Results from K2K

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K2K

- Neutrino beam generated at KEK
  - ➔ 98% ν_μ, mean E_ν 1.3 GeV
- Near detectors at KEK sample beam 300 m from proton target
- Beam is directed through the earth to Super-K 250 km away

K2K Collaboration

Japan (55 physicists):

- ICRR
- KEK
- Kobe University
- Kyoto University
- Niigata University
- Okayama University
- Osaka University
- Science University of Tokyo
- University of Tokyo
- Tohoku University
- Tokyo Inst. of Tech.

Korea (18):

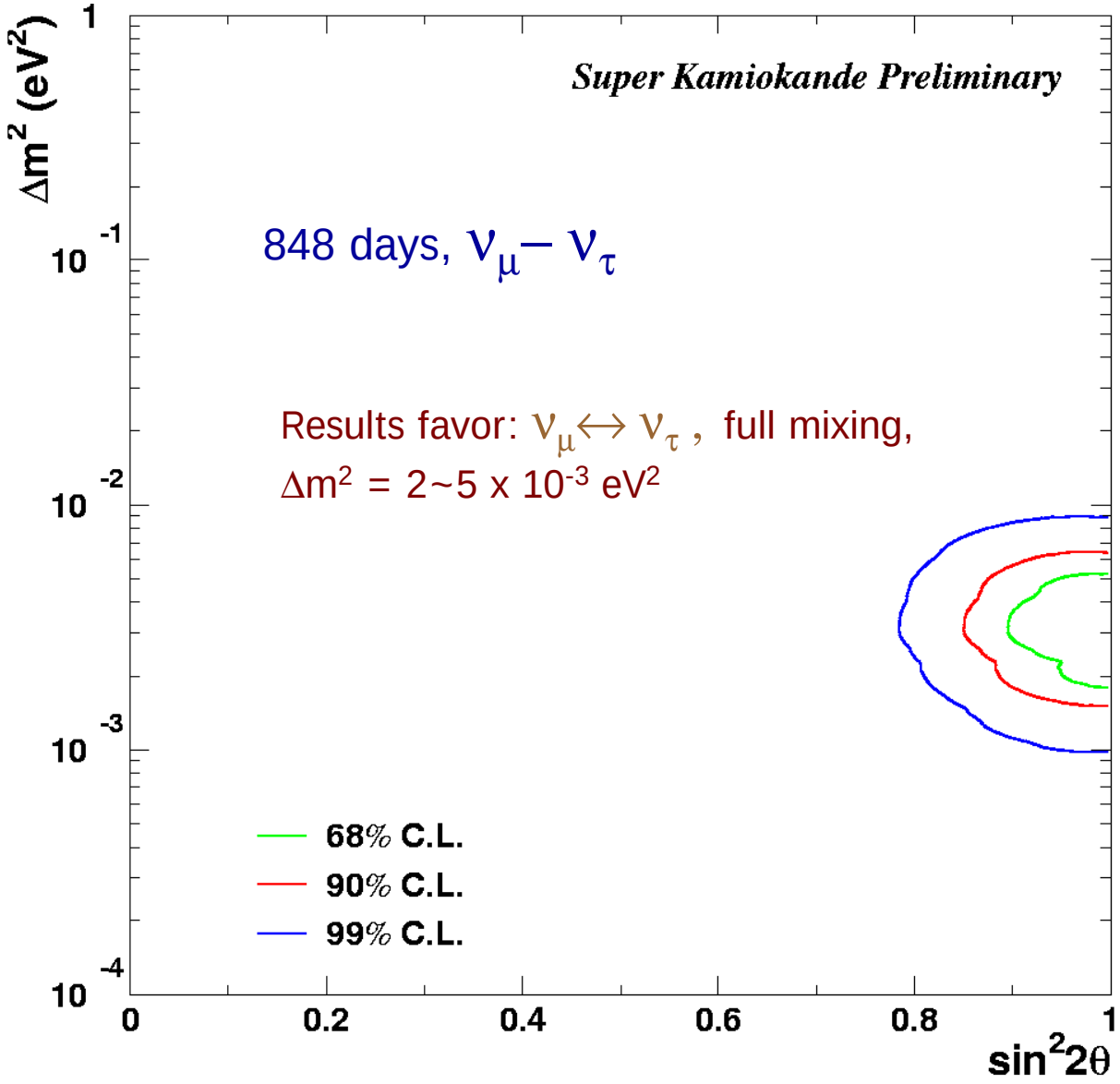
- Chonnam National University
- Dongshin University
- Korea University
- Seoul National University

USA (24):

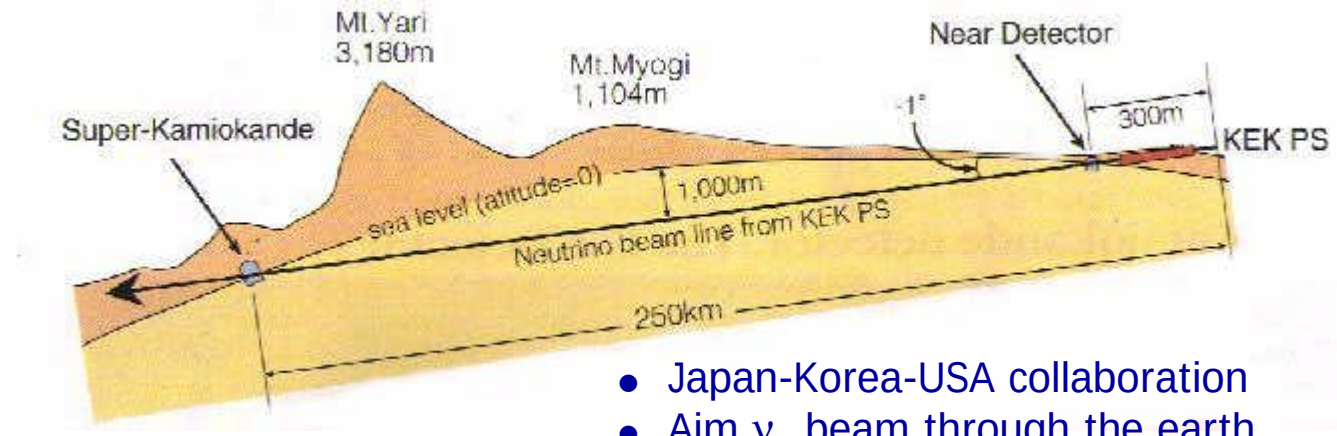
- Boston University
- SUNY at Stony Brook
- University of California, Irvine
- University of Hawaii
- University of Washington
- Warsaw University

Motivation: check Super-K results on neutrino oscillations

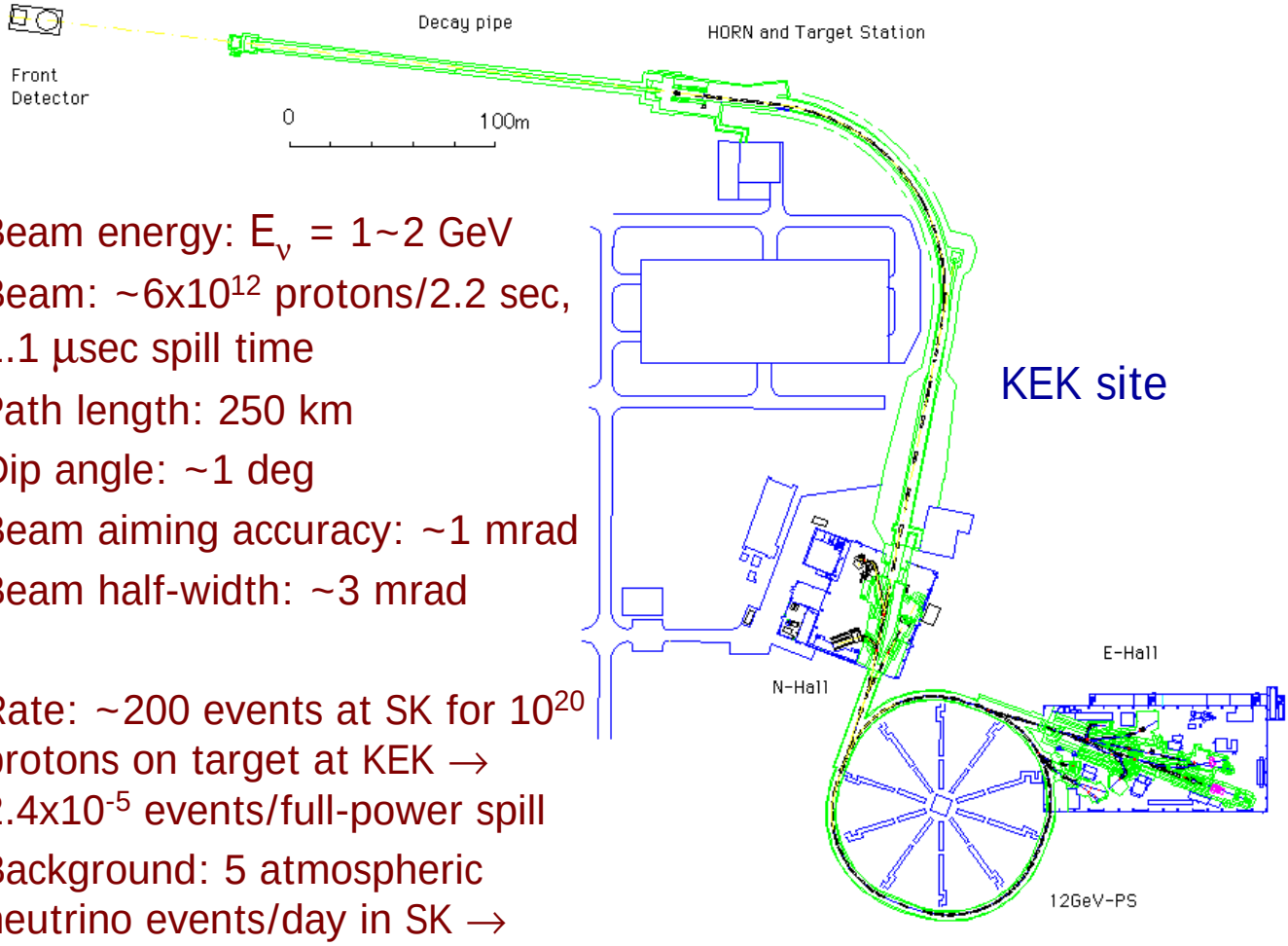
- Super-Kamiokande allowed region from atmospheric neutrino data
  - All samples: fully contained, partially contained and upward muon events
  - 2-flavor analysis, physical region only



K2K: Long Baseline Neutrino Experiment (KEK E362)



- Japan-Korea-USA collaboration
- Aim ν_μ beam through the earth from KEK to Super-Kamiokande



KEK site

Beam energy: E_ν = 1~2 GeV

Beam: ~6×10^{12} protons/2.2 sec, 1.1 μsec spill time

Path length: 250 km

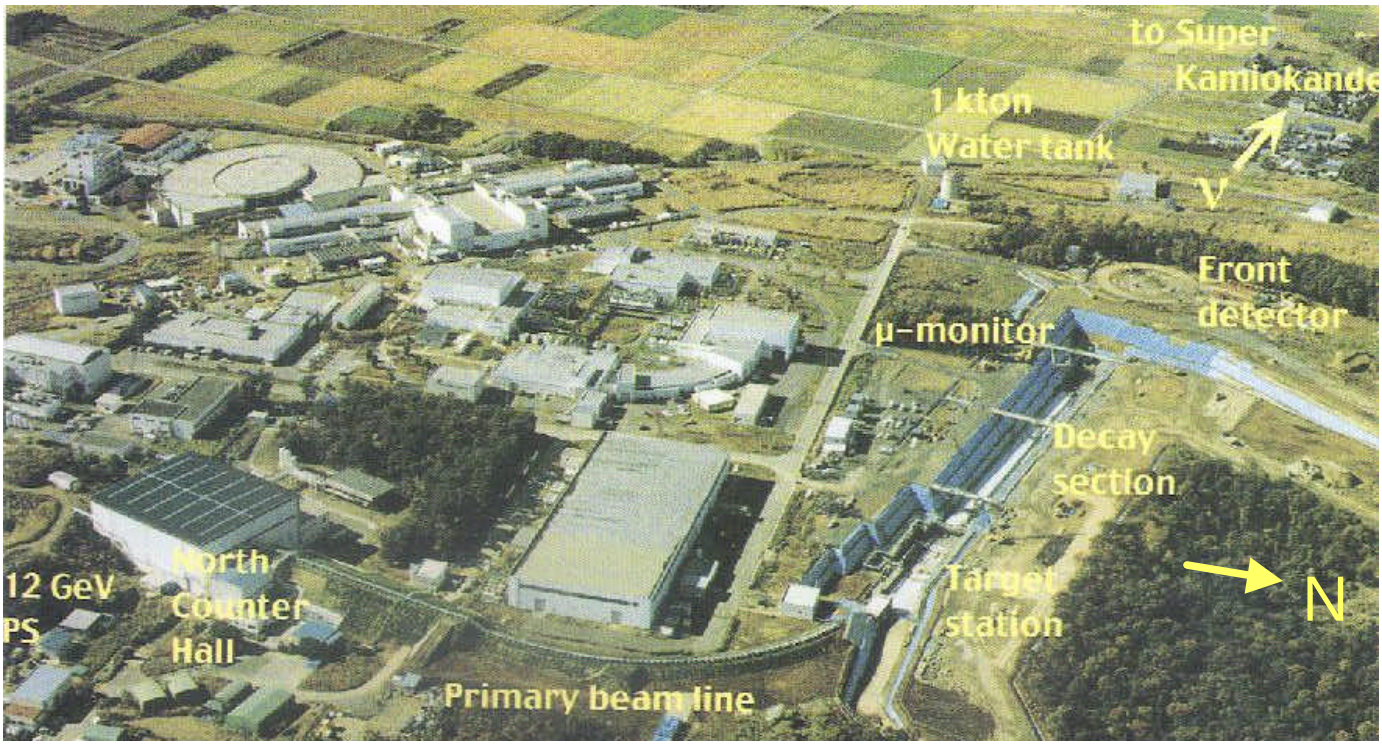
Dip angle: ~1 deg

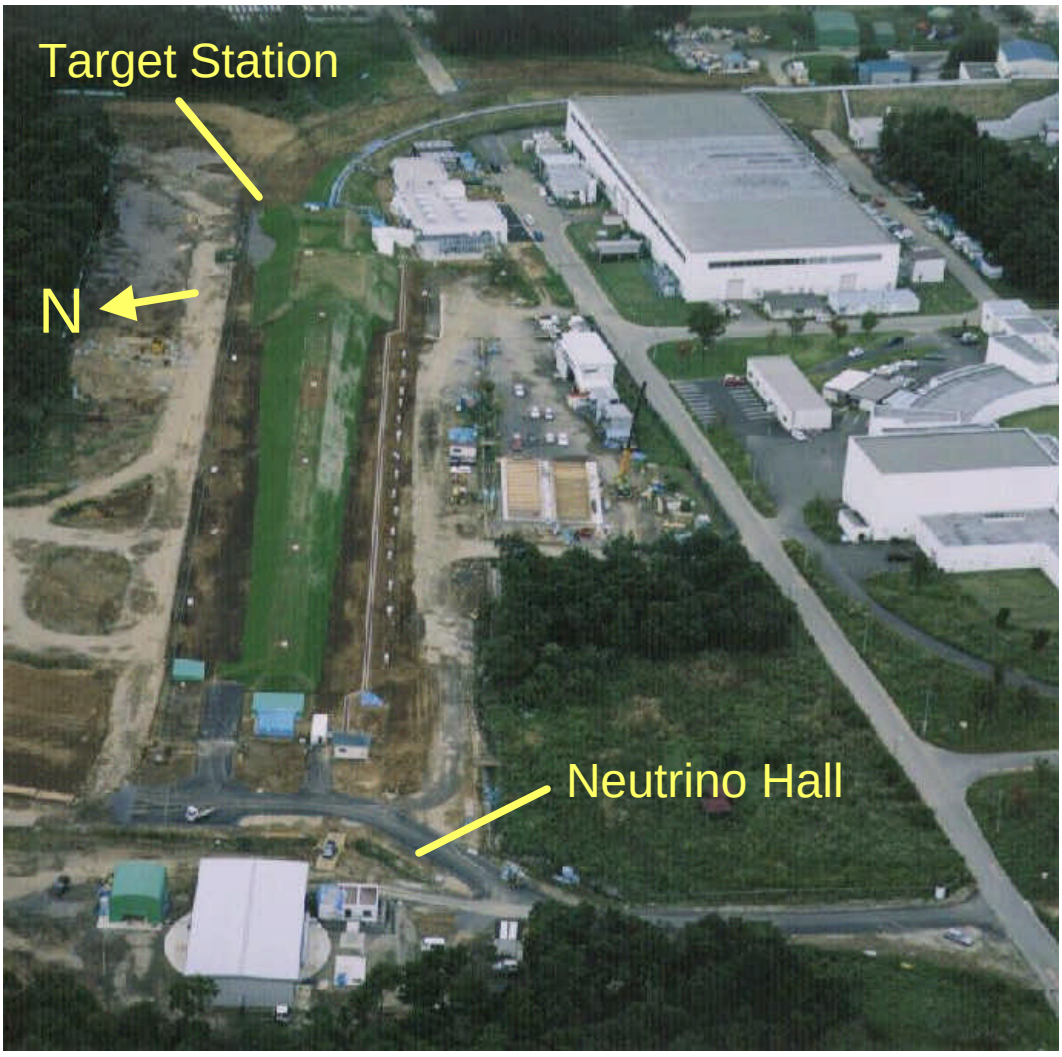
Beam aiming accuracy: ~1 mrad

Beam half-width: ~3 mrad

Rate: ~200 events at SK for 10^{20} protons on target at KEK → 2.4×10^{-5} events/full-power spill

Background: 5 atmospheric neutrino events/day in SK → P(BG)=6×10^{-11} per spill

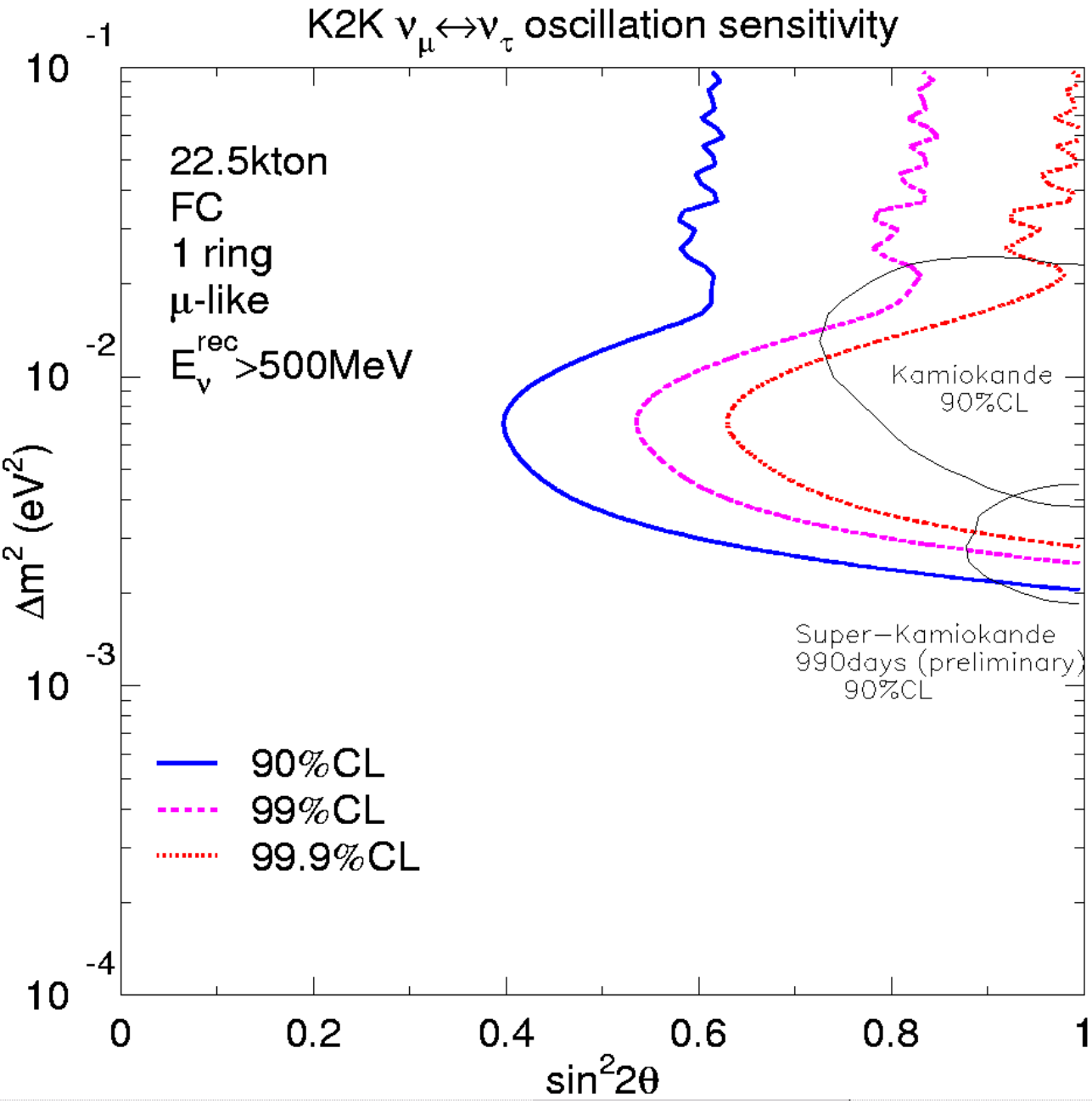




KEK n beamline during (above) and after (left) construction

K2K Sensitive Region

Curves show allowed regions for past experiments, and sensitivity region for K2K, at 90% CL

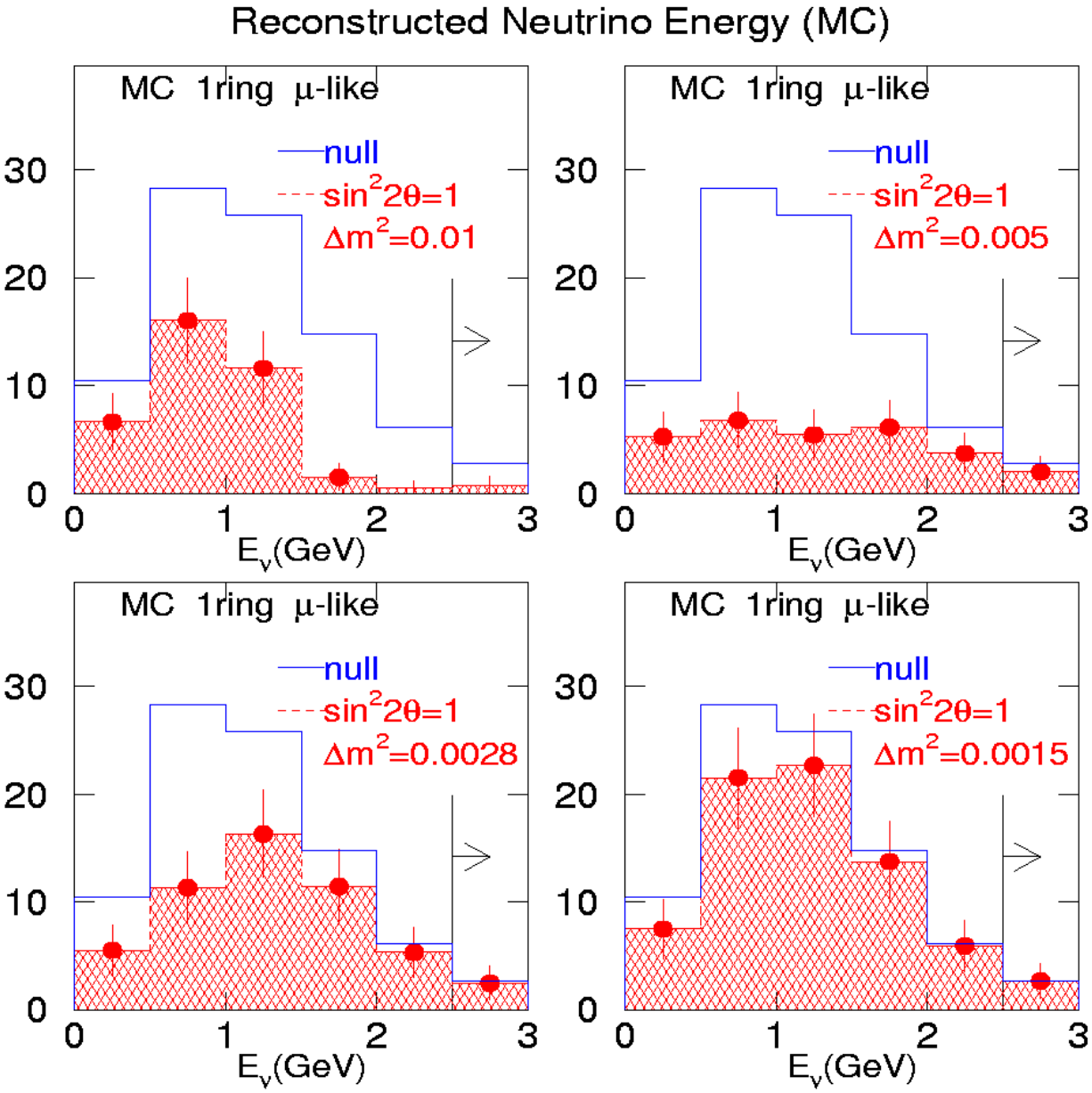


Oscillation effects clearly visible in E spectrum

Predicted far-detector E_ν spectra from beam Monte Carlo

— = no oscillations (10^{20} pot → 190 events @ SK)

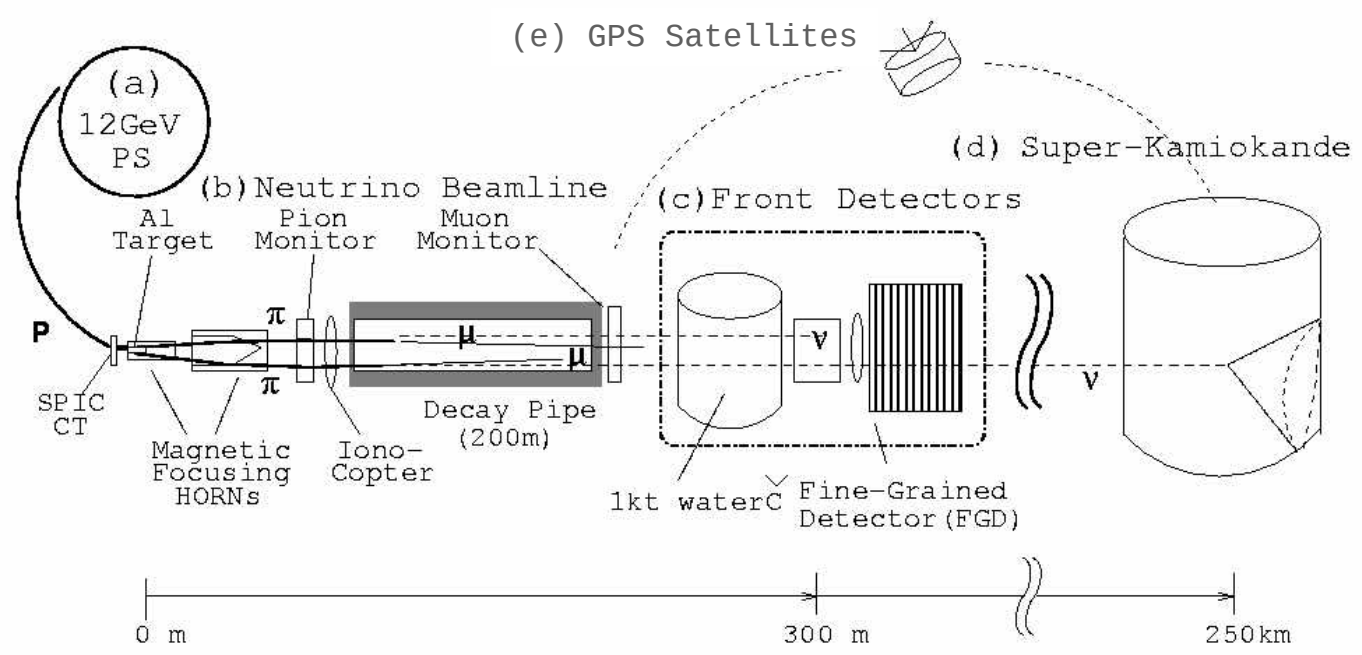
▭ = full $\nu_\tau - \nu_\mu$ mixing, various Δm^2 values



Functional overview of K2K

Components of K2K:

- KEK 12 GeV proton synchrotron
  - ~ 6E12 protons per 2.2 sec
- KEK Neutrino beamline
  - 2-horn design (250 kA) with Al target
  - pion monitors for p, θ, ϕ spectra in target hall
  - 200 m decay pipe with muon monitor at end
- KEK Near detectors
  - 1 kT Water Cherenkov tank
  - Sci-Fi tracker with water target layers
  - Fe muon tracker/ranger
- Super-K serves as far detector
- GPS system provides time sync to <100 nsec



K2K detector elements at KEK

Beam monitors

- Proton beamline monitors
- Pion monitors after target
- Muon monitor at beam dump

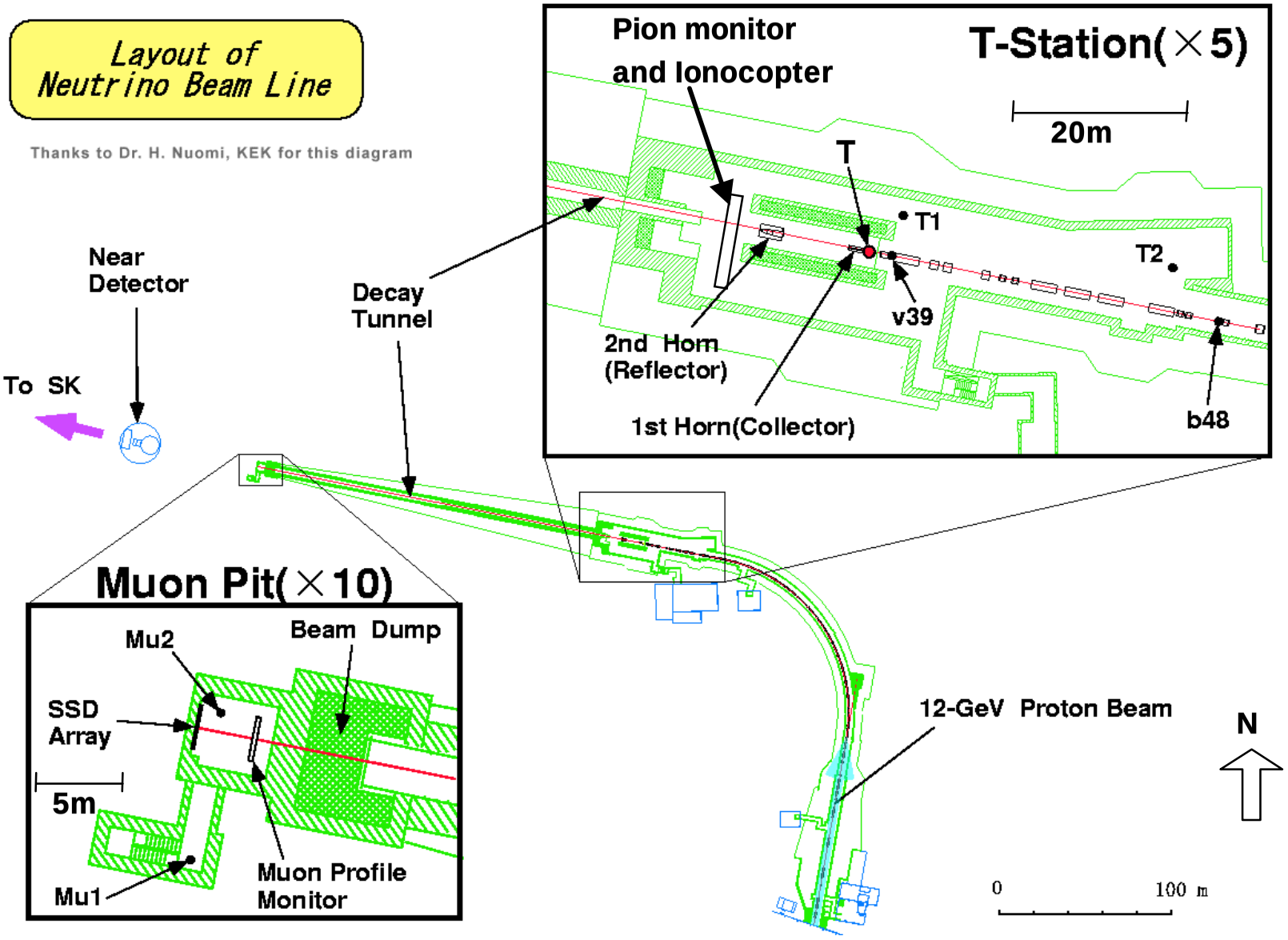
Near Detectors

- 1 kT water Cherenkov
  - mini-Super-K
  - L = 300m
  - Water tank from E261 (Kamiokande/IMB beam test expt)
  - Most systematics common with SuperK
- Fine-grained detector (FGD)
  - Scintillating fiber / Water targets (SciFi)
  - Pb-glass wall (PBG)
  - Muon range detector (MRD)

Near detector functions

- Check accuracy of neutrino beam and interaction Monte Carlo codes used to predict SK event rates
  - Beam aim
    - During run: muon profile at beam dump monitor
    - Offline: beam profile via muon range detector
  - Spill timing
    - Dual independent GPS receivers at each site
  - Absolute neutrino flux vs time
    - Current Transformer (CT) monitors in proton beam
    - Independently measured event rates in
      - 1 kT water Cherenkov detector
      - Sci-Fi detector
      - MRD
  - Neutrino energy spectrum
    - Pion monitor: pion kinematics
    - CC interactions in 1 kT, Sci-Fi, MRD
  - Extrapolation to Super-K
    - Pion monitor: pion kinematics
  - Neutrino interaction model accuracy
    - 1 kT data on CC-1π, NC-π^0, etc
    - Sci-Fi data on CC-QE interactions, etc

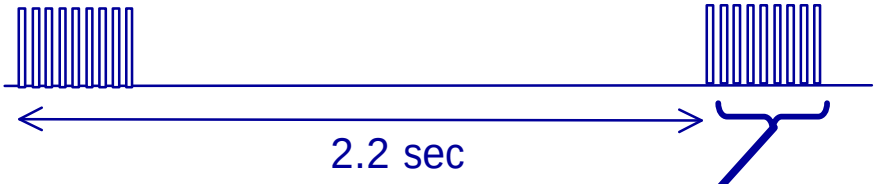
KEK ν_μ beamline and monitors



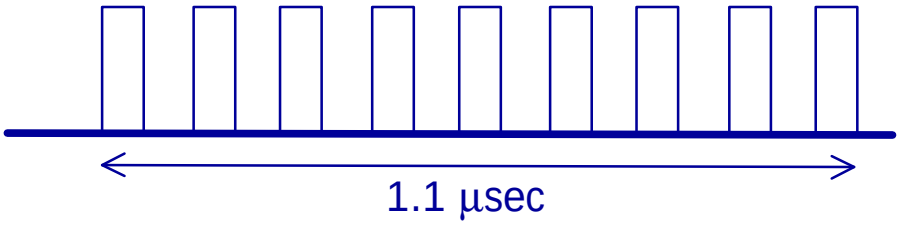
Beam spill structure

Each spill ~6×10^{12} protons on target (pot)

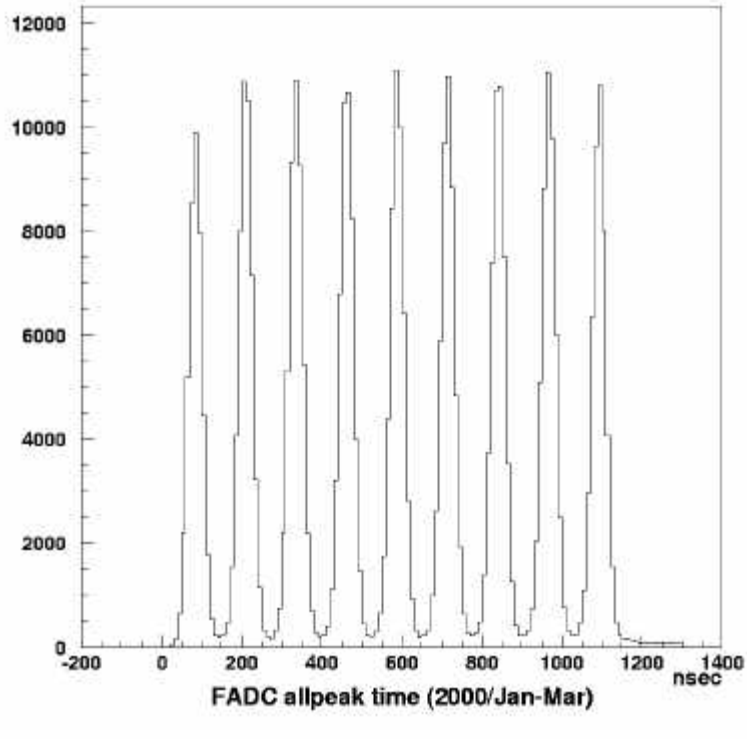
Spill rate: 0.45 Hz



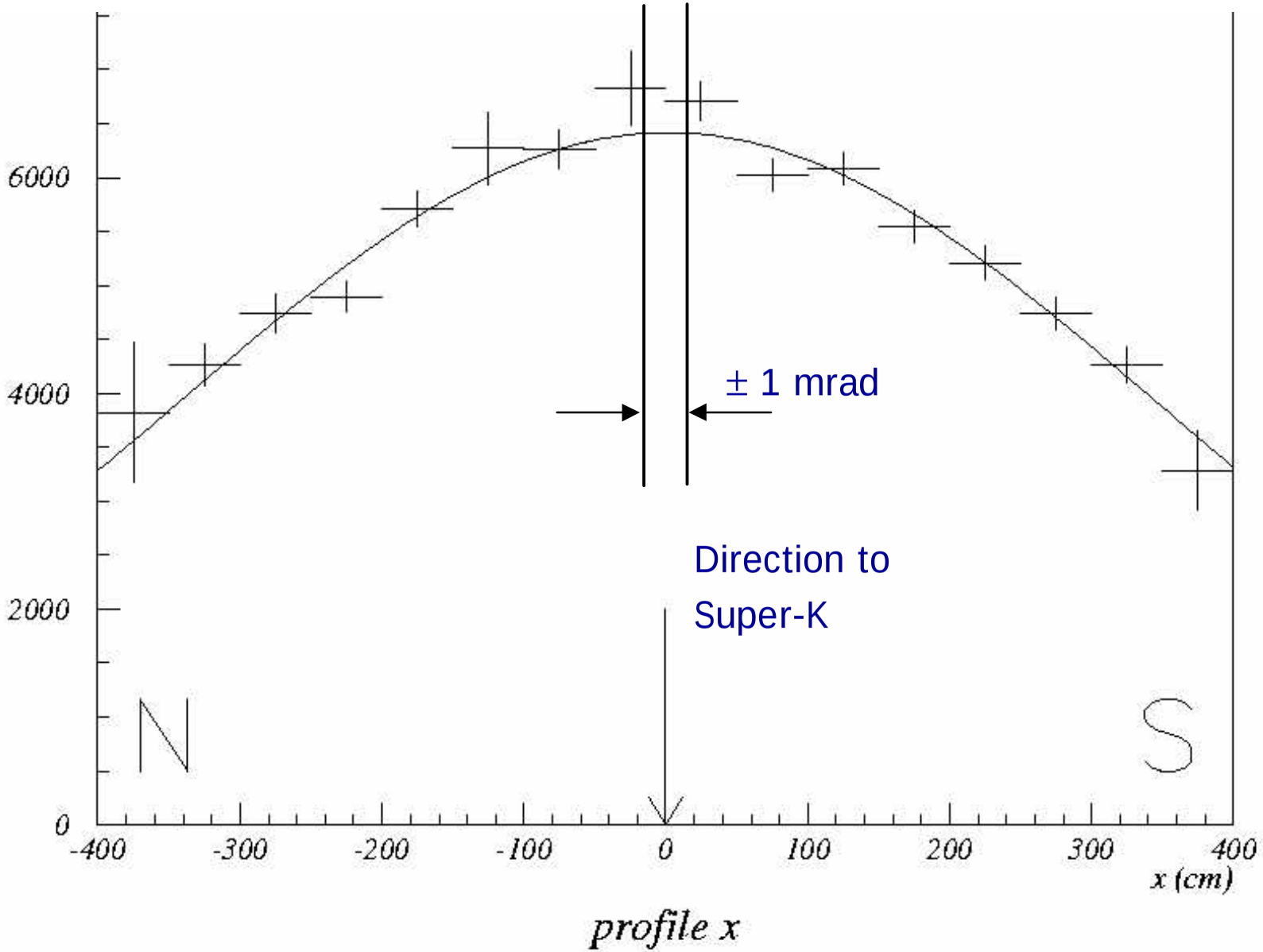
Spill bunch structure



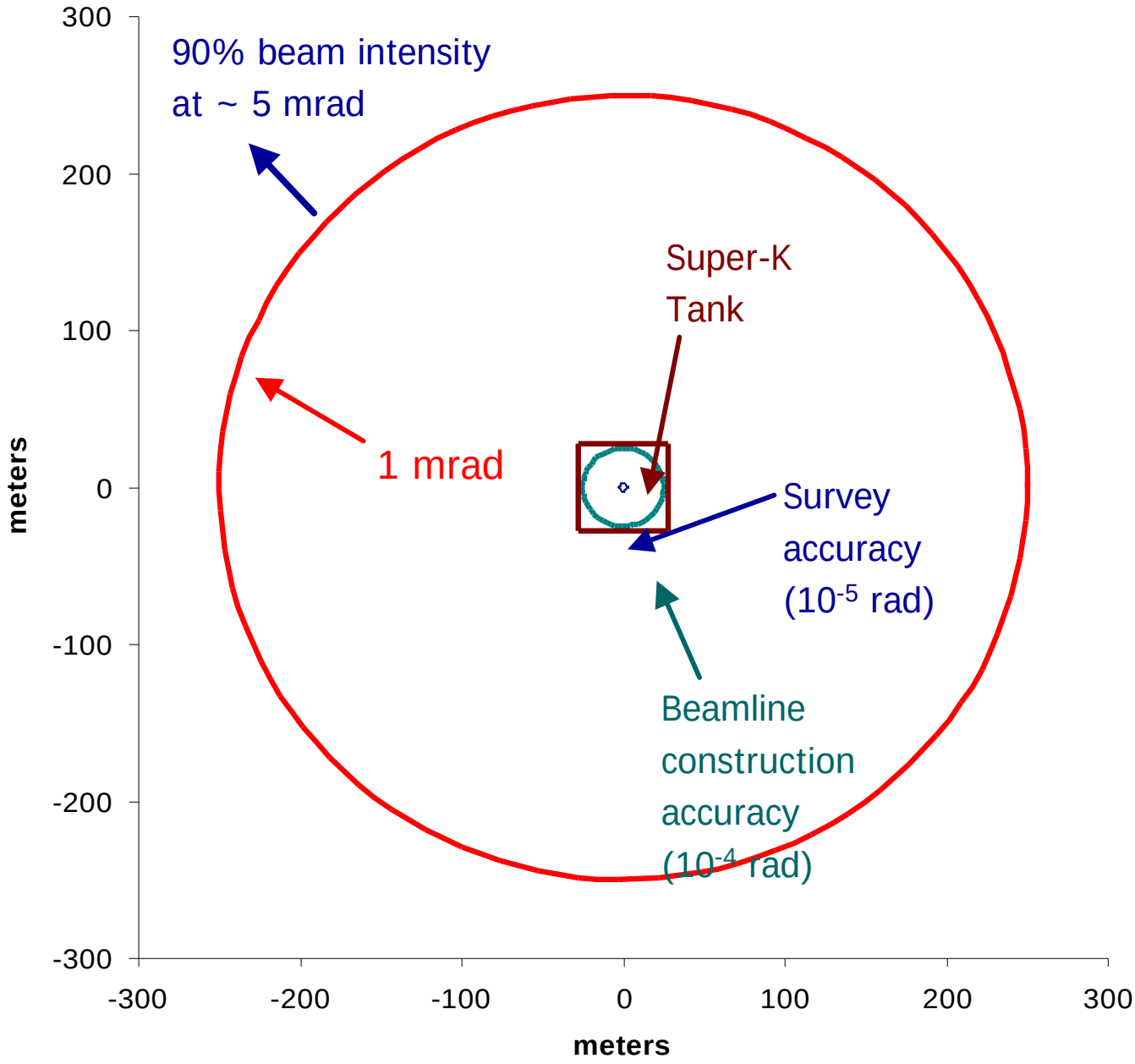
…seen in 1kT FADC:



Beam aiming

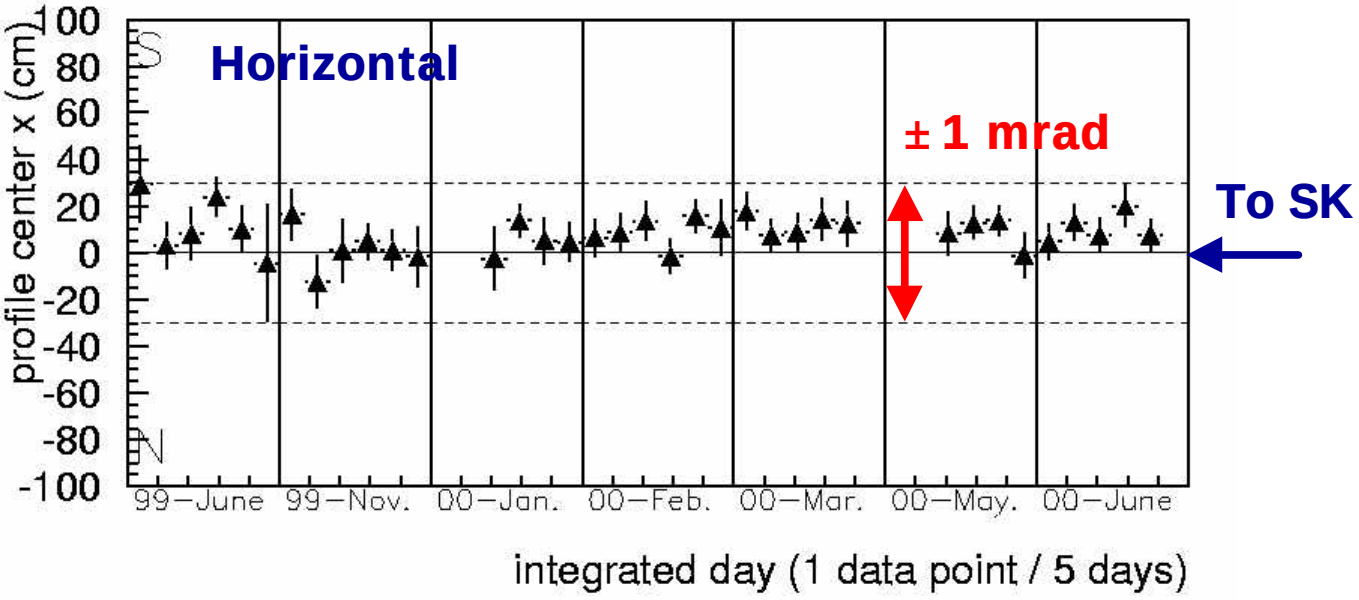

6000
4000
2000
0
-400
-300
-200
-100
0
100
200
300
400
x (cm)
± 1 mrad
Direction to
Super-K
N
S
profile x

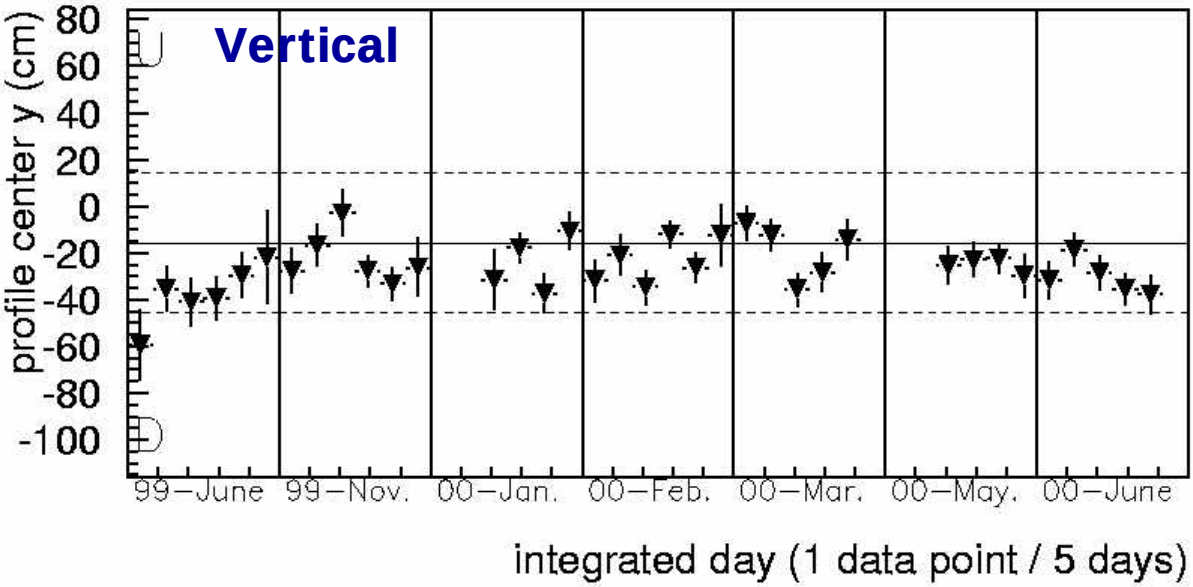
K2K beam aiming accuracy at Super-K



Beam stability

From muon detector:
stability of neutrino beam pointing

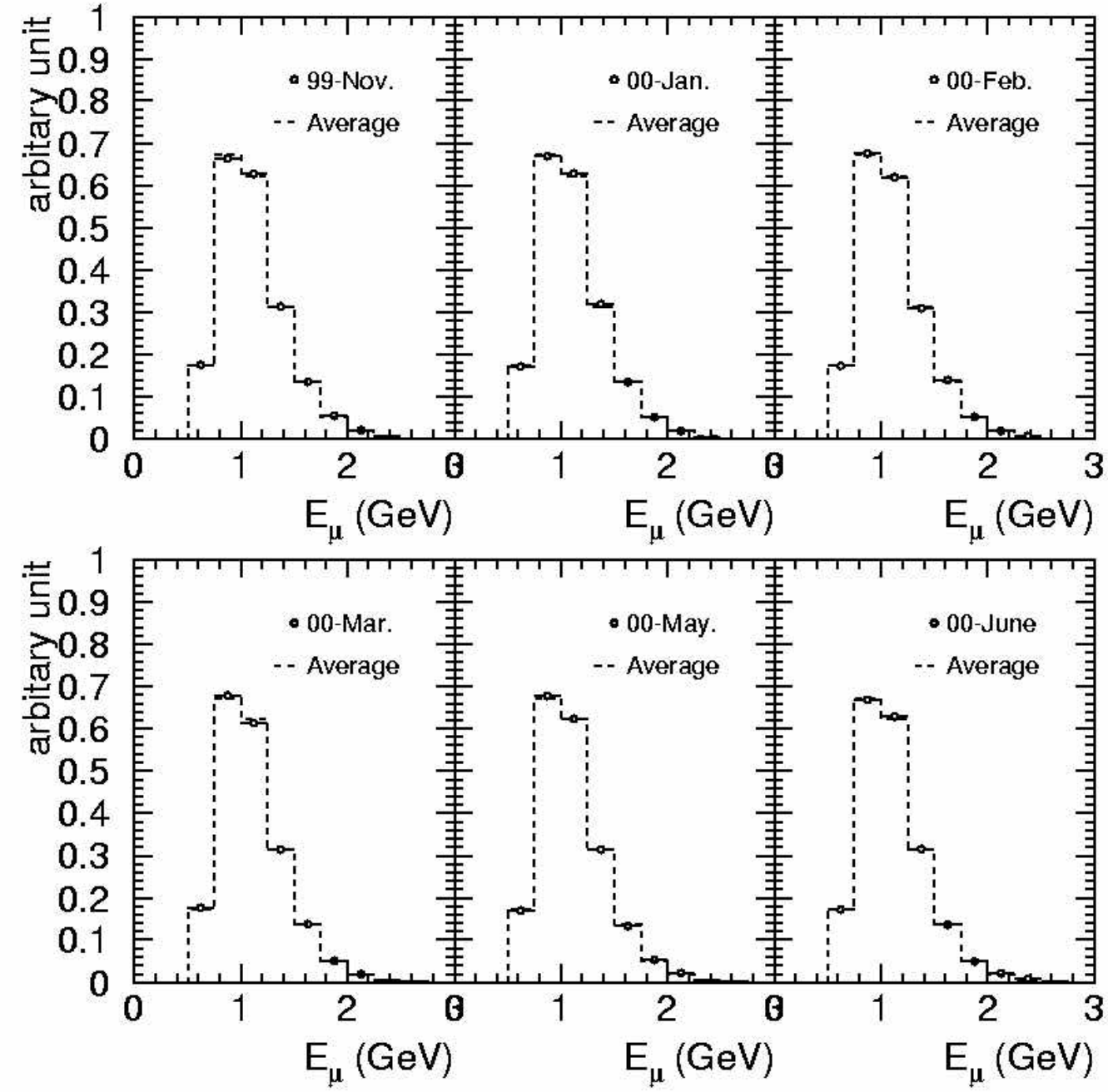




Beam stability

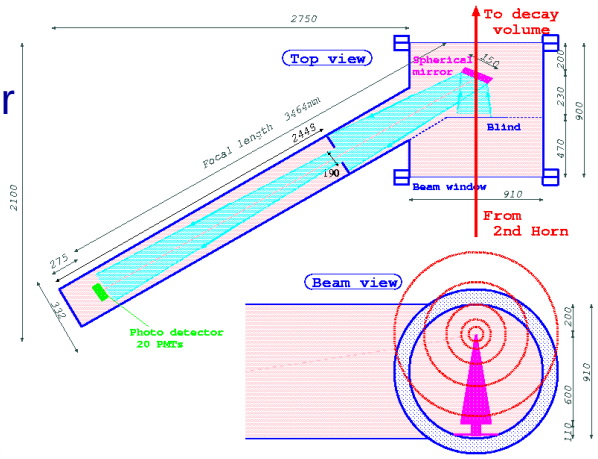
From muon detector:

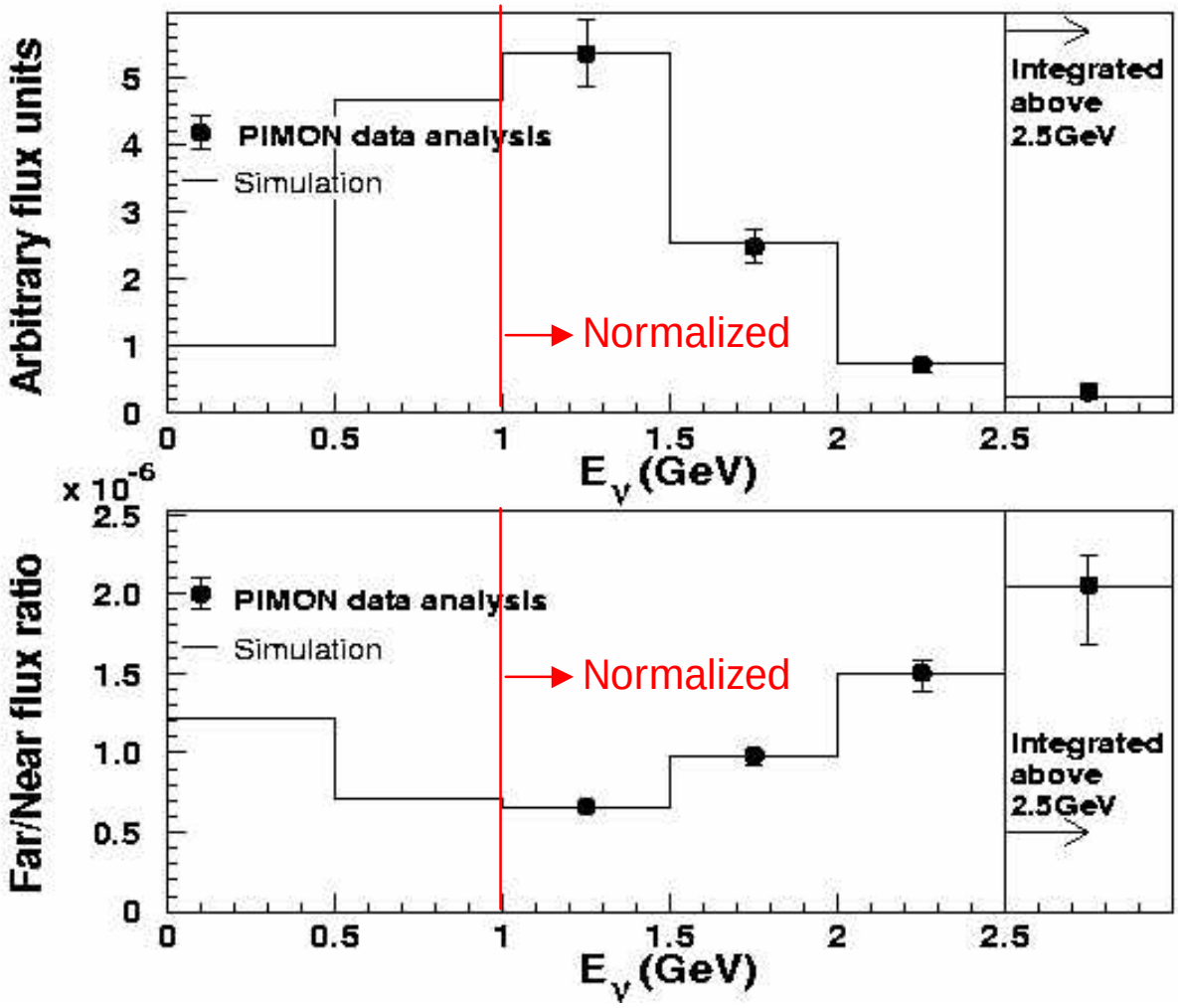
Stability of observed muon energy spectrum



Pion monitor data vs beam MC

- PiMon: Gas Cherenkov detector
  - Samples p vs θ_{BEAM} in target hall
  - Novel design with wedge reflector in beam
  - Normally retracted, special calibration runs
- Plots: PiMon data vs beam MC
  - Near detector spectrum
  - Far/near ratio

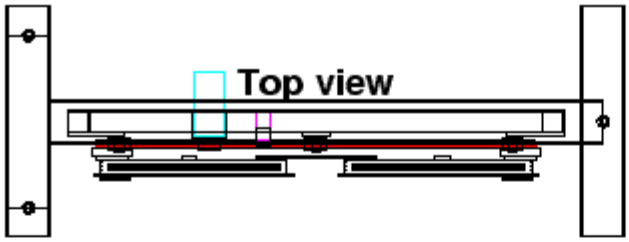


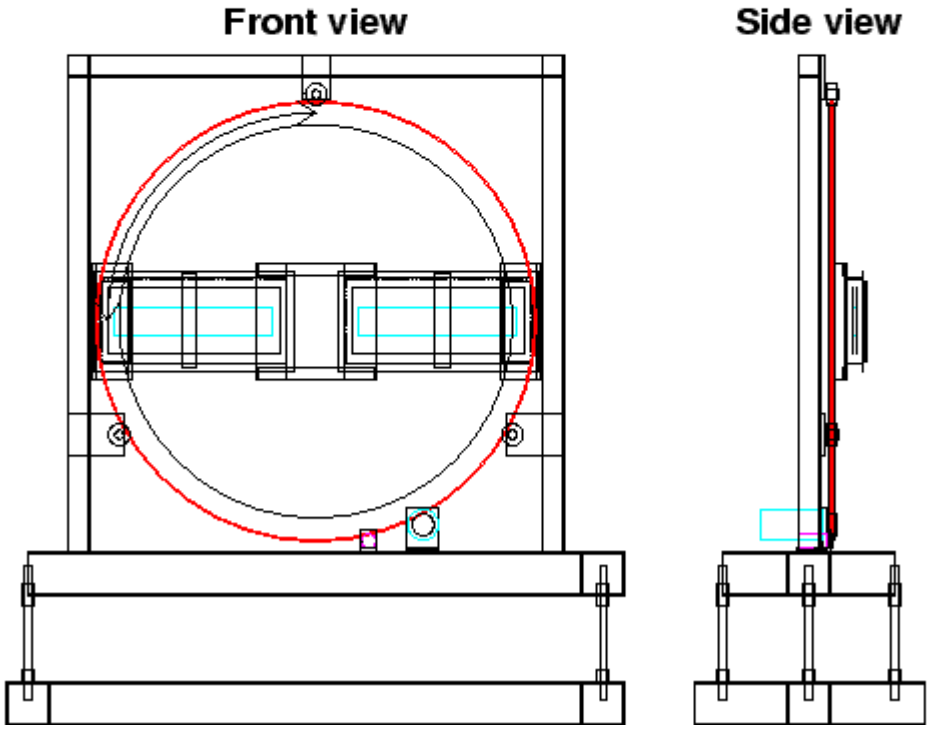


Ionocopter

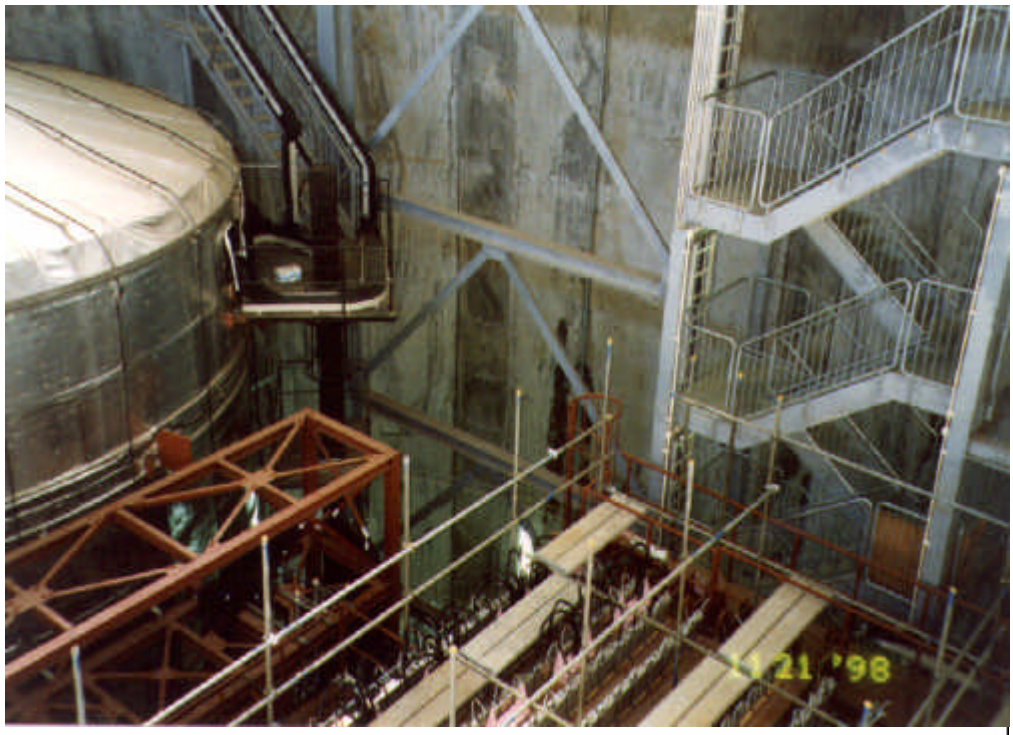
- Rotatable ionization chambers
- Located near pion monitor
- Periodically inserted to check azimuthal uniformity of beam

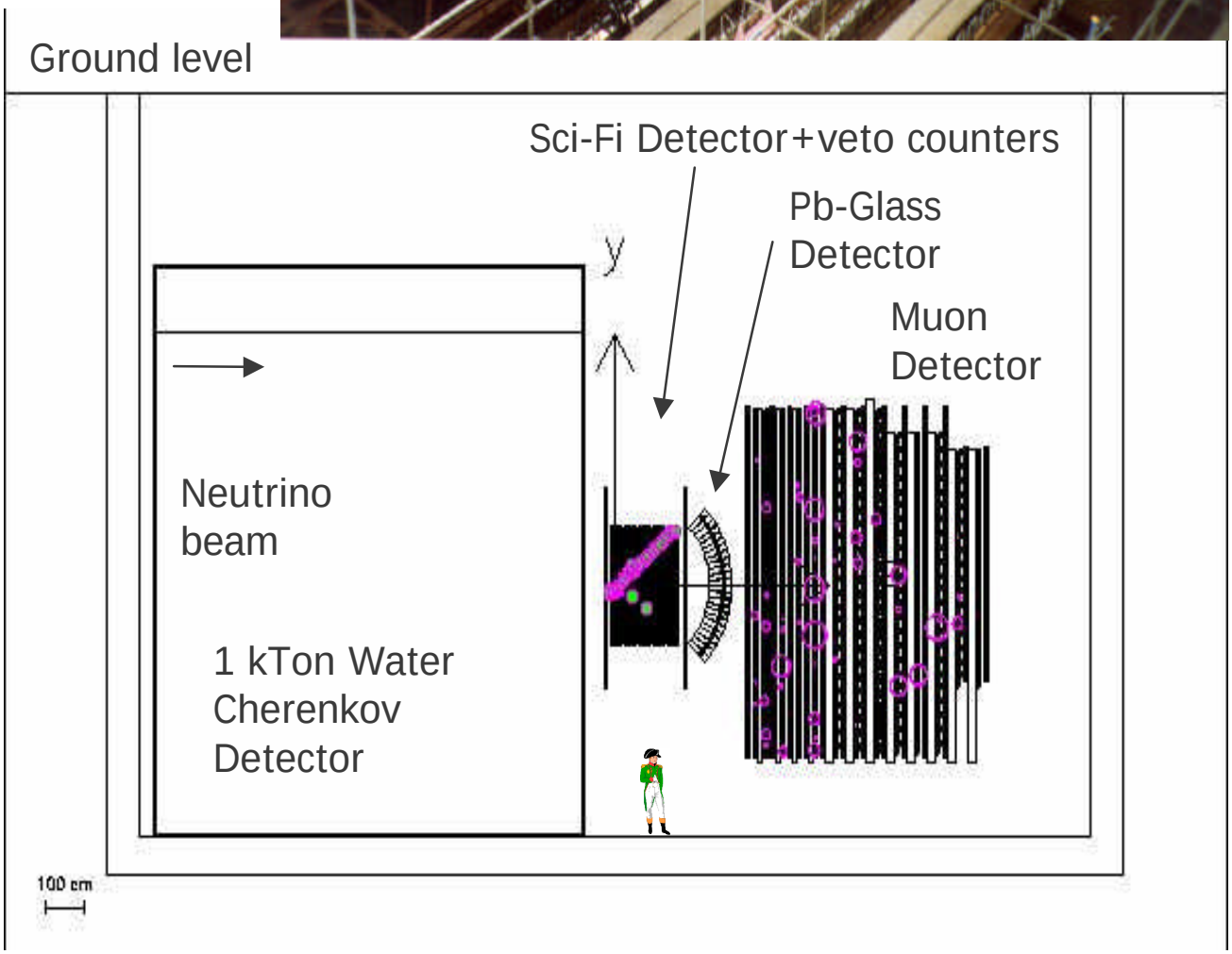
Results: Uniform within resolution of Ionocopter



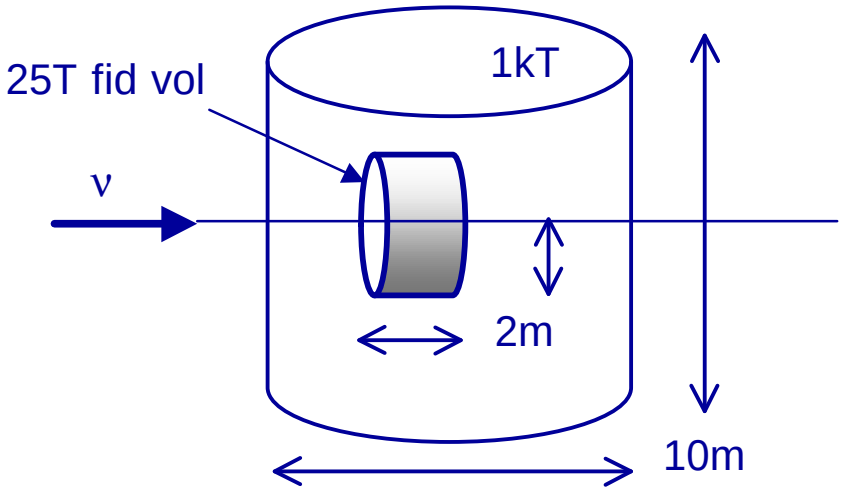


K2K Near Detector Hall



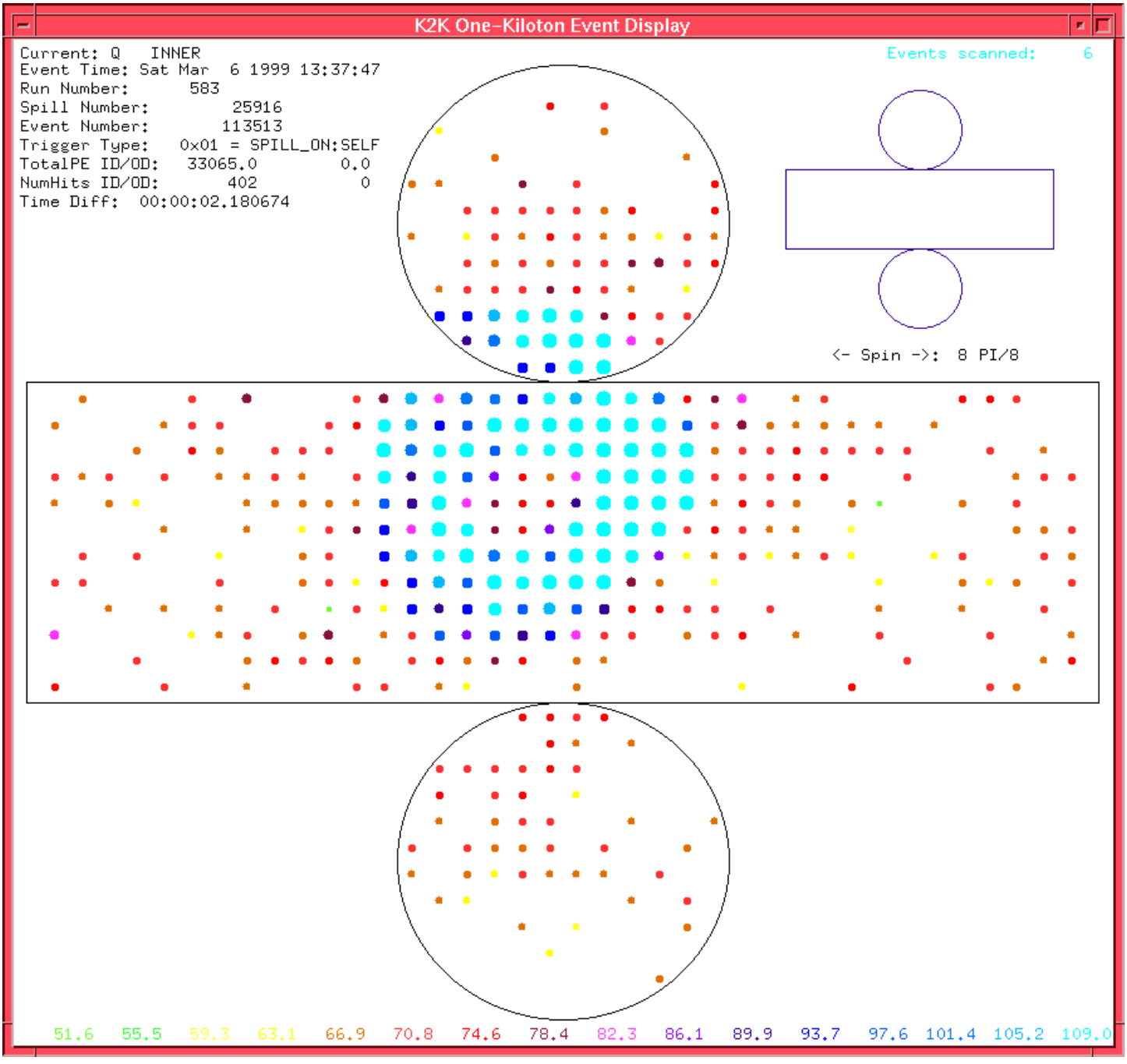


1kT Water Cerenkov Detector

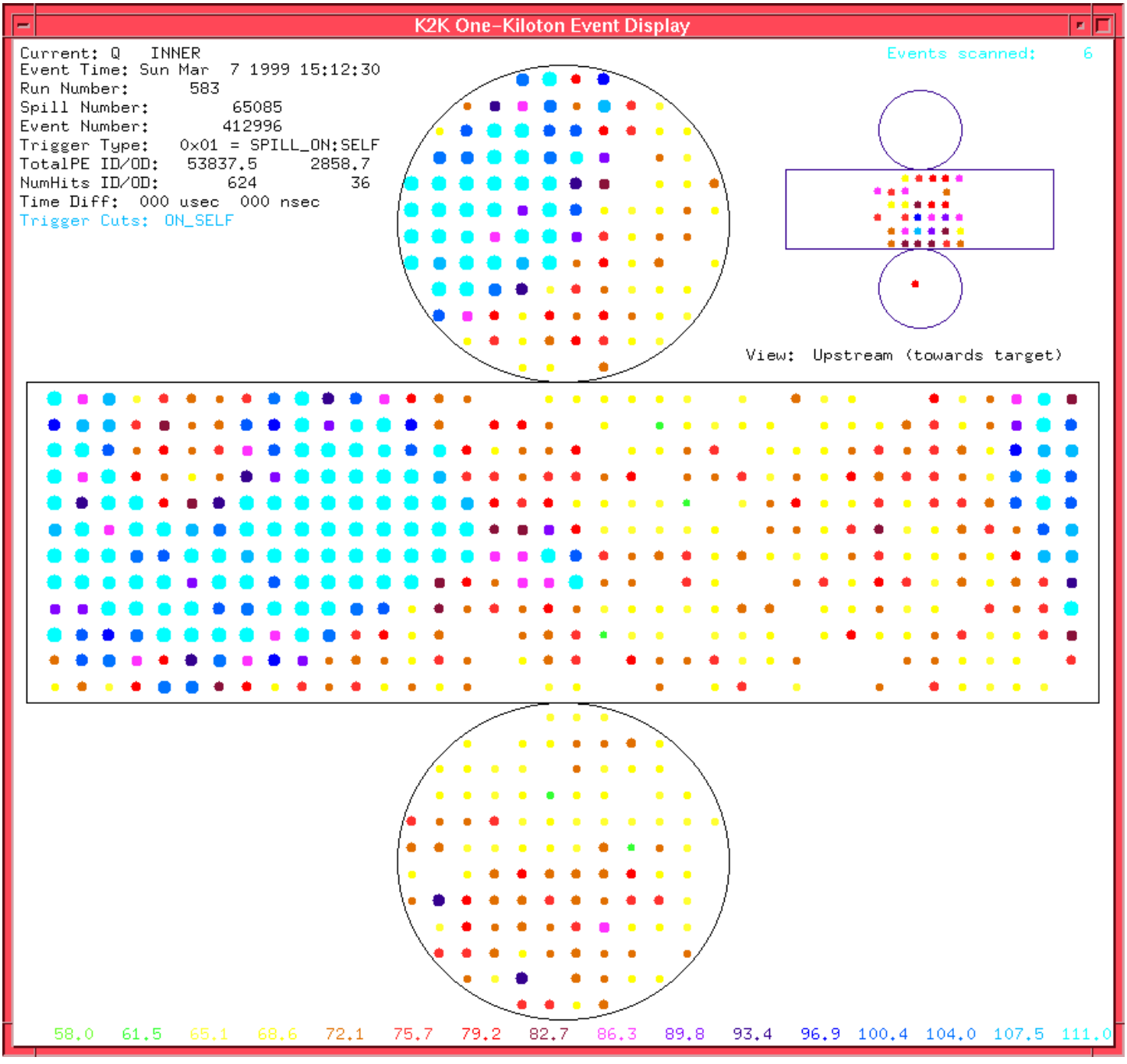


- Miniature Super-Kamiokande detector:
  - Same PMTs, PMT spacing, photocathode coverage
  - Same event fitting and particle ID (PID) procedures
- Flash ADC (FADC) measures analog sum of all PMTs
  - Event = peak >1000 pe (~100 MeV) in FADC signal
- Neutrino event selection:
  - No detector activity within 1.2 μs before spill
  - FADC signal shows only 1 event in spill
  - Reconstructed vertex within 25T fiducial volume
- Detection efficiencies:
  - Same MC used as in all Super-K analyses
  - 87% for CC interactions, 55% for NC inelastic
  - Overall efficiency 72% assuming expected CC/NC ratio
- Event rate: $<\nu_\mu$ events per pot$> = 3.2 \times 10^{-15}$
  - Corrected for spills with >1 event

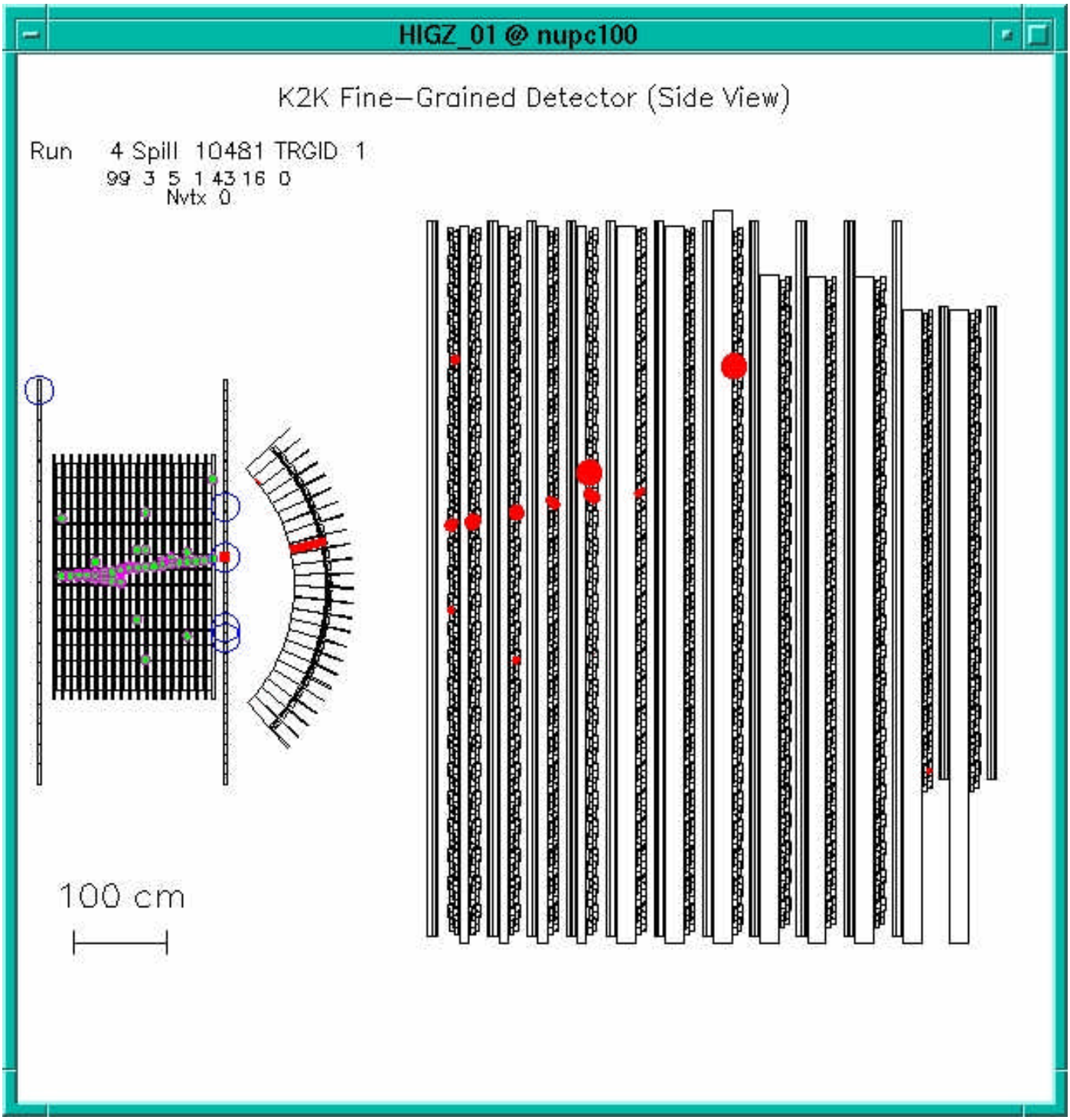
Neutrino event in 1 kT detector



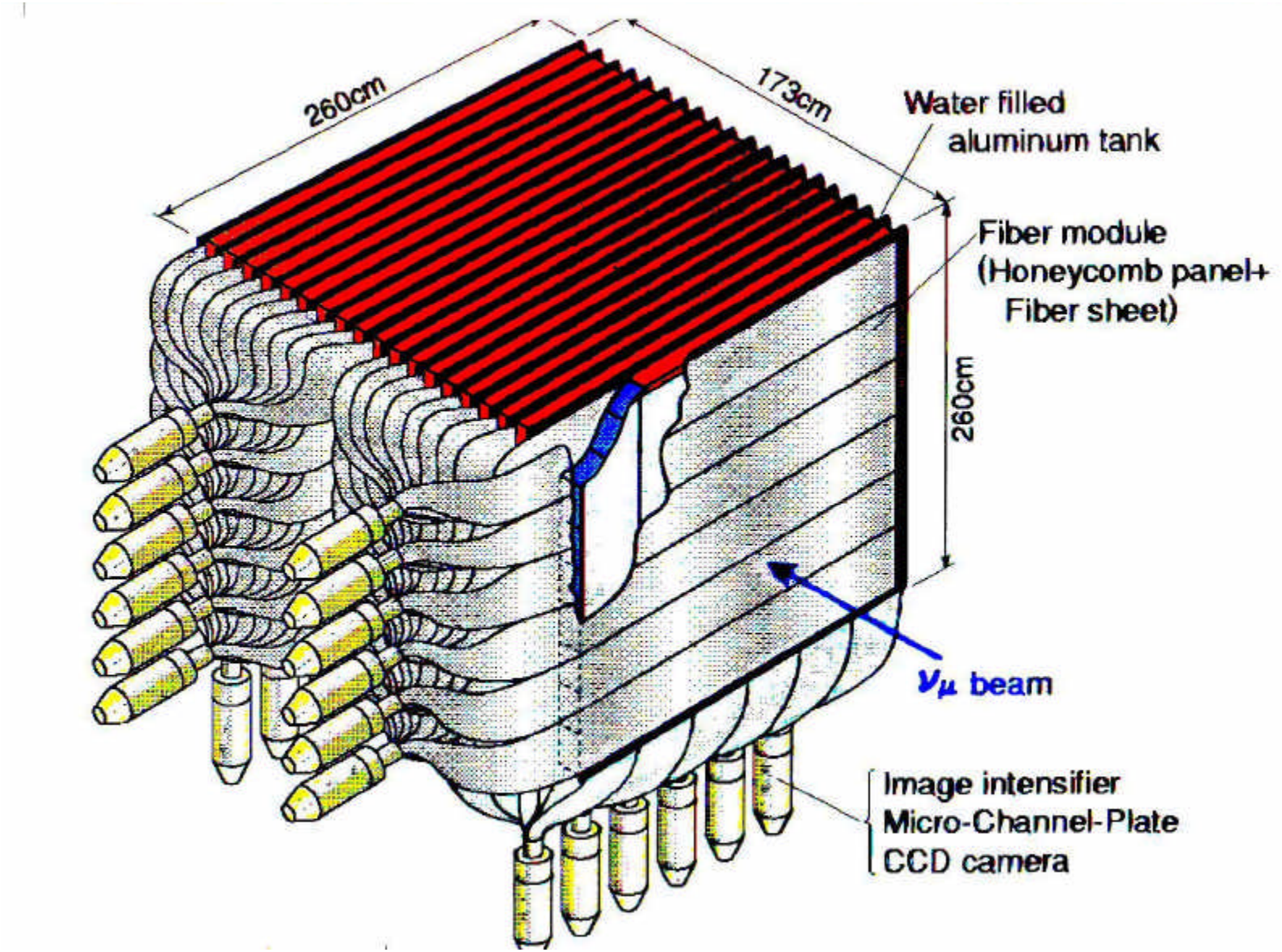
Beam induced muon in 1 kT detector



Fine-grained detector (Sci-Fi, PBG, veto counters and MRD)

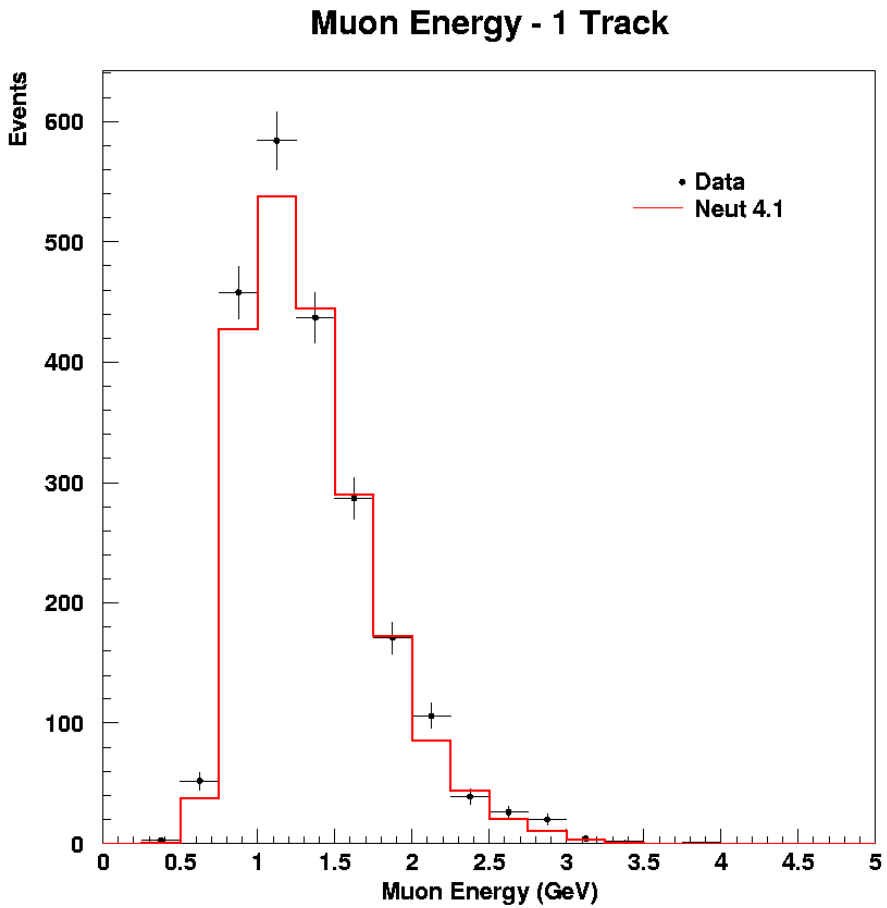


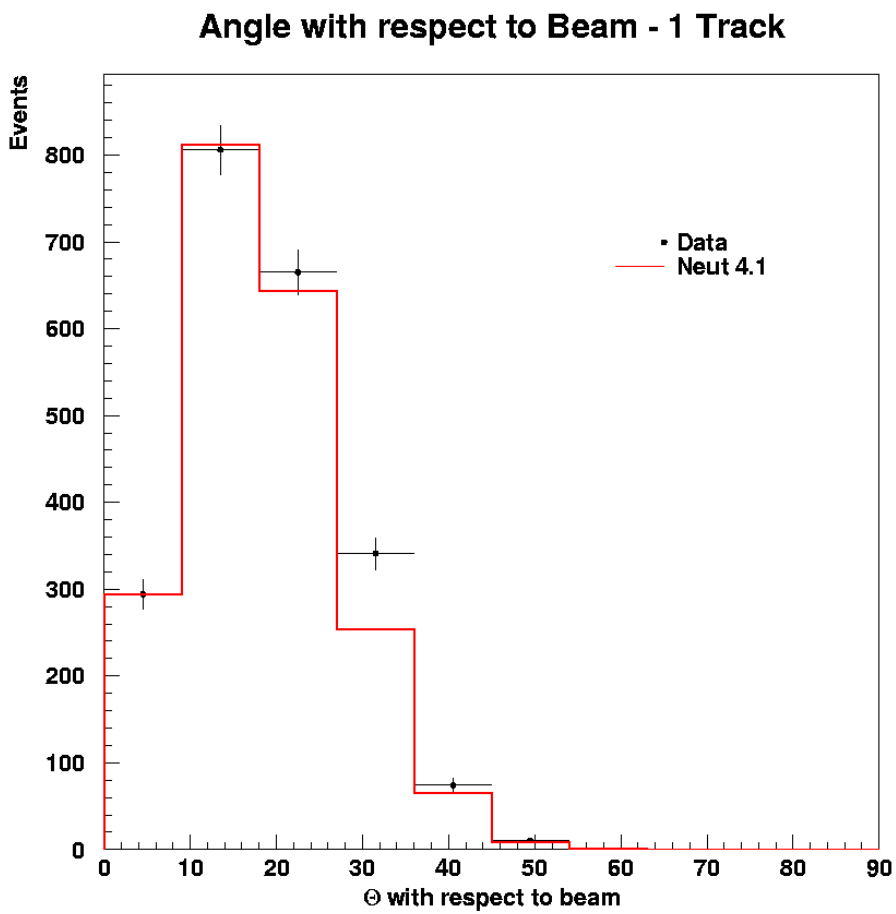
K2K scintillating fiber detector



Sci-Fi detector

Single track muon events (MC=same as Super-K):

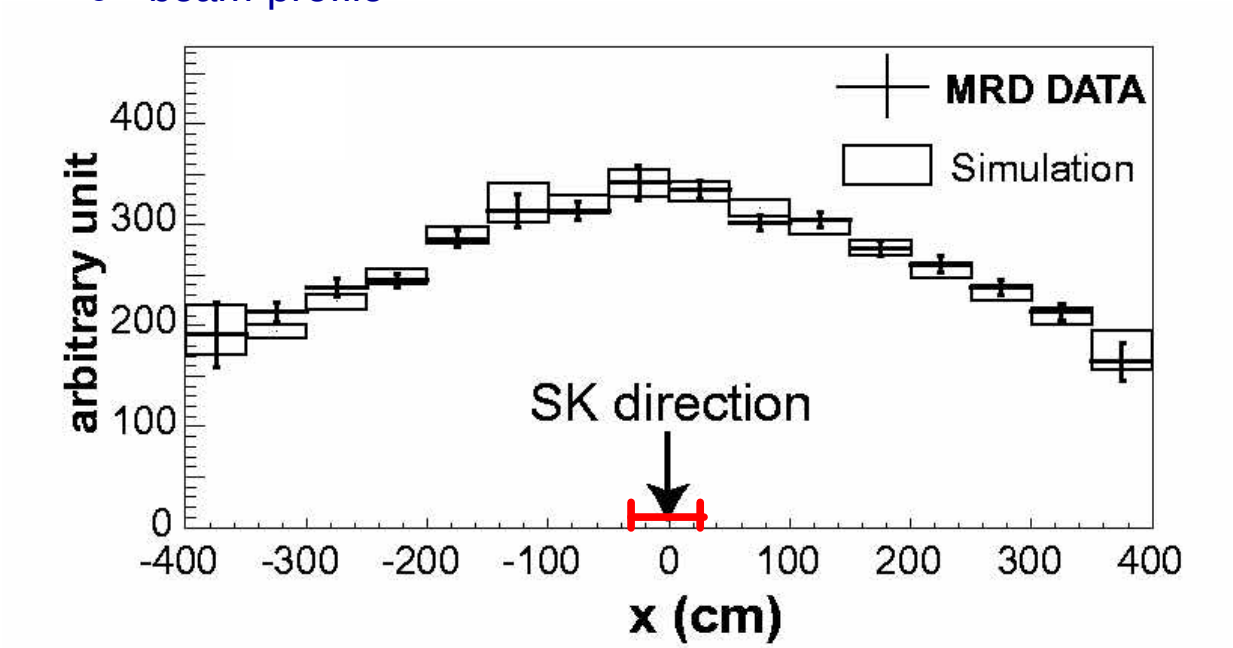




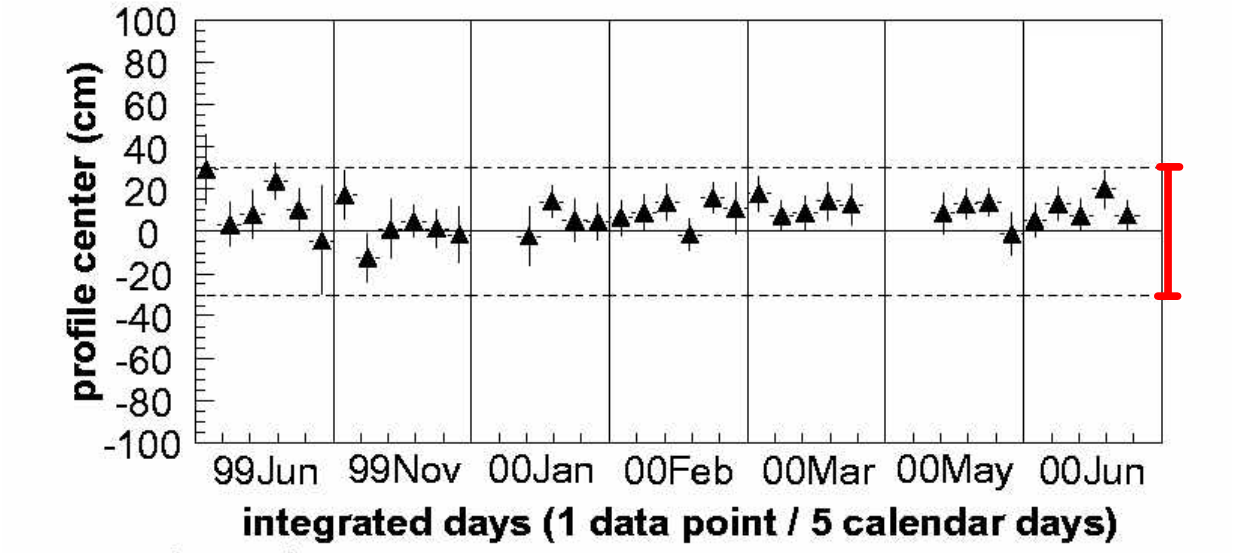
Beam profile and direction

Beam direction data from muon detector:

- beam profile



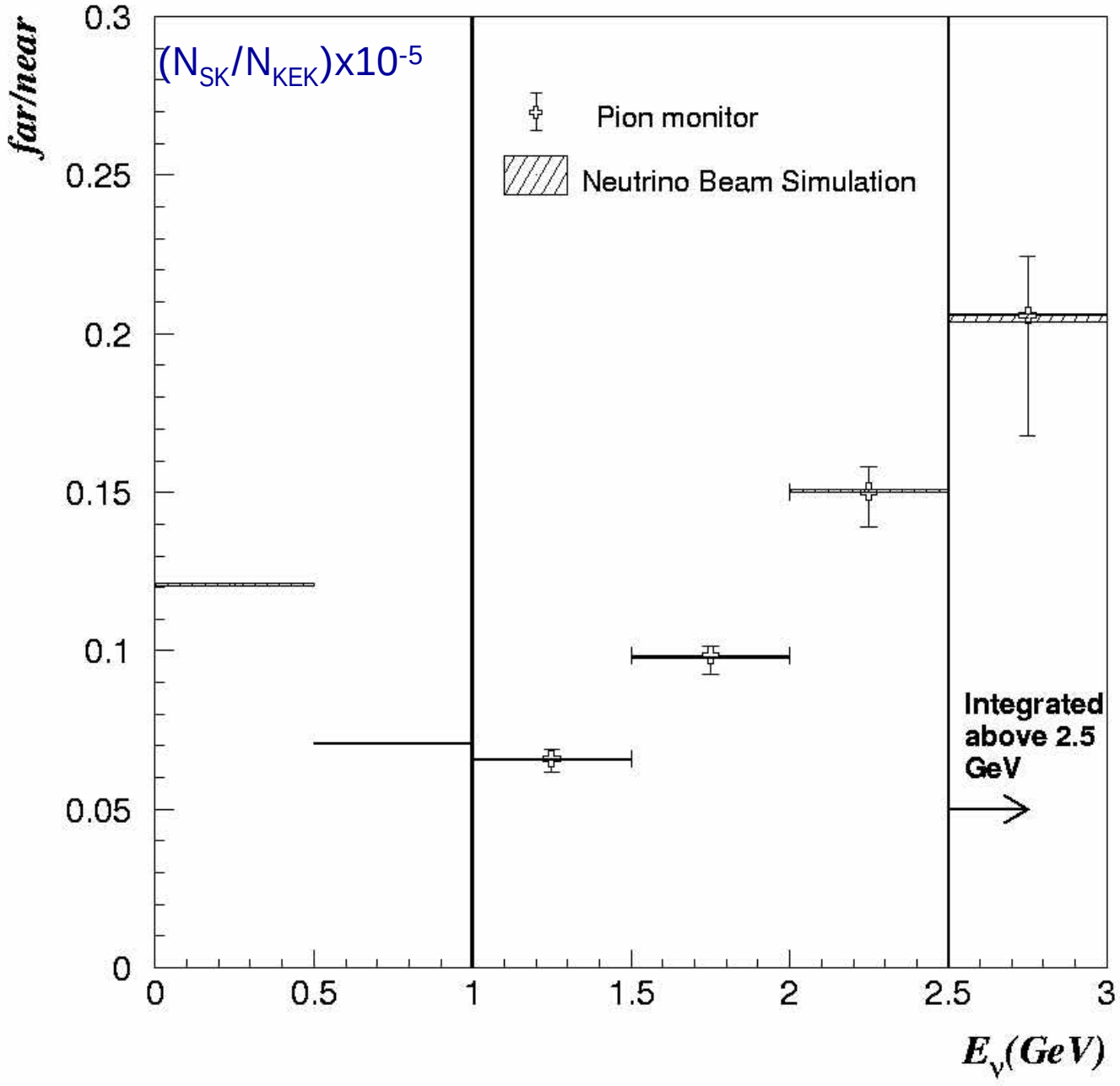
- stability of center direction vs time



Far / Near ratio

From pion monitor data:

Compare pi-monitor prediction to beam MC prediction for SK/KEK



K2K run history

2/99 First fast extraction, detector commissioning

3/99 Begin engineering run
- 3×10^{12} protons/spill
- Horn: 175 kA, 2 cm diameter target

4/99 Attempt to start data taking
- Horn cooling water leak!

5/99 Neutrino data taking run
- Horn run at various current levels
- Horn current feeder cables fail after few days!

6/99 Neutrino data taking run
- 4.5×10^{12} protons/spill
- Horn: 200 kA
- First K2K event detected at Super-K

7/99 Summer shutdown

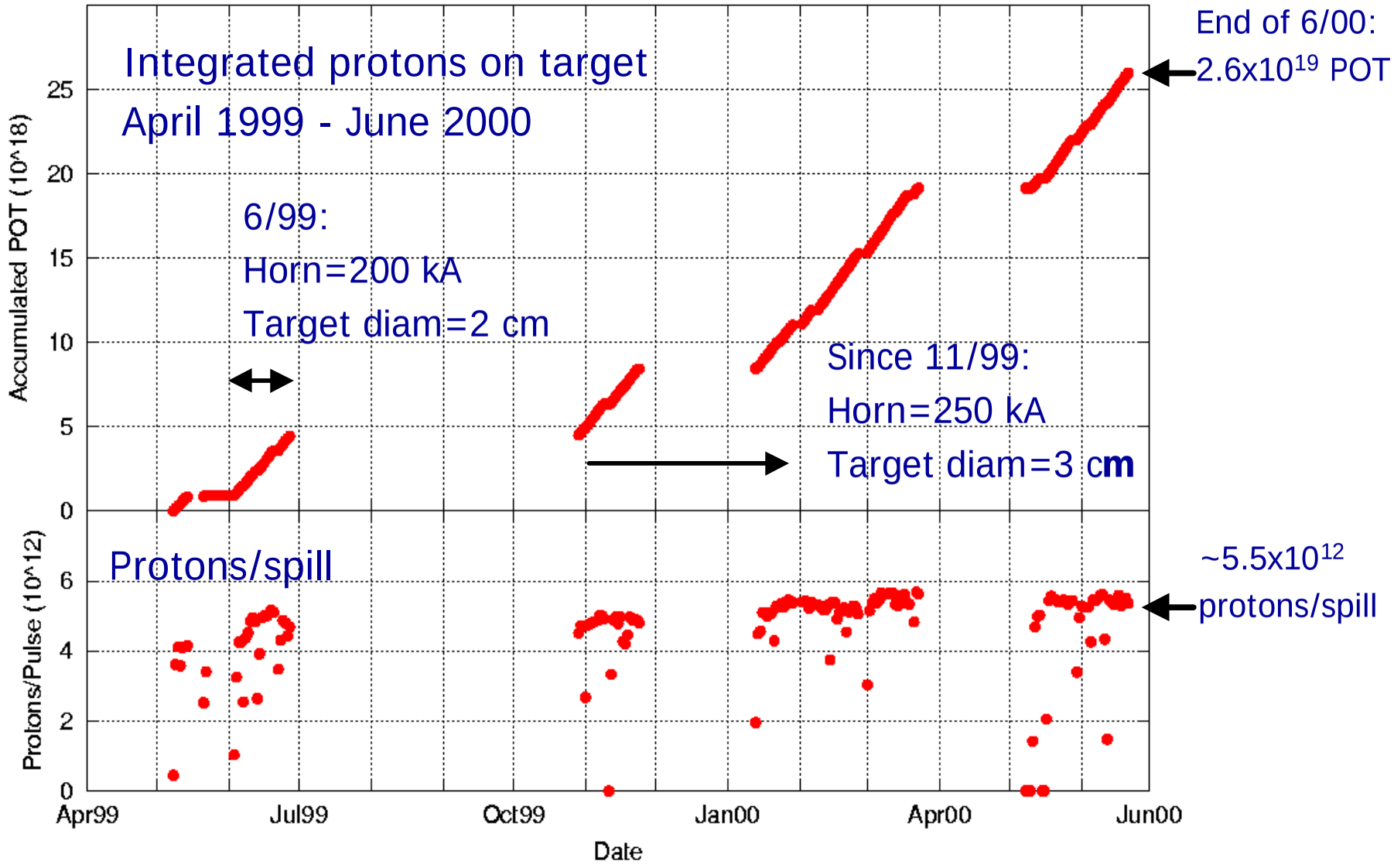
11/99 Neutrino data taking run
- 5×10^{12} protons/spill
- New horn: 3 cm diam target, 250 kA

1/00 Neutrino data taking run
- 5×10^{12} protons/spill
- Horn: 250 kA

7/00 Summer shutdown

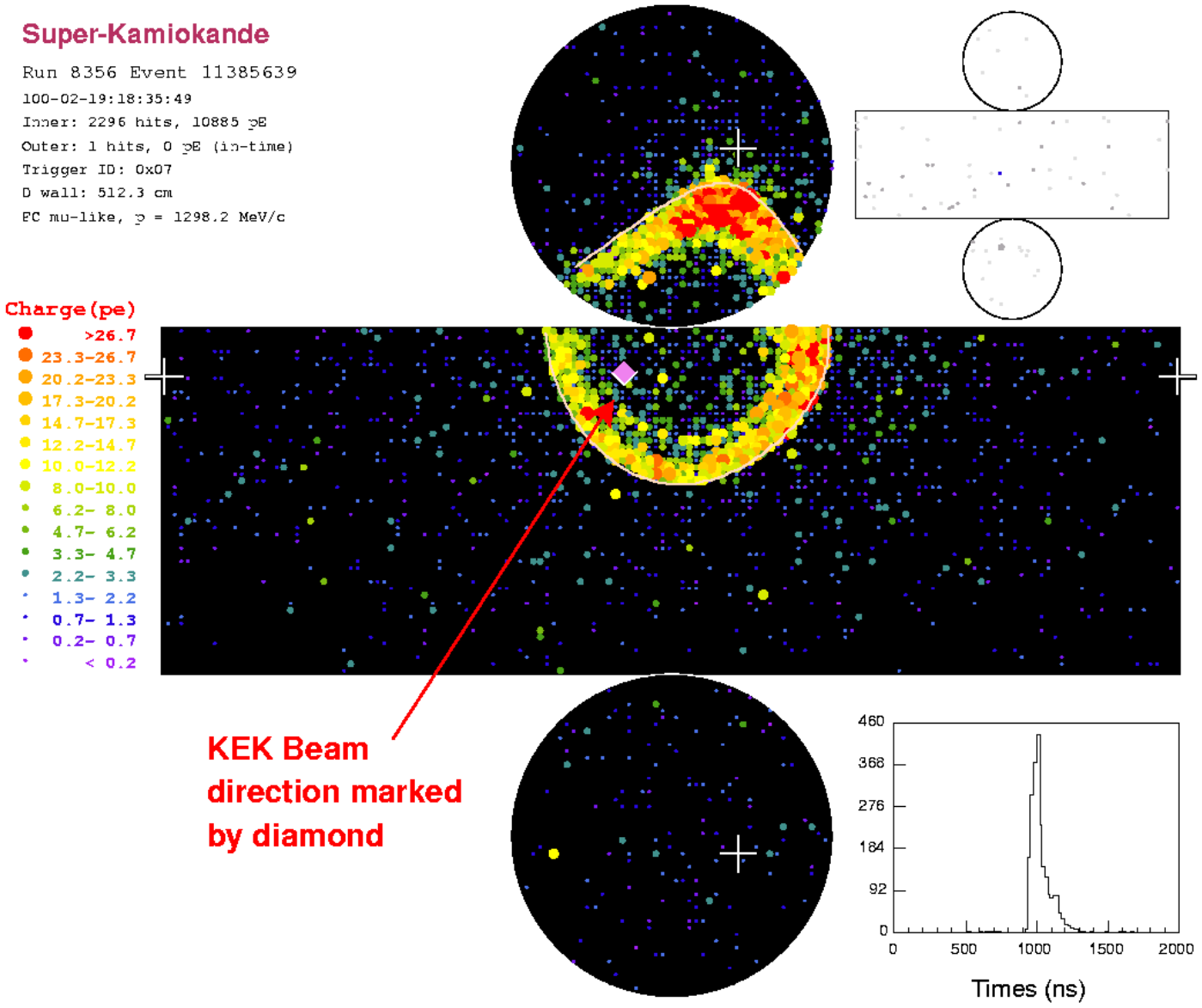
1/01 Neutrino data taking run (until 7/01)
- 6×10^{12} protons/spill
- Horn: 250 kA

K2K Protons on Target (POT) vs time

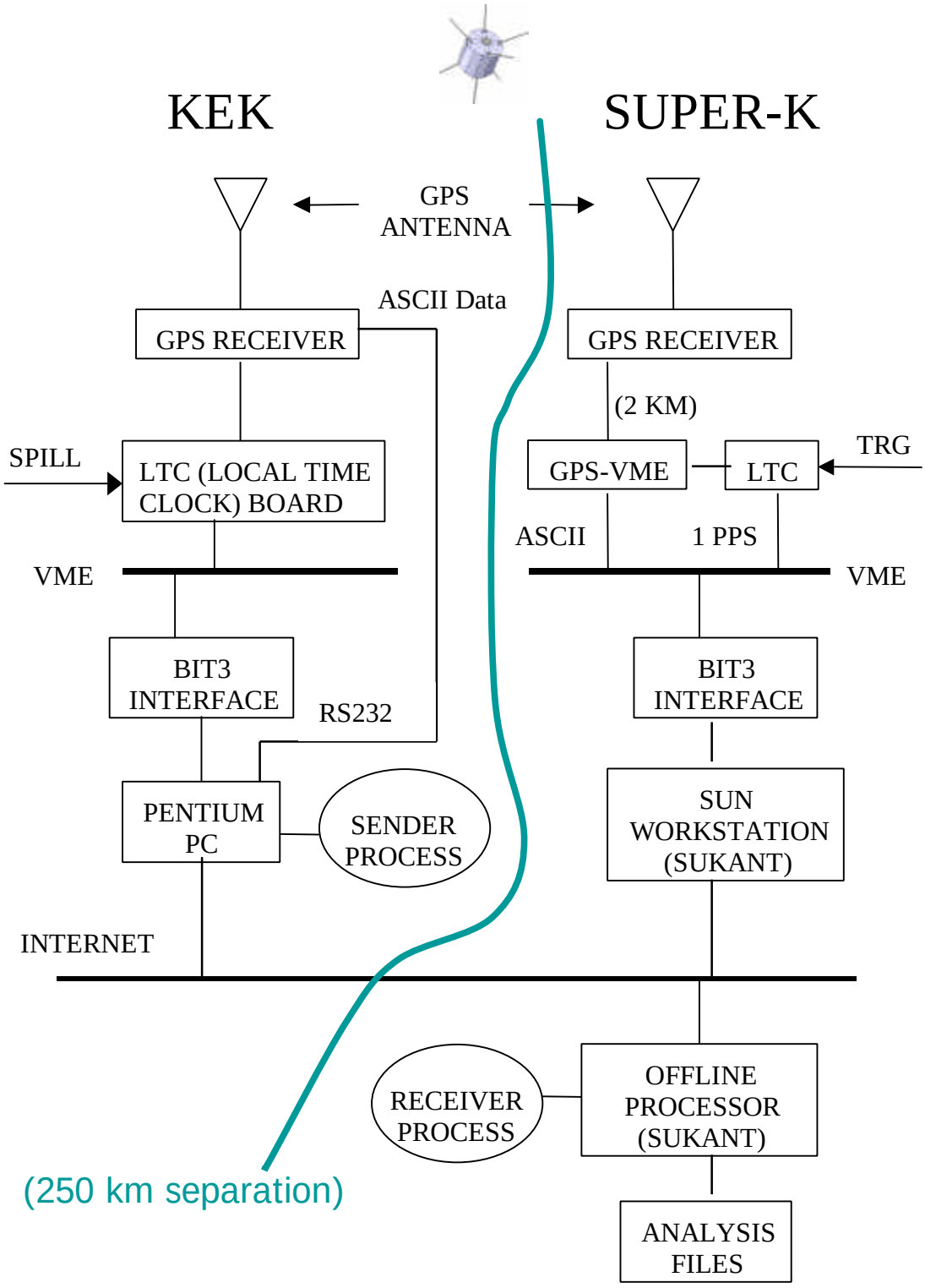


K2K event in Super-Kamiokande

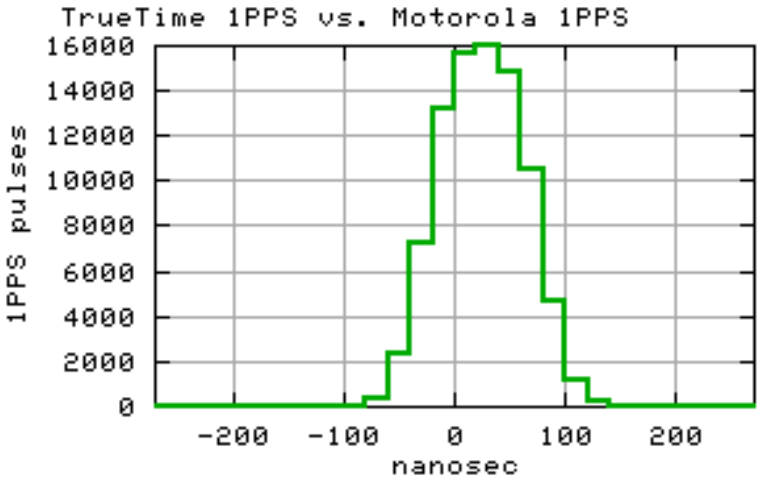
- Muon-like Cherenkov ring nicely aligned with KEK direction
- Outer Detector (inset) shows no incoming tracks



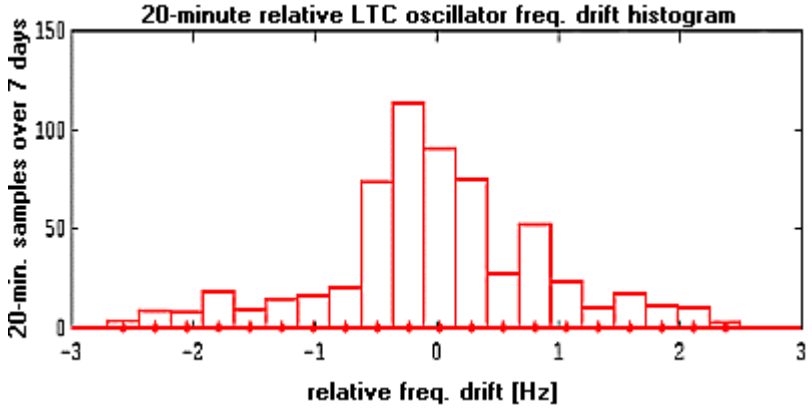
K2K Time Synchronization Overview



K2K GPS time synch



Jitter histogram: Δt between the primary and backup clocks, direct comparison over a 24-hour period.

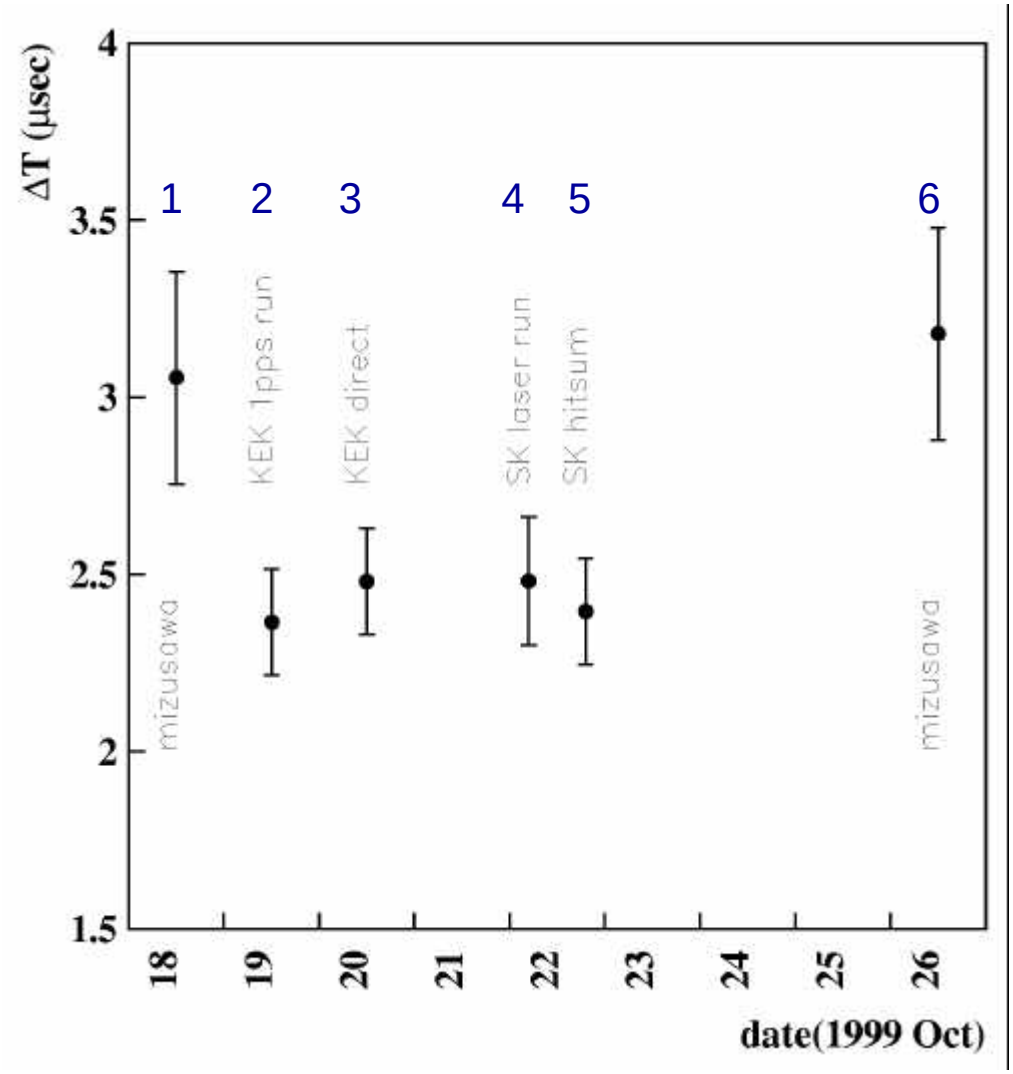


Drift histogram: 20-min averages of corrected 50 MHz oscillator frequency over a 7-day period

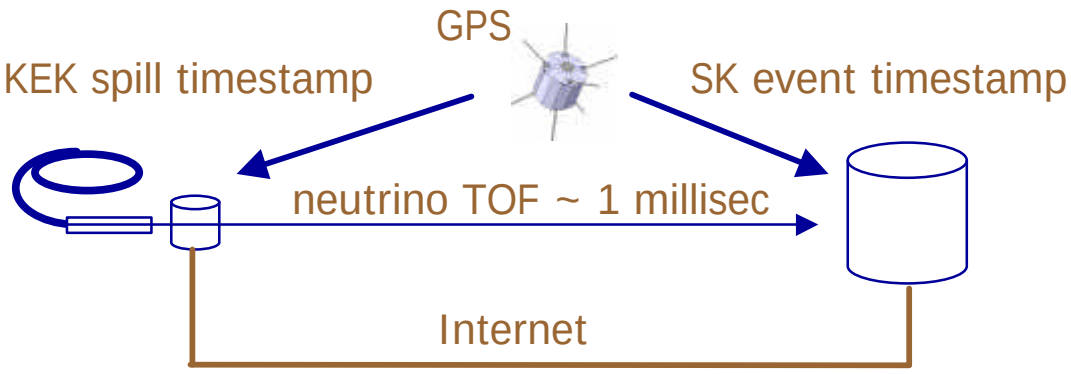
Atomic clock check of K2K GPS time synch system

1. Borrow atomic clock from Misuzawa lab and take to KEK
2. Check K2K GPS clock 1 PPS output
3. Check K2K TRG signal
4. Take to SK: check laser calibration trigger
5. Check normal SK trigger (GPS timestamp)
6. Return to Misuzawa and recheck against lab standard

$\rightarrow \Delta t_{GPS}$(KEK-SK) = 115 ± 237 nsec



Finding K2K events at SK



Event selection criteria:

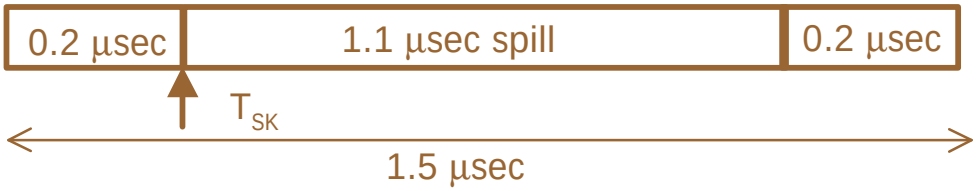
Expected arrival time at SK: $T_{SK} = T_{SPILL} + TOF$

$TOF = 830\,\mu\text{sec}$

$\Delta T_{SPILL} = 1.1\,\mu\text{sec}$

$\sigma_{GPS} \approx 0.1\,\mu\text{sec}$

So use 1.5 μsec acceptance window: $\Delta T_{SK} = T_{SK}{}^{+1.3\mu\text{sec}}_{-0.2\mu\text{sec}}$



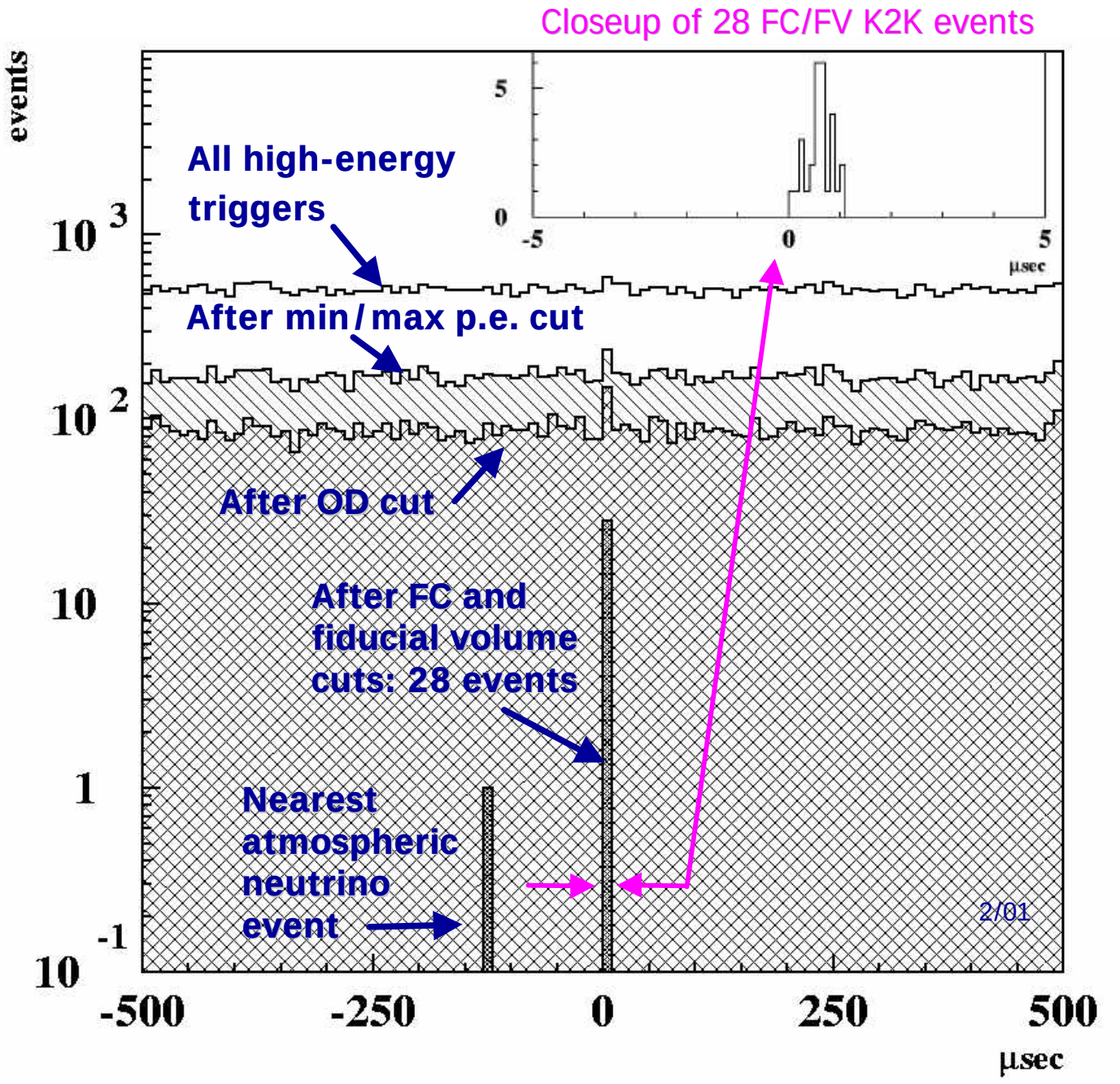
Select FC events at SK with:

- GPS timestamp within ΔT_{SK}
- Total PMT signal $200 \le Q \le 50000$ photoelectrons
- Fully contained event: $N_{HIT\text{-}OD}$ <10 PMTs
- Inside 22.5 kT fiducial volume

Dt for SK events

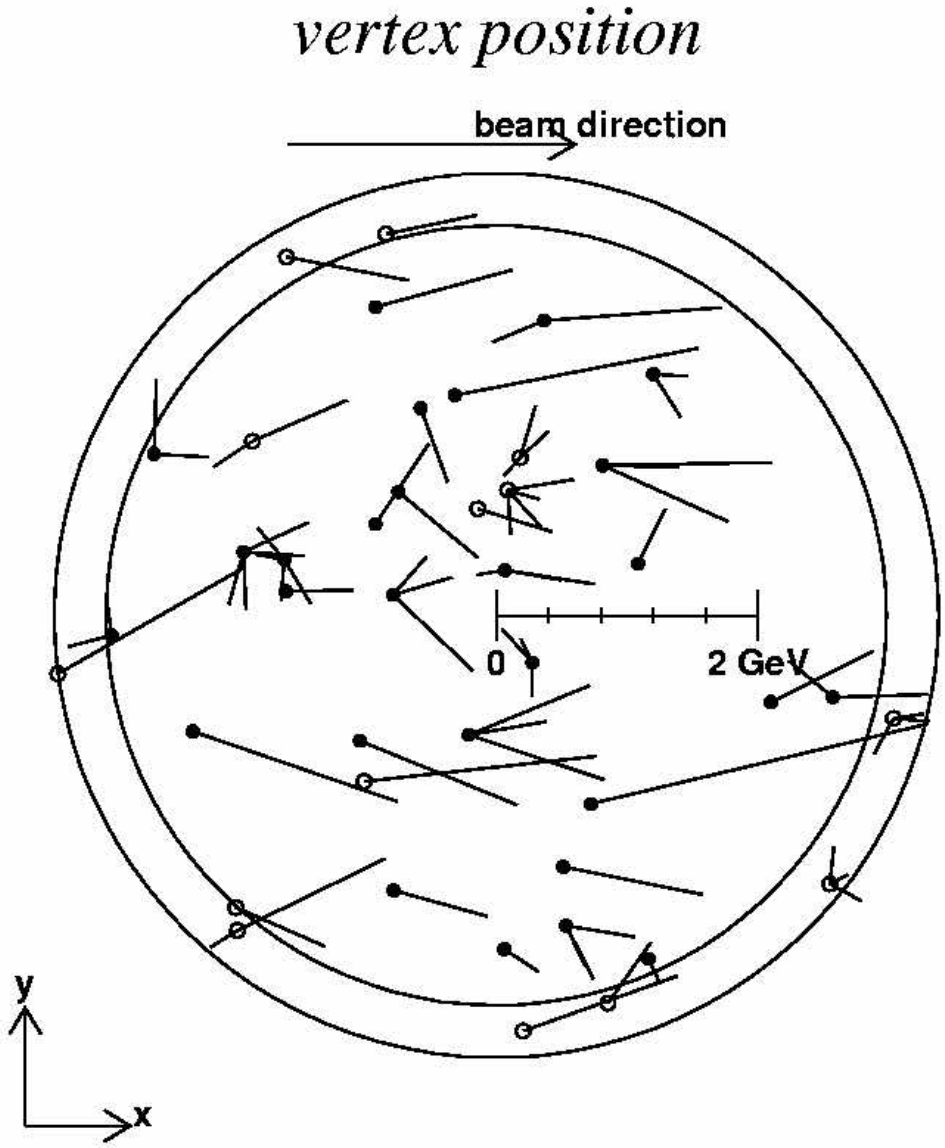
Time difference between (KEK spill time + L/c) and SuperK event trigger times, from GPS timestamps

(1.1 μsec spill length, ~100 nsec timing accuracy)



SK events: vertex and direction

Vertex location, direction of muon, and muon momentum are indicated (includes multiring and OD events)



How to calculate expected number of events at Super-K

- Expected number of events at Super-K (for no oscillations) is given by:

$$N_{SK} = R_{EFF}\ R_{RATE}\ R_{LIVETIME}\ R_{MASS}\ N_{NEAR}$$

where

$R_{EFF} = \dfrac{\varepsilon_{SK}}{\varepsilon_{NEAR}}$ detection efficiency ratio

$R_{RATE} = \dfrac{\eta_{SK}}{\eta_{NEAR}}$ event rate ratio : $\eta = \int \Phi(E)\sigma(E)dE$

$R_{LIVETIME} = \dfrac{T_{SK}}{T_{NEAR}}$ livetime (measured by pot) ratio

$R_{MASS} = \dfrac{M_{SK}}{M_{NEAR}}$ fiducial mass ratio

N_{NEAR} = number of events observed in near detector

- Use 1kT water Cherenkov data for N_{NEAR}
  - Errors on N_{NEAR} : systematic=5%, statistical<1%
  - Most other systematics are common and cancel
  - Other near detectors provide consistency check
- Systematic errors on other quantities:
  - On N_{SK}: 3% (mainly due to fid. vol. uncertainty)
  - On near/far extrapolation: + 6%, -7% (pion monitor uncertainty + uncertainty in low bins of E spectrum)
  - Overall quadrature sum for SK-expected: +9%, -10%

SK event summary

Summary through end of 2000 run:

- Superk livetime for FC events: 2.25 x 10^{19} pot
- Events observed vs expected (from 1 kT data):

Event type (FC, inside fid.vol.)	SK Observed	SK Expected (no osc)	SK Expected (Δm^2=3x10^{-3} eV^2)
1-ring Mu-like	14	20.8 ± 3.2	11.7 ± 1.9
1-ring e-like	1	1.9 ± 0.4	1.6 ± 0.3
Multi-ring	13	15.1 ± 2.5	11.4 ± 2.0
Total	28	$37.8^{+3.5}_{-3.8}$	24.7 ± 2.7

- Comparison of predicted total events (no-osc) from individual near detector subsystems:

KEK detector used for extrapolation	SK expected (no osc)
1 kT	37.8 ± 3.6
Sci-Fi	37.2 ± 7.3
Muon detector	41.0 ± 7.0

Conclusions

- Paper just submitted to PRL: hep-ex/0103001
- Next run in progress: 1/11/01 ~ 7/11/01

Results from 6/99 through 6/00 runs:

- Integrated exposure = 2.3 x 10^{19} pot
- Fully-contained, inside fiducial volume, in-time events at SK :
  - observed: 28
  - expected (no oscillations): $38 \pm 0.2(\text{stat}) \pm 4(\text{sys})$
- Statistics still too low for conclusions
  - Current run should add ~20x10^{18} pot $\rightarrow$ ~ 20 events in far detector
  - Next update at end of run $\rightarrow$ new results by summer
- Results are "not inconsistent with" Super-K data