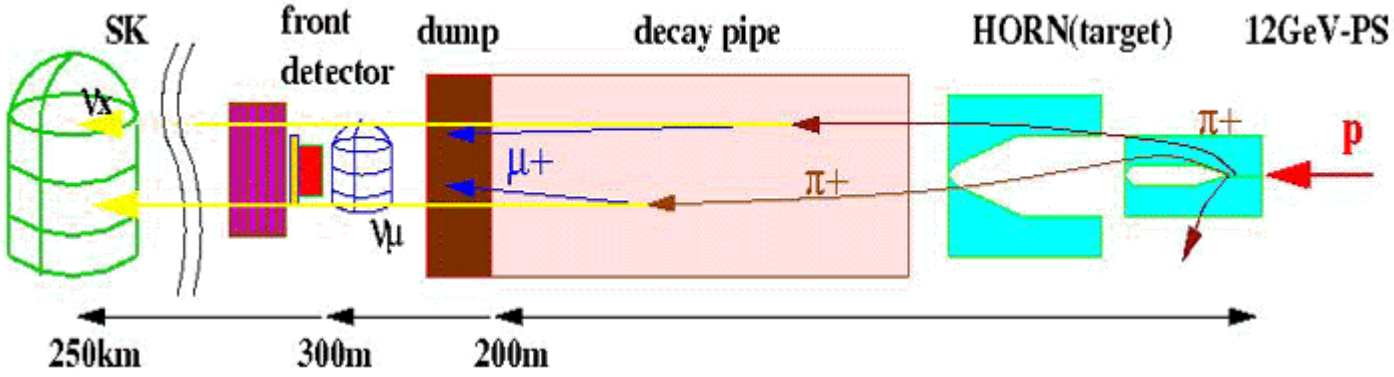
K2K (KEK to Kamioka) Long Baseline Experiment

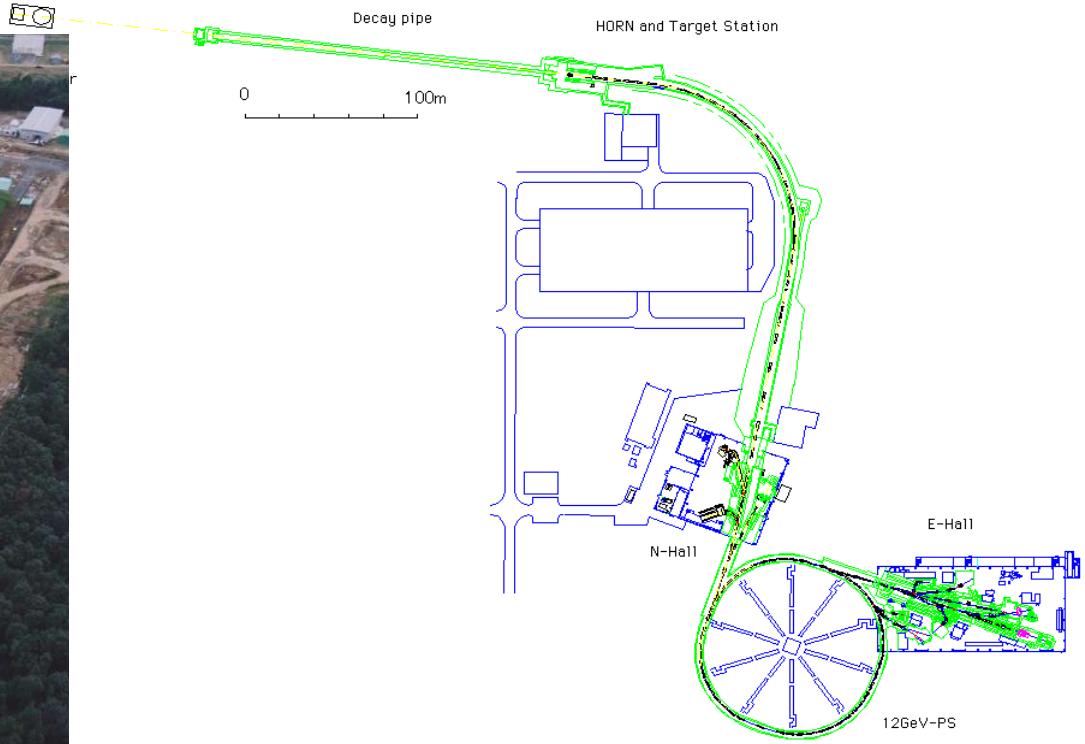
~ 1 GeV muon neutrinos

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

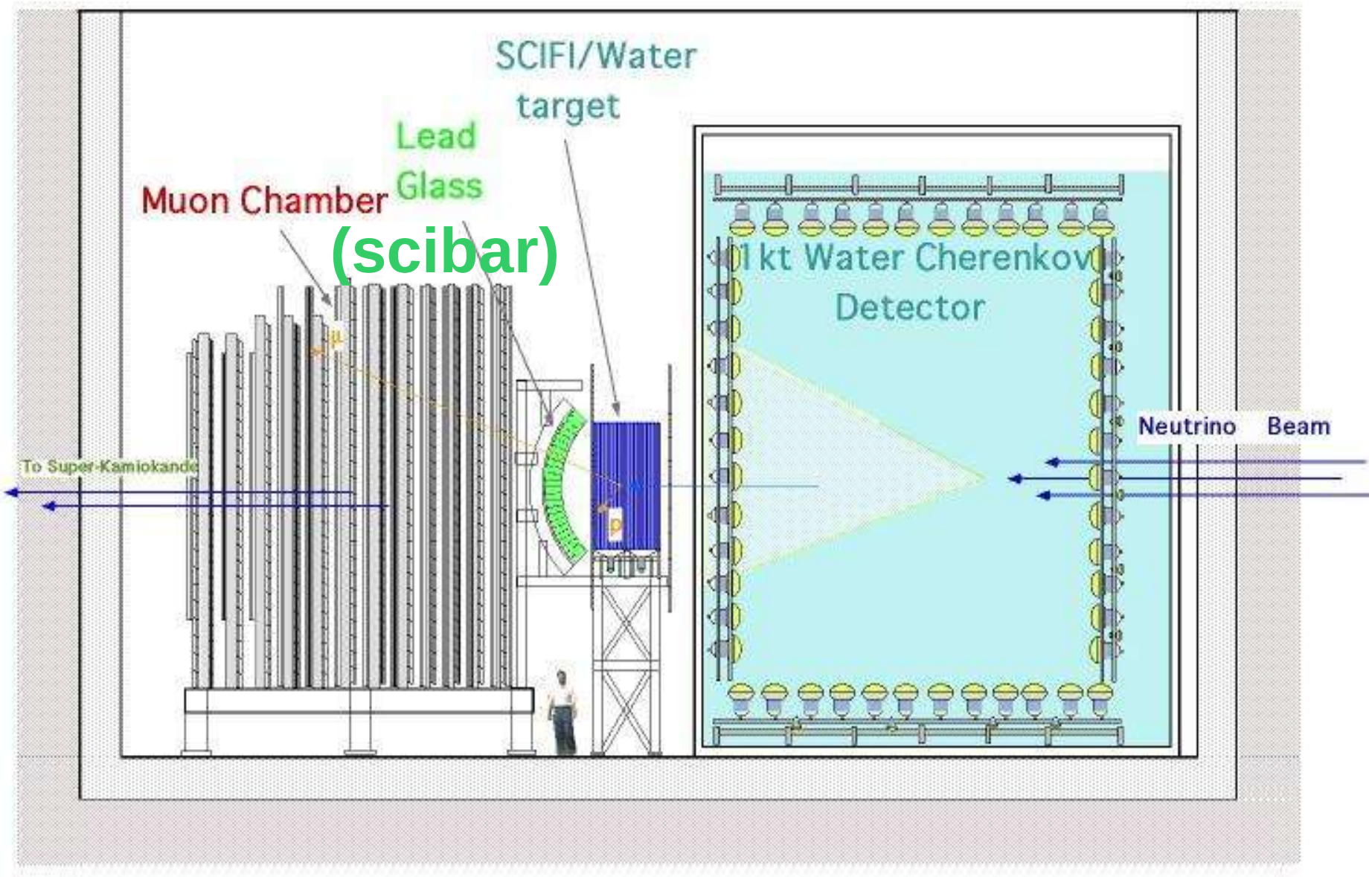


The Neutrino Beamline at KEK



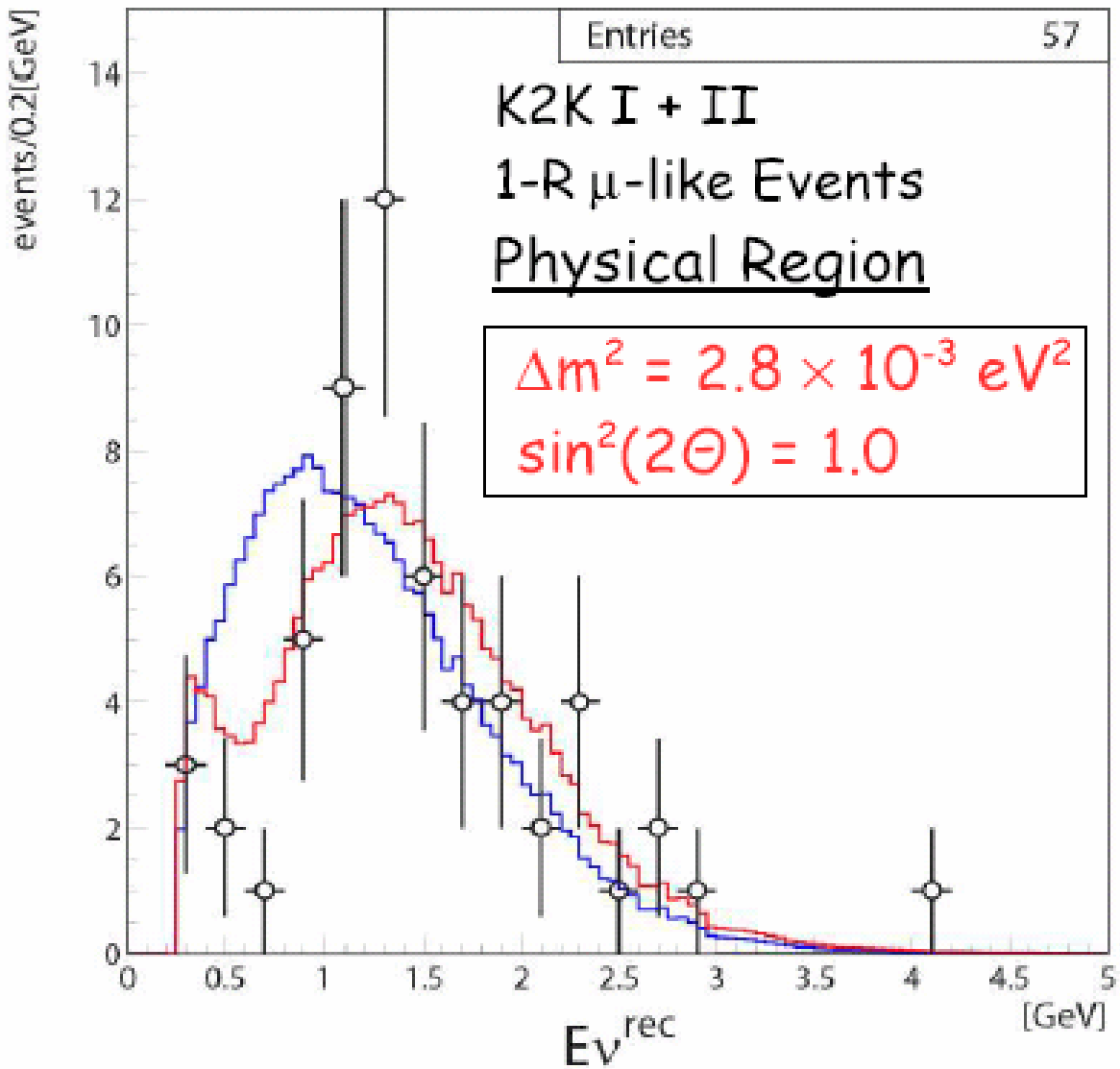


The Near Detector (300 m away)



Characterize the ν beam for extrapolation to SK

Results from K2K

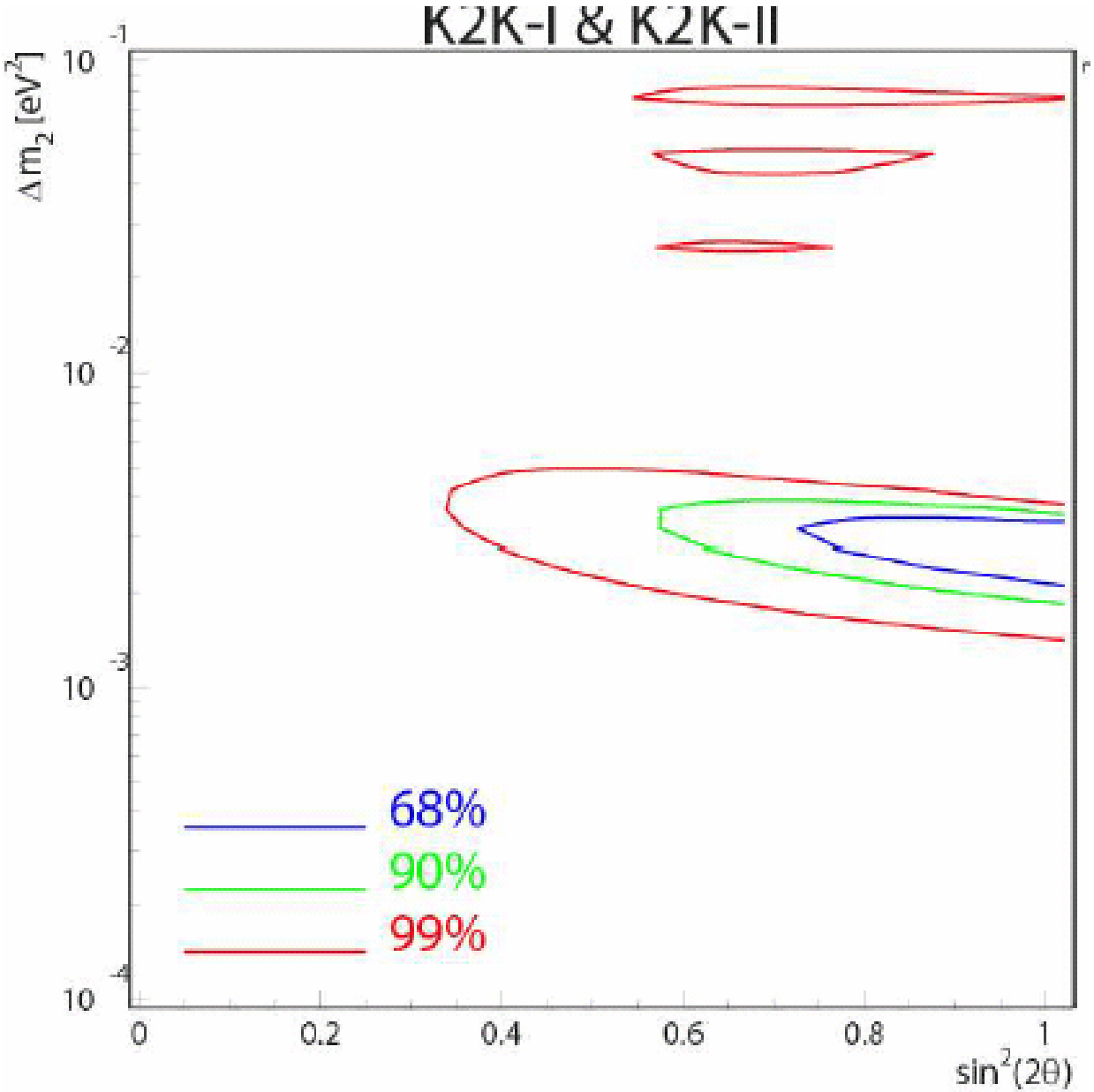


Single-ring μ-like events

Total 107 beam events observed; expect 149.7

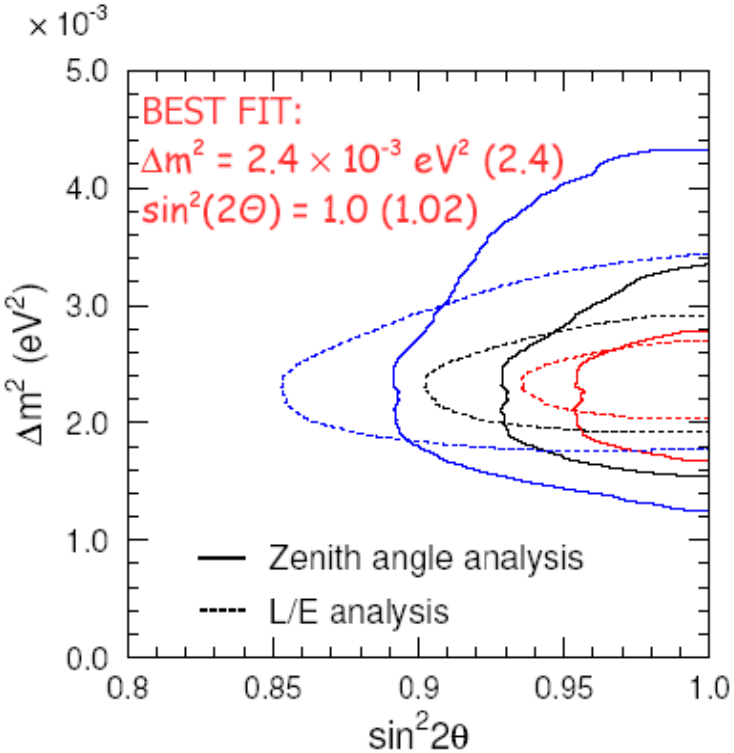
Suppression observed, spectral distortion consistent with oscillations

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

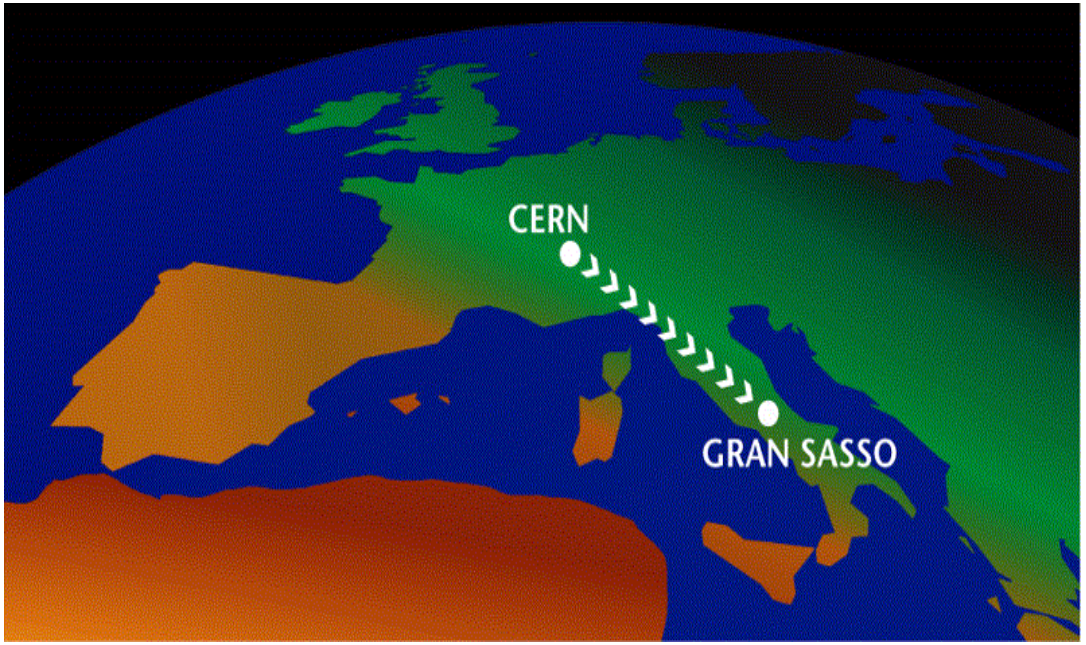


Future Long Baseline Experiments

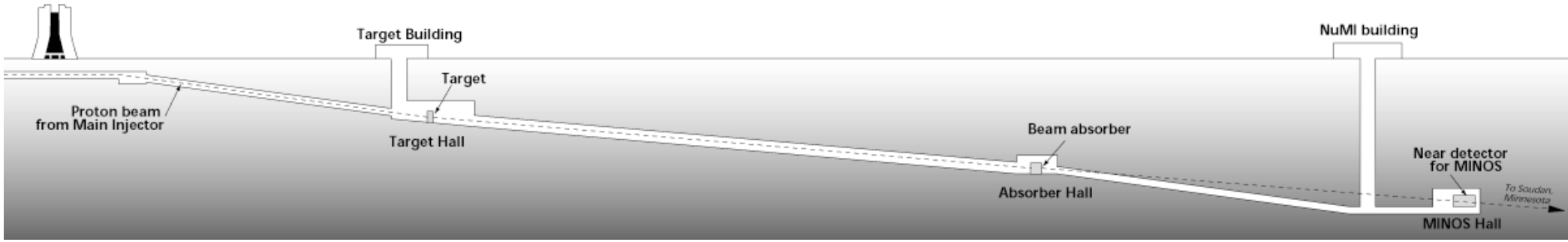
start 2005-6, 730 km distance

MINOS: Fermilab to Soudan

CNGS: CERN to Gran Sasso

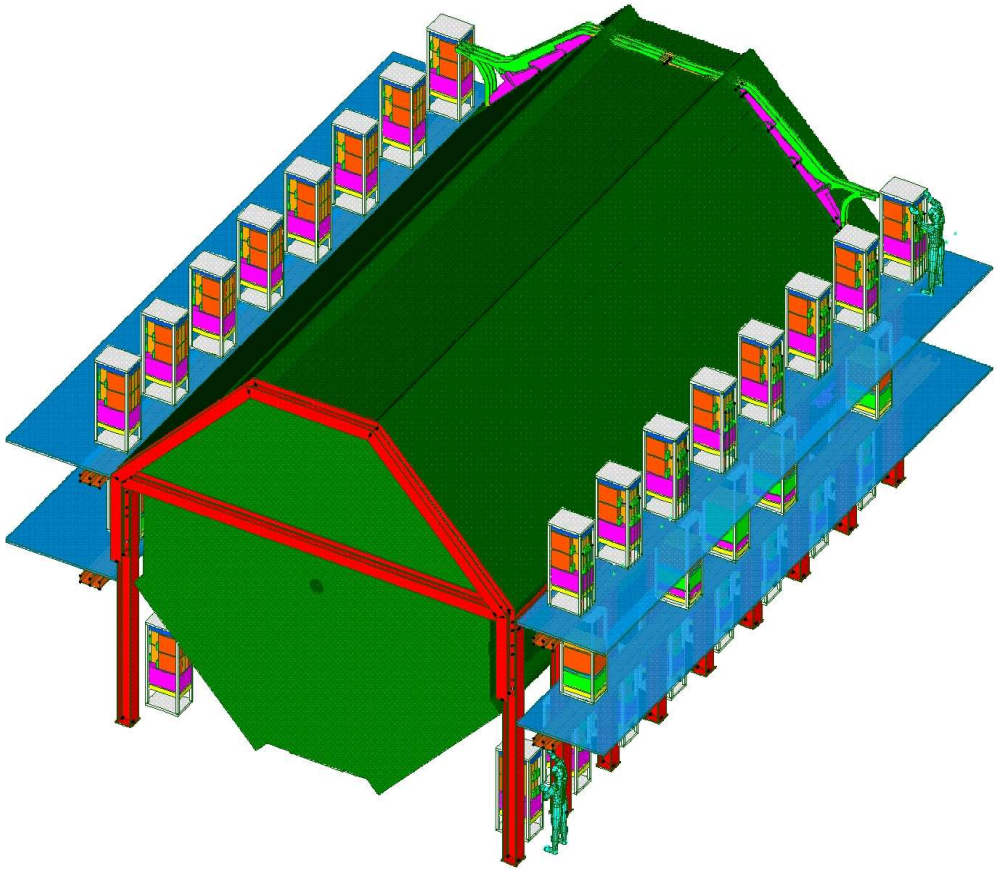


NuMI Beamline at Fermilab



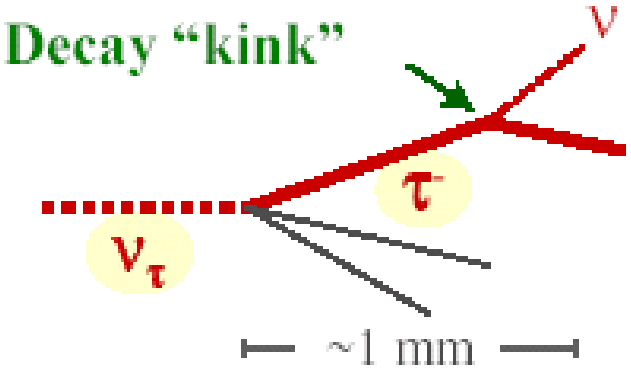
MINOS Detector at the Soudan mine

iron plates
+ scintillating fibers
w/ magnetic field



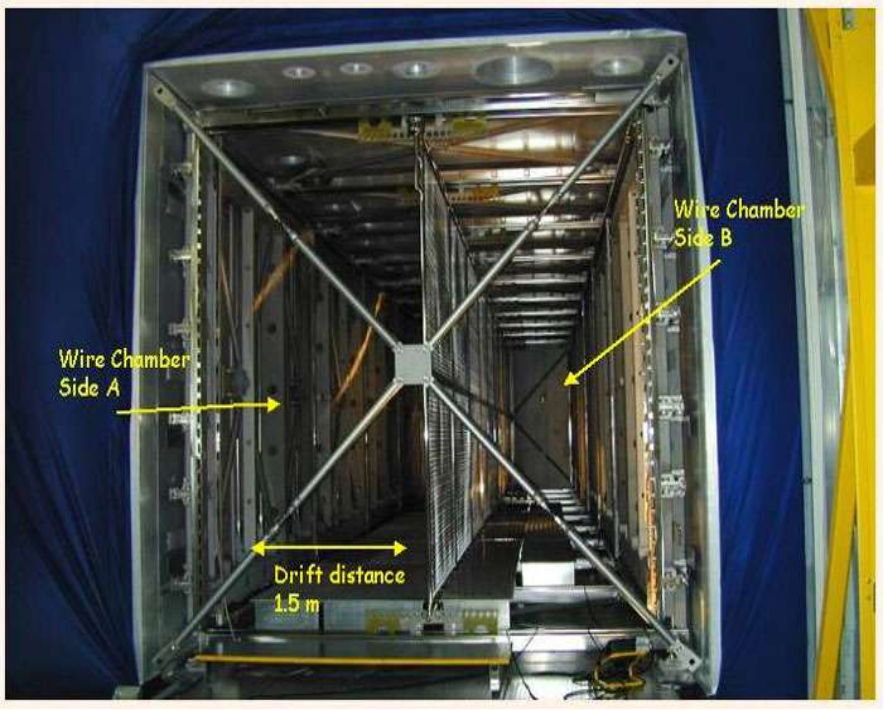
CNGS

CERN Neutrinos to Gran Sasso

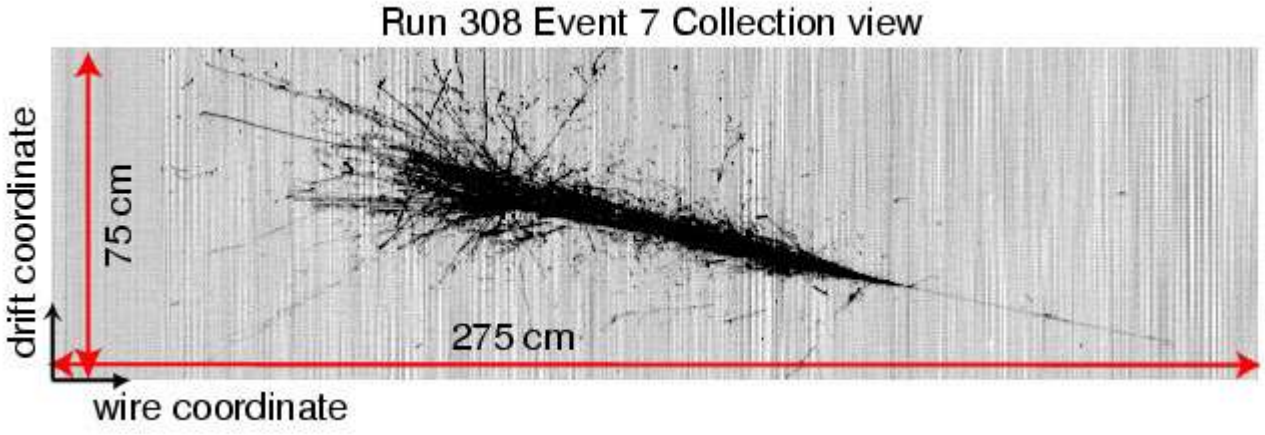


Look for τ neutrinos explicitly

ICARUS Liquid Argon Time Projection Chamber

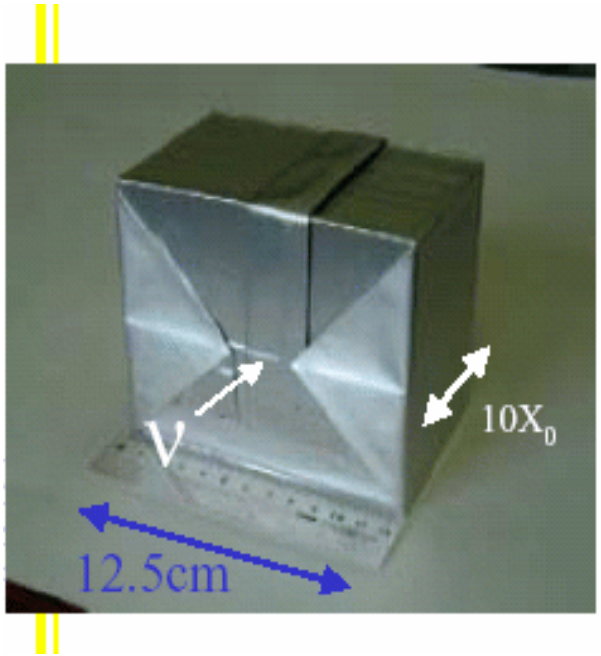


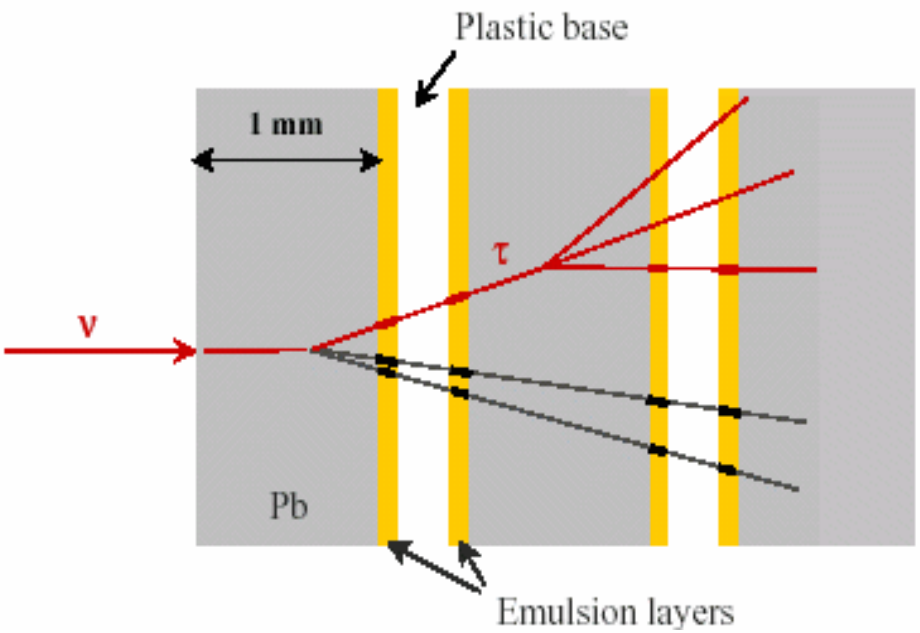
"Digital Bubble Chamber"

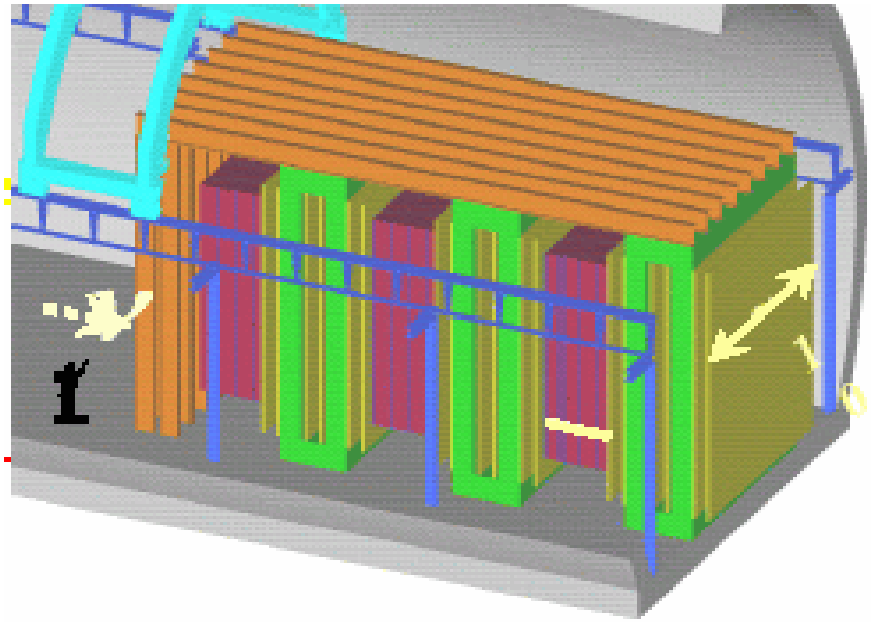


OPERA

lead/emulsion sandwich + scintillator planes





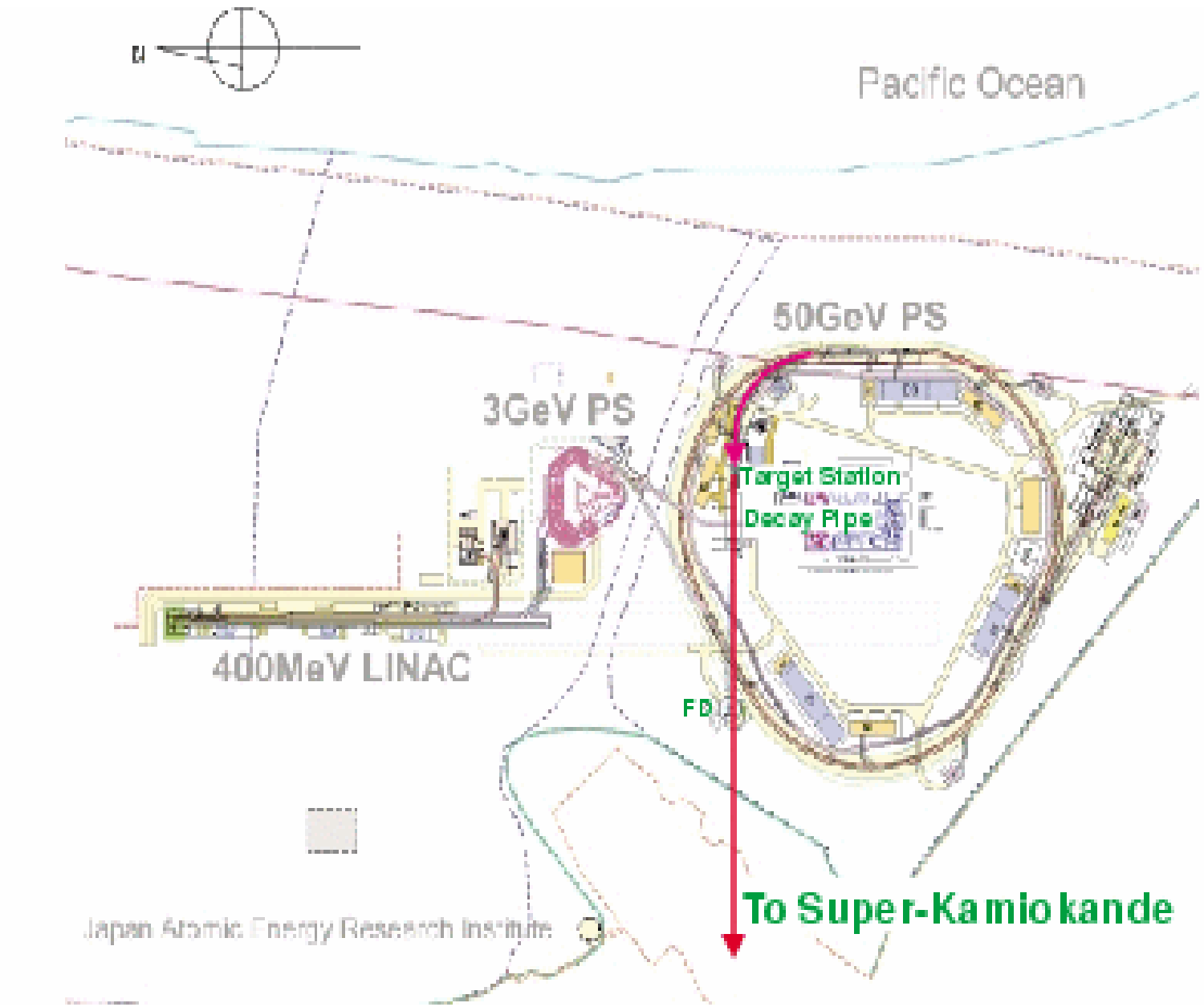


Extract bricks for scanning if electronic detector indicates τ-like event

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



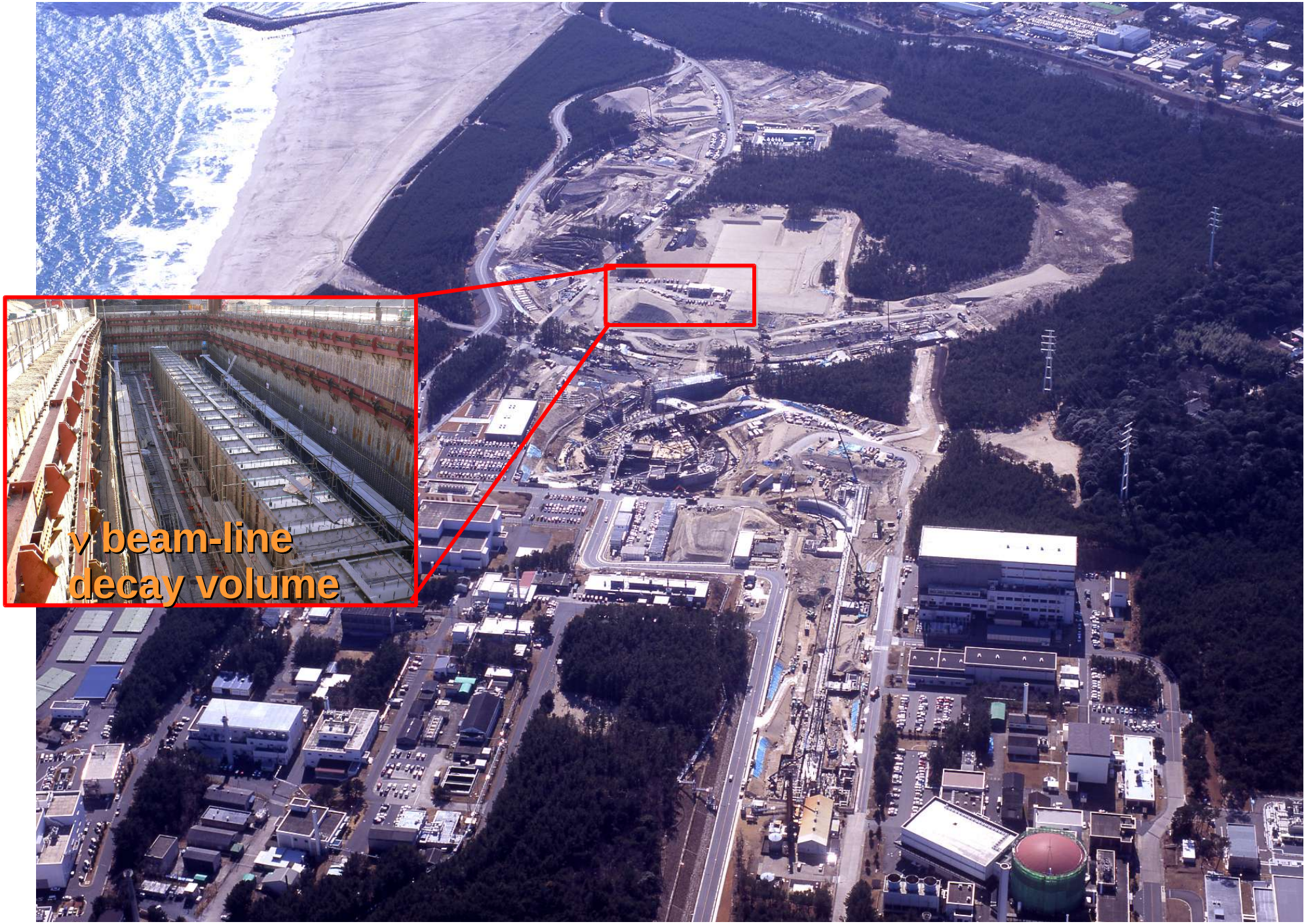
Near
+ 2 km
detectors,

Super-K
refurbished
by 2006

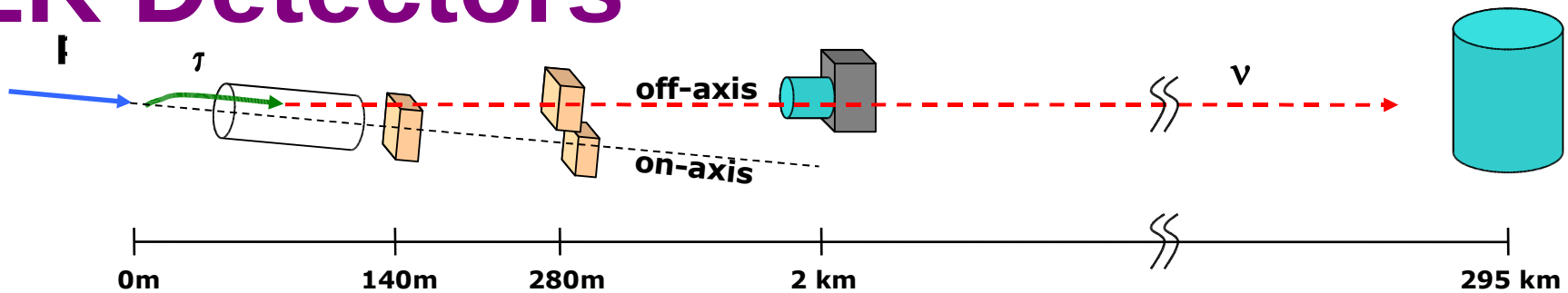
Start 2009

Beam
neutrino
energy
tuned to
oscillation
minimum

J-PARC beamline under construction now



T2K Detectors



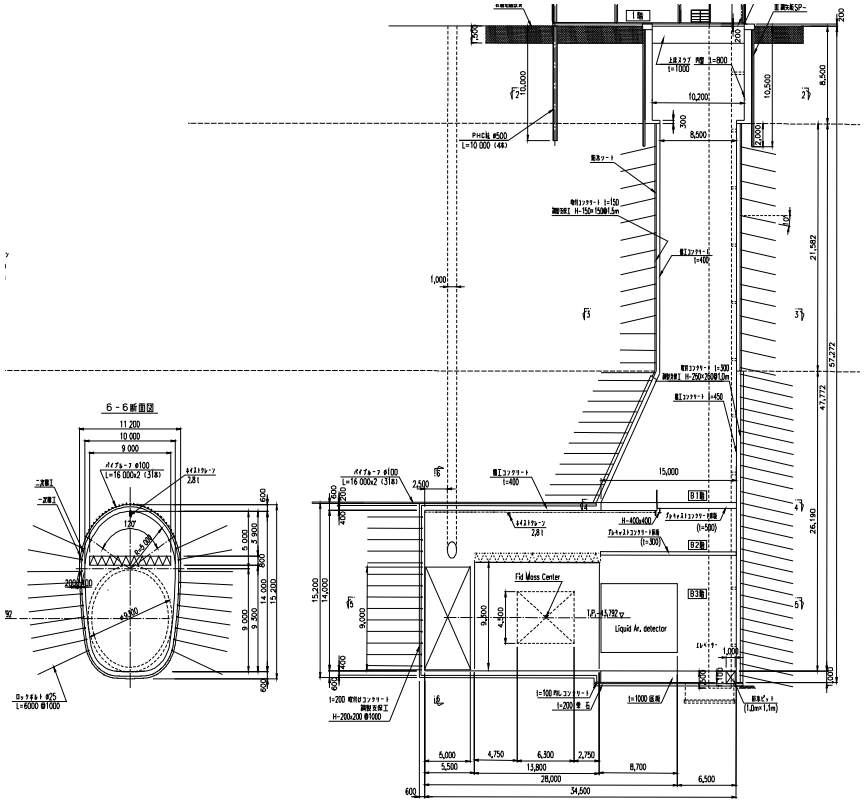
1. Near detector at 280 m: fine-grained tracker

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

SK Data Tutorial Today

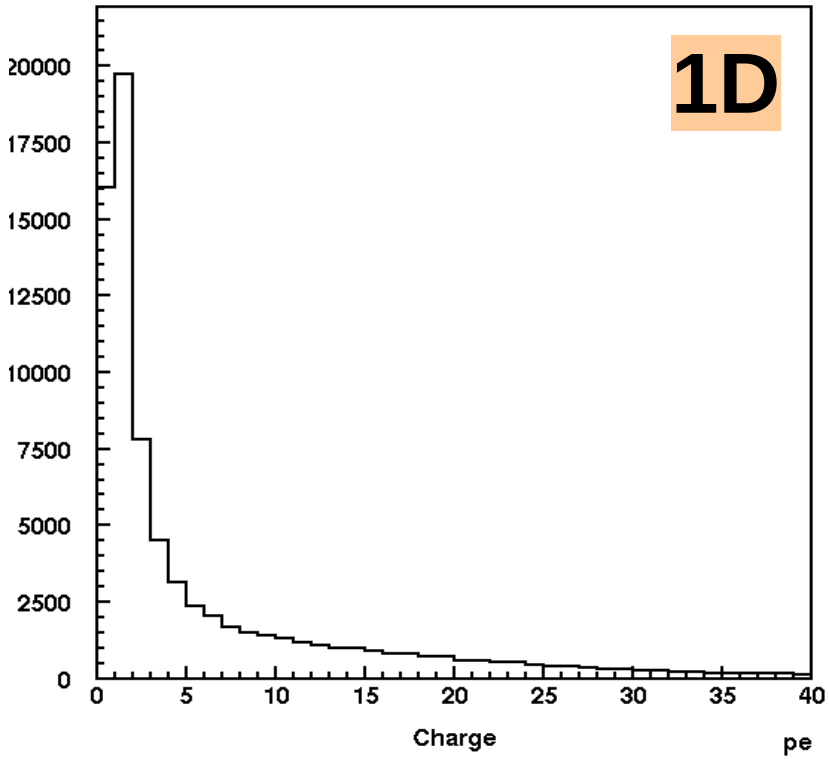
1. Run superscan to eyeball data files ☑

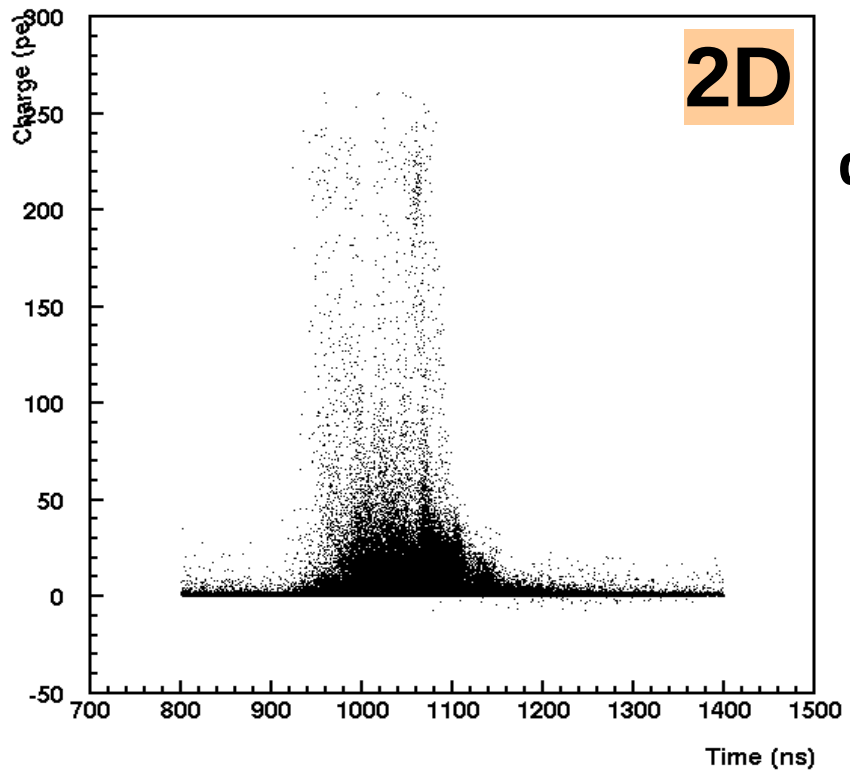
2.1 Set up and run sample program to look at charges and times for events ☑

2.2 Make and view histograms (distributions) **TODAY**

- Histograms made directly in program
- Ntuples made using PAW

Histogram: a distribution of some variable(s)





density of dots ∝ number of events in bin

Cernlib/PAW: software package that allows manipulation of histogram structures

- create histogram
- 'fill' with data
- output histo to file

Ntuple: list of 'events' and their variables

e.g. run no., event no. , total charge, mean t

```
2000, 1, 42.,1020.
2000, 2, 13.,982.
2000, 3, 22.,984.
```

Note: an 'event' need not be an SK event (trigger); you can make an ntuple of tube hits, or any kinds of items ('event' ≡ an item in the list)

PAW will allow you to plot distributions of any chosen variable, or any variable vs any other, with 'cuts' (conditions)

```
e.g.   nt/plot 1.q%t t>800&&t<1000
```

means plot charge vs time for times between 800 and 1000

very powerful!

Making a histogram in the program:

- Open data file (skopenf)
- Loop over events
    - Read one event (skread)
        (information stashed locally)
    - Loop over PMT hits
        - For each hit, fill charge
            and time histograms
- Close data file (skclosef)
- Output histogram to file

Later, view histogram with PAW (or Root)

Making simple ntuples:

- Open data file (skopenf)
- Loop over events
    - Read one event (skread)
        (information stashed locally)
    - Loop over PMT hits
        - For each hit, output list of
            variables to a text file
- Close data file (skclosef)

Later, use PAW to make ntuples from text file, and plot desired variables

Next 2 weeks: I will be in Japan, but other HEP profs (who would like to recruit students for research) will speak