Super-Kamiokande and K2K: Recent Results, Status, and Plans

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8/15/02

Super-Kamiokande and K2K

Super-Kamiokande Neutrino Observatory

- In Mozumi mine of Kamioka Mining Co, near Toyama City
- Detects both natural (atmospheric,solar) and artificial (K2K) neutrinos

K2K (KEK to Kamiokande) long baseline experiment

- Neutrino beam is generated and sampled at KEK (national particle physics lab, near Tokyo)
- Beam goes through the earth to Super-K, 250 km away

The Super-Kamiokande Collaboration

Japan

- ICRR, University of Tokyo
- High Energy Accelerator Research Organization(KEK)
- Gifu University
- Kobe University
- Kyoto University
- Niigata University
- Osaka University
- Tohoku University
- Tokai University
- Tokyo Institute for Technology
- Tokyo University of Science

Korea

- Seoul National University

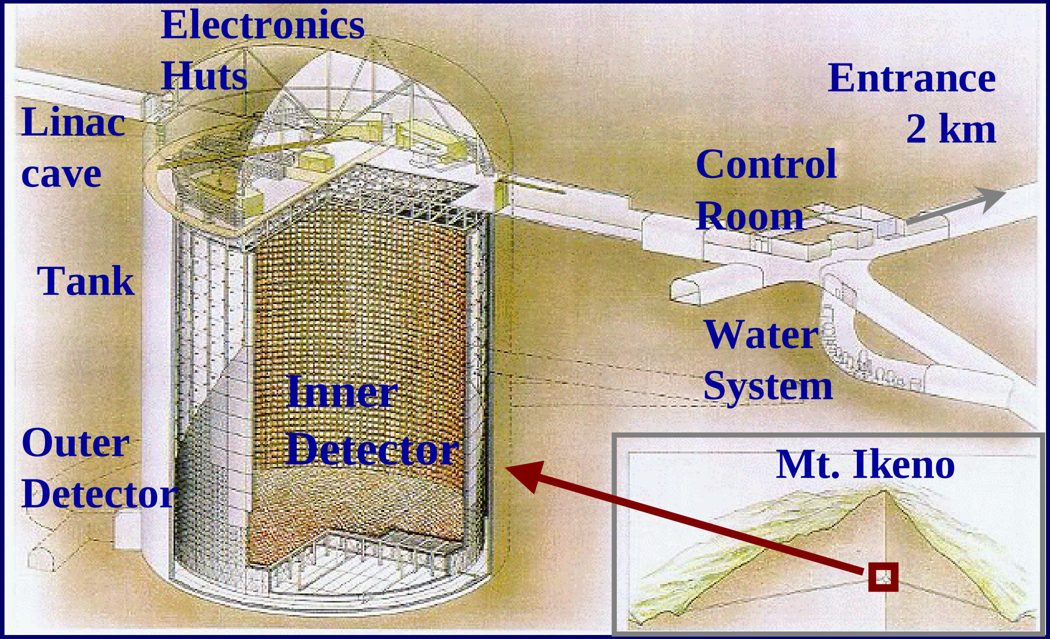
Poland

- Warsaw University

USA

- Boston University
- Brookhaven National Laboratory
- University of California, Irvine
- California St. Univ, Dominguez Hills
- George Mason University
- University of Hawaii, Manoa
- Los Alamos National Laboratory
- Louisiana State University
- MIT
- University of Maryland
- SUNY / Stony Brook
- University of Washington, Seattle

Super-Kamiokande



- US-Japan collaboration
- (~100 physicists)
- 50,000 ton ring-imaging water Cherenkov detector
- Inner Detector: 11,146 phototubes, 20” diameter
- Outer Detector: 1,885 phototubes, 8” diameter

- Began operation in April, 1996
- Published first evidence for neutrino mass in June, 1998
- Typically measures neutrino interaction location to within 25 cm, arrival direction to within few degrees
- Typically records about 15 neutrino events per second

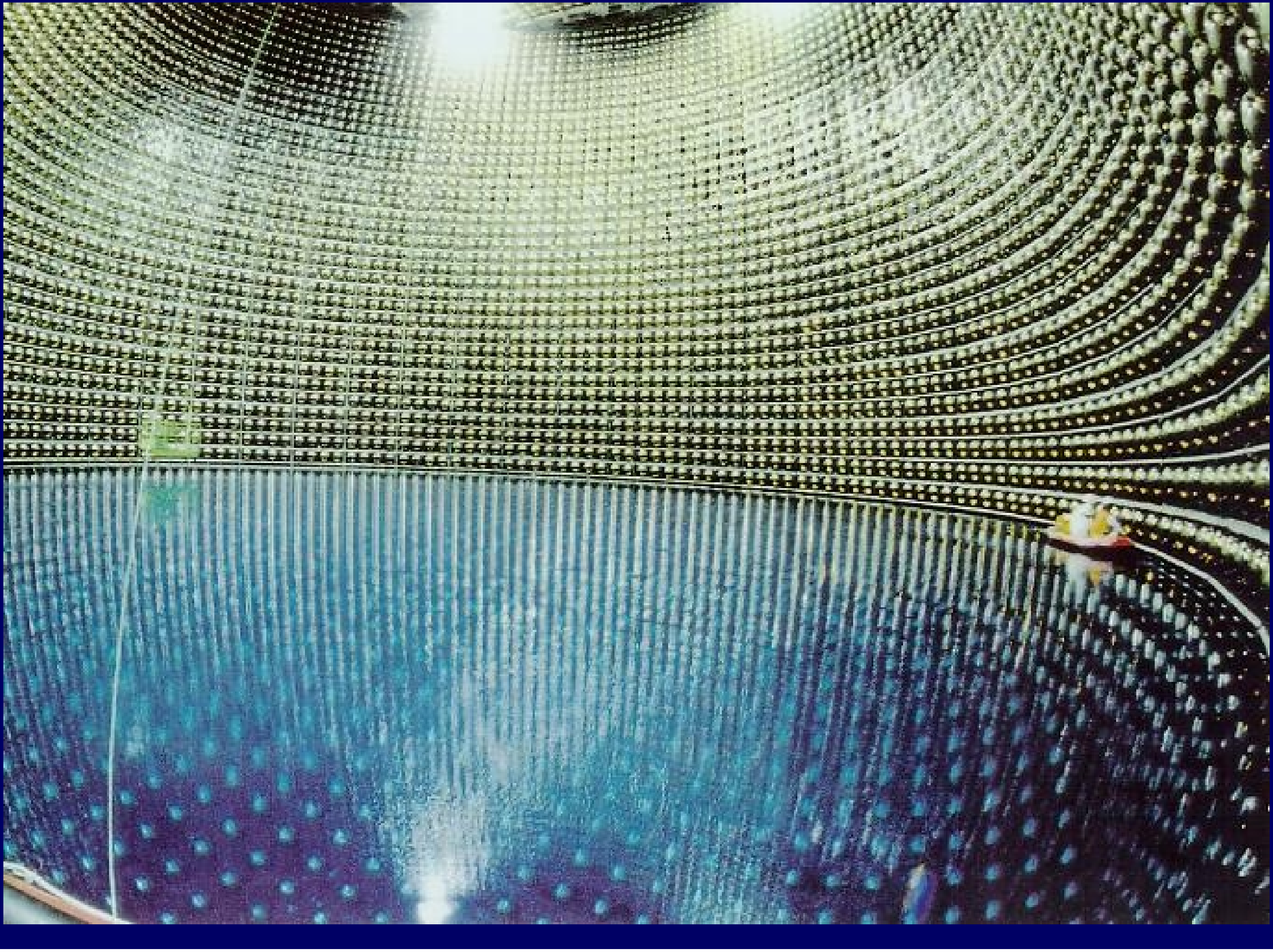
See website for more info: http://www.phys.washington.edu/~superk/

The problem in a nutshell…

- Roz Chast, *Scientific American*, 5/02

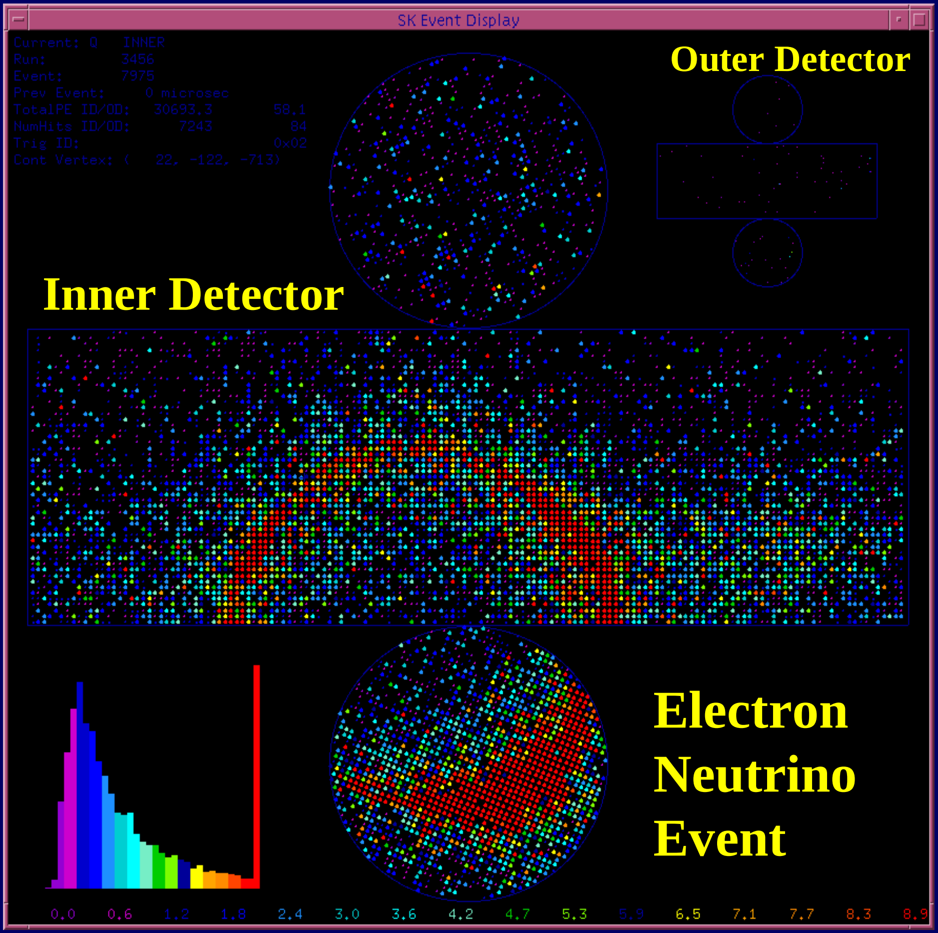
Checking tubes by boat as the tank fills (1996)

- Each photomultiplier tube is 20 inches in diameter!



Neutrino event displays: ν_e and ν_μ

Electrons scatter in water and produce fuzzy Cherenkov rings;
Muons travel in straight lines and produce sharper rings



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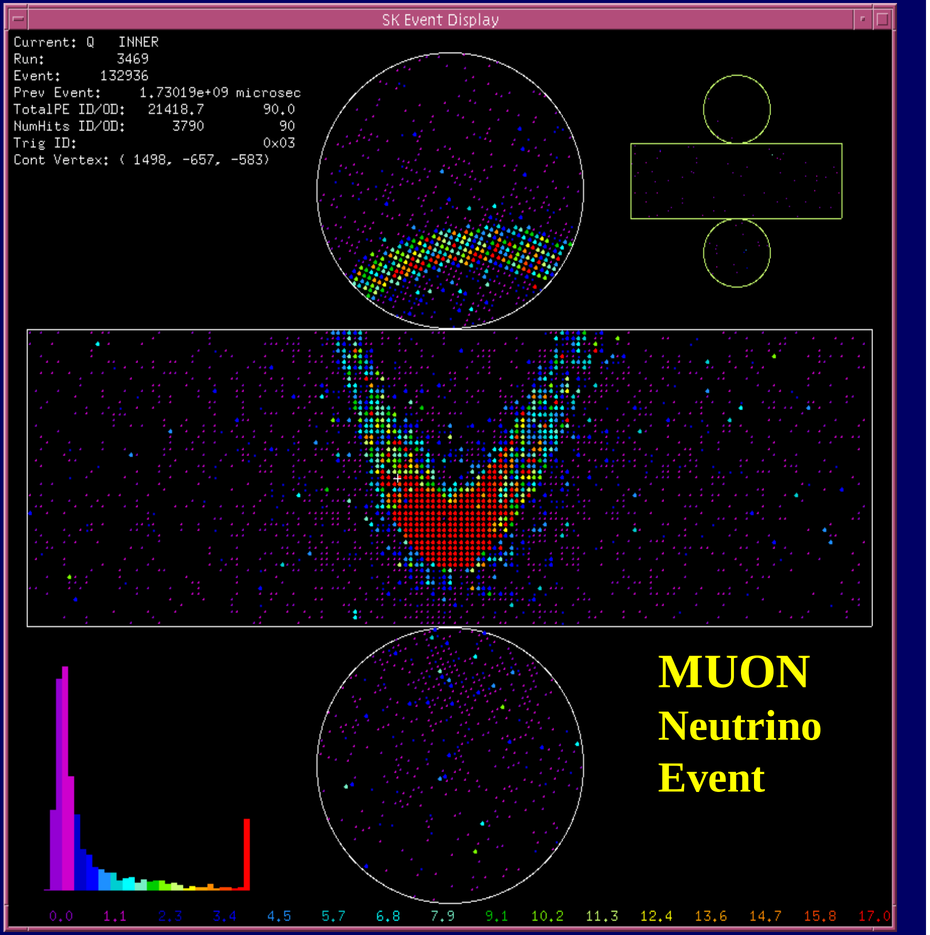
NumHits ID/OD:     7243          84
Trig ID:                       0x02
Cont Vertex: (   22, -122, -713)
```



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Event:      132936
Prev Event:     1.73019e+09 microsec
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NumHits ID/OD:     3790          90
Trig ID:                       0x03
Cont Vertex: ( 1498, -657, -583)
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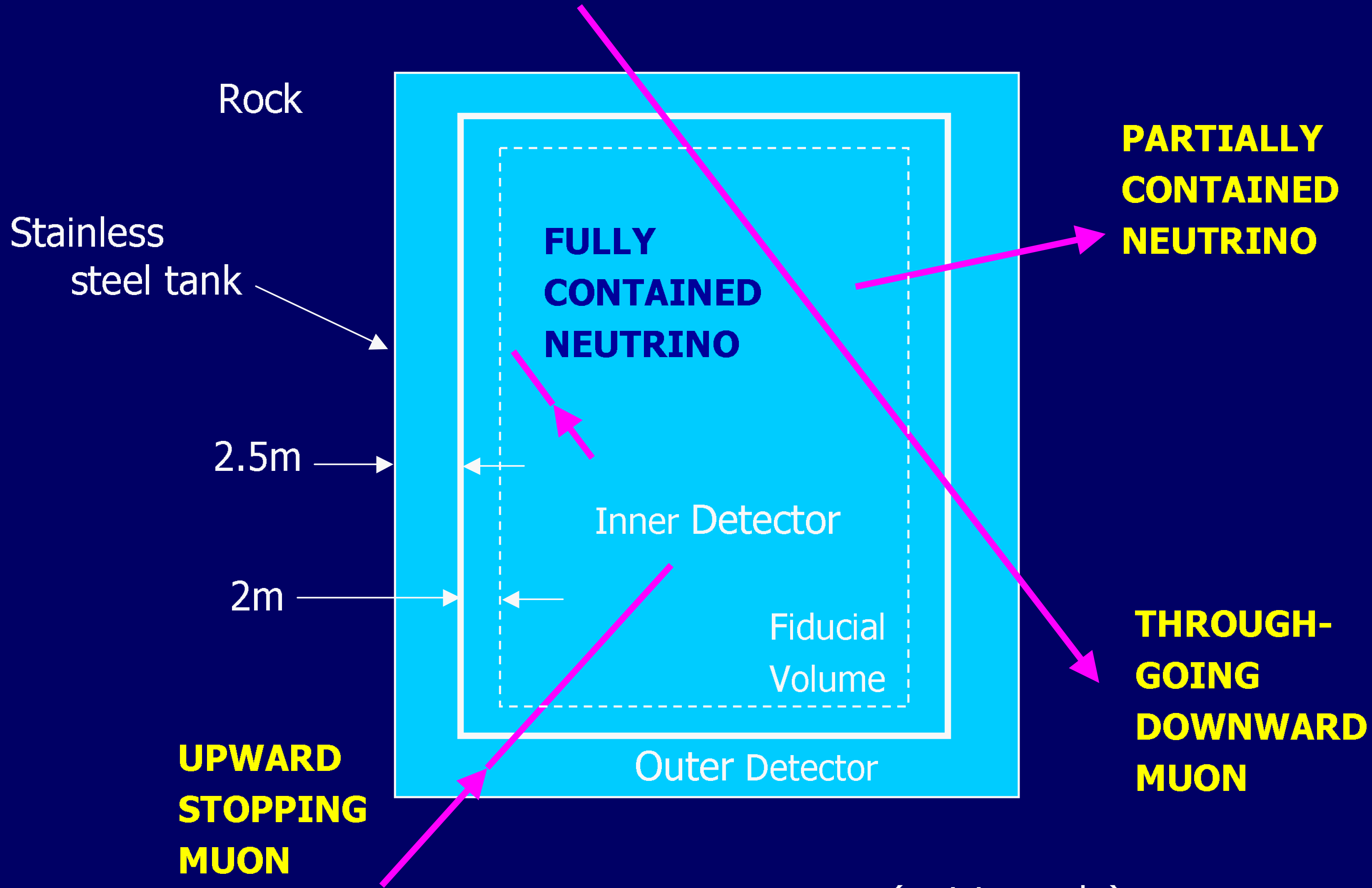
Super-K Detector Geometry and Event Types



(not to scale)

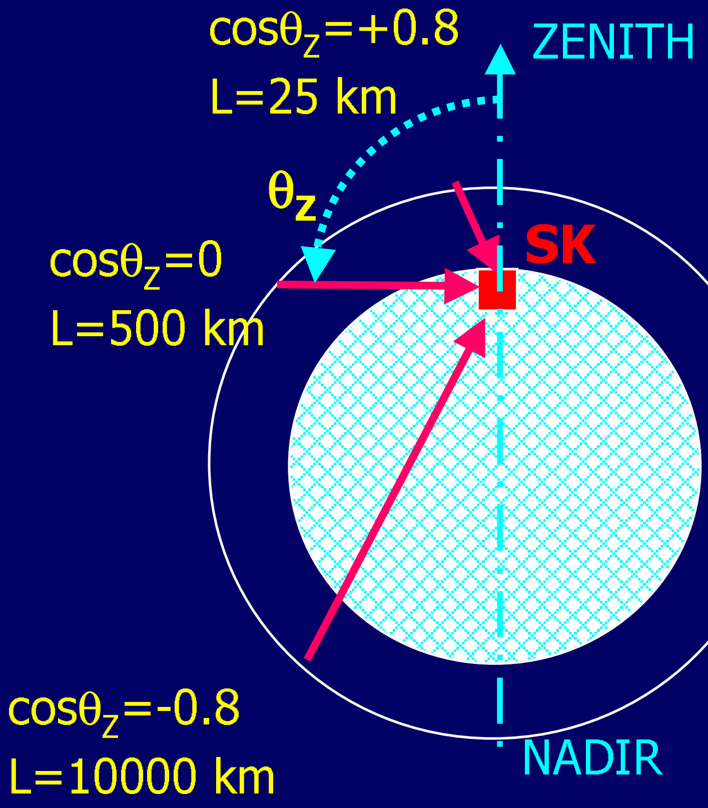
Atmospheric Neutrinos

- Produced by cosmic rays in upper atmosphere (altitude Z=15~20 km)

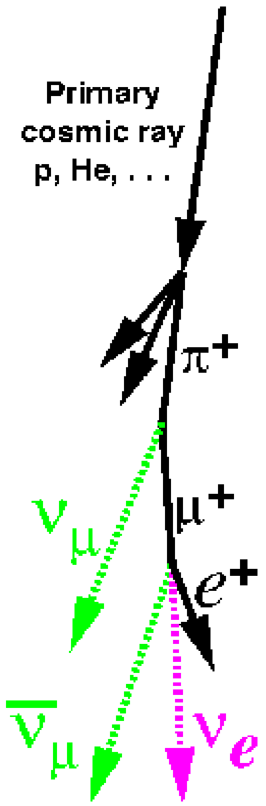
  $p+A \rightarrow \pi,K \rightarrow \nu$

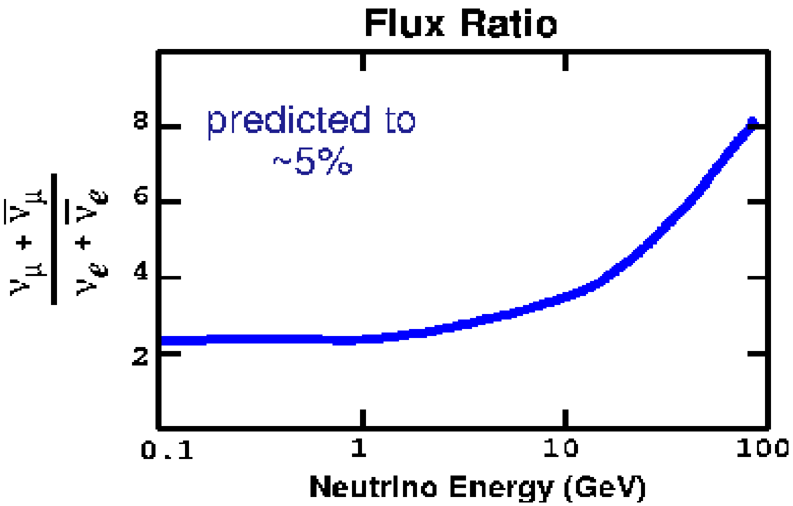
- Flight path L to SK detector depends on zenith angle θ_Z:

  $L=f(\theta_Z ,R,Z)$



Atmospheric neutrino “double ratio”





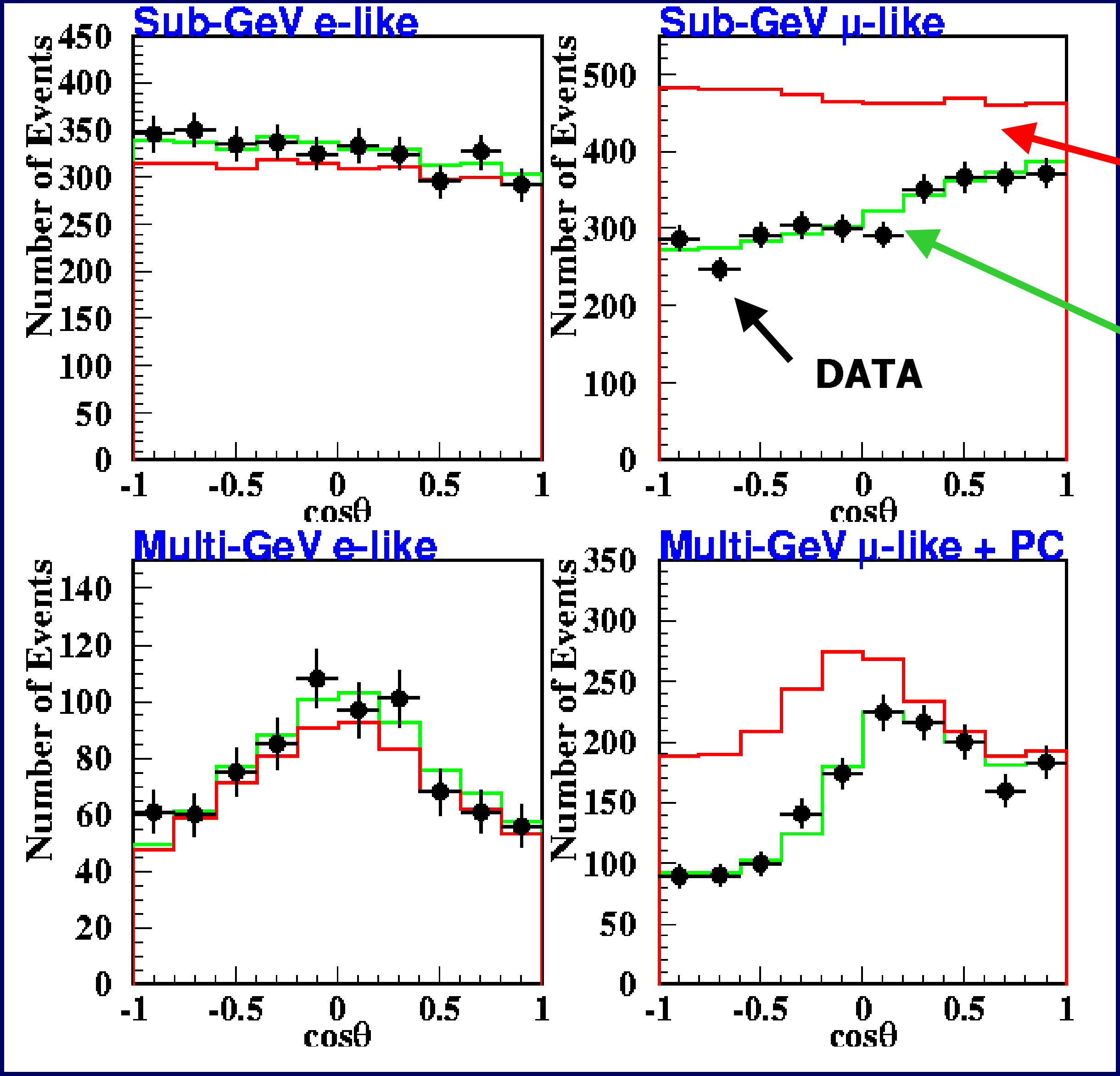
$$R = \frac{(N_\mu/N_e)_{\text{DATA}}}{(N_\mu/N_e)_{\text{M.C.}}}$$

$R_{SK} = 0.66 \pm 0.03$ (stat) $\pm$ 0.08 (sys)

~8σ effect

Atmospheric ν puzzle: what happened to the ν_μ ?

Atmospheric neutrino results



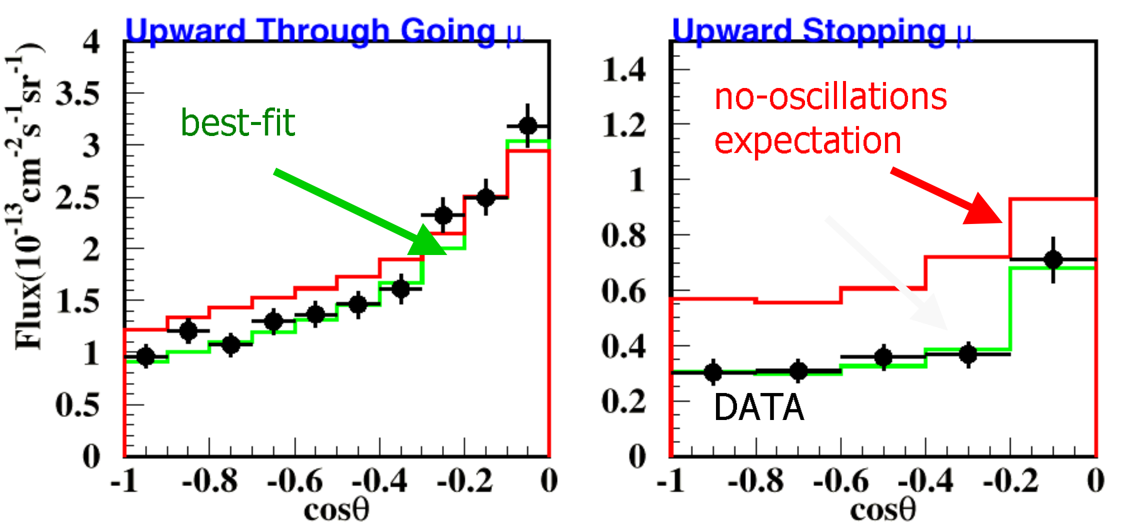
no-oscillations expectation

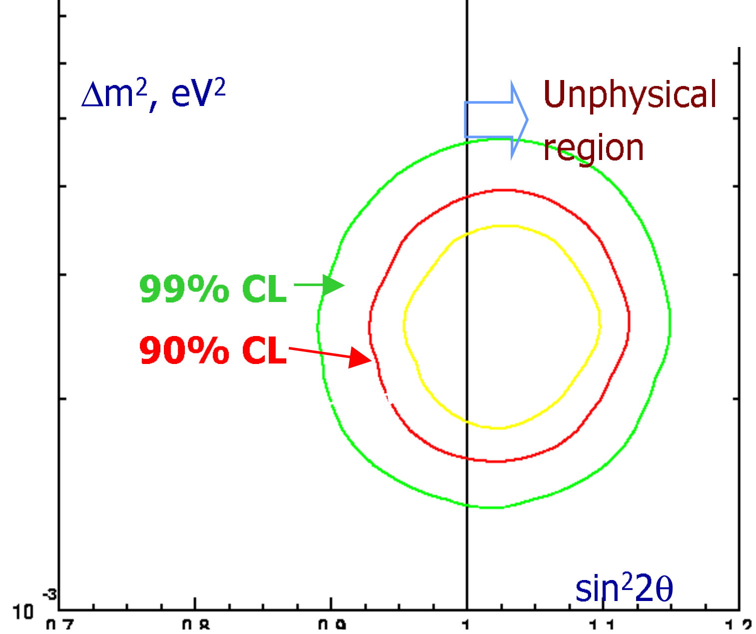
best-fit

($\Delta m^2 \sim 3\text{x}10^{-3}$ eV^2)

Atmospheric neutrino results

Combined fit to
- fully-contained
- partially contained
- upward muons





Best fit for μ–τ, full mixing, physical region only:

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

χ^2=162 / 170 DOF

(No-osc. hypothesis:

χ^2=456 / 170 DOF)

Why not $\nu_\mu \leftrightarrow \nu_e$?

For $\nu_\mu \leftrightarrow \nu_e$ hypothesis:

- best fit at $\Delta m^2=3\times10^{-3}\ \mathrm{eV}^2$, $\sin^2(2\theta)=0.93$,
  - but $\chi^2=255/170$ DOF
  - $P(\nu_\mu \leftrightarrow \nu_e)/P(\nu_\mu \leftrightarrow \nu_\tau)$ negligible
- up/down asymmetry for electrons:

  Observed = -0.036 ± 0.067 ± 0.02

  No-oscillation expected = 0.0 ± 0.02

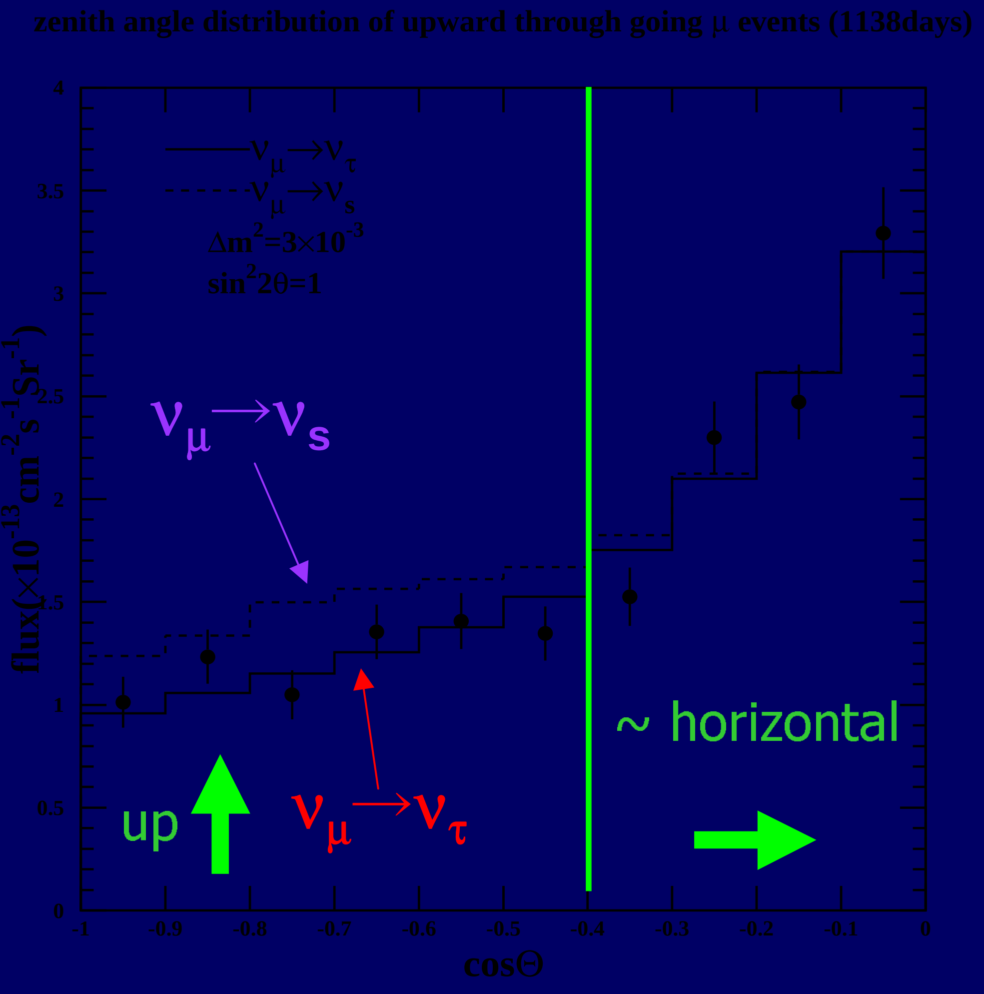
  Best-fit oscillation expected = 0.205

  (3.4σ discrepancy)
- Anyway... results from CHOOZ experiment exclude $\nu_\mu \leftrightarrow \nu_e$ with high confidence in this region of parameter space

Why not $\nu_\mu \leftrightarrow \nu_S$?

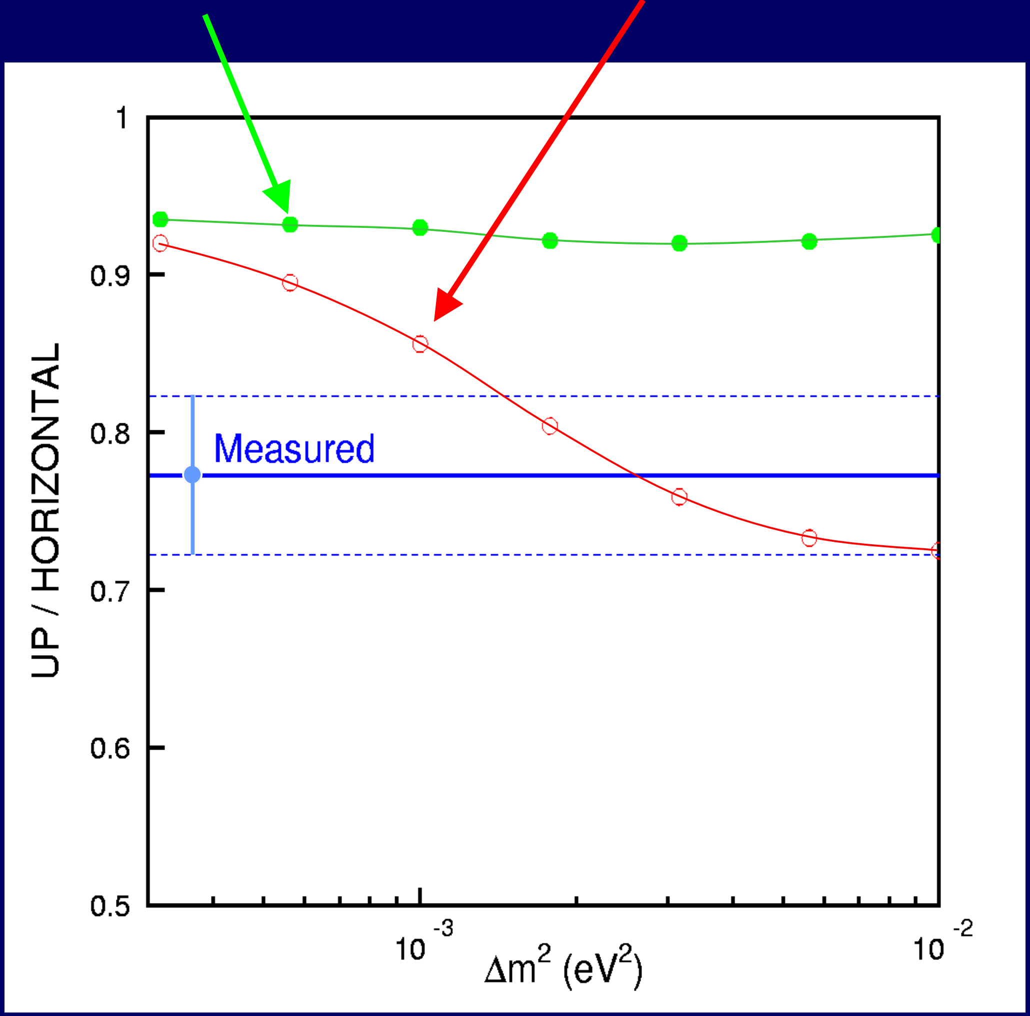
- High energy sample (partially contained and upward-muon) analysis disfavors ν_s
- $\nu_\mu \leftrightarrow \nu_S$ oscillations are suppressed by matter effects in earth
  - Coherent forward scattering of ν_μ and ν_τ are identical
    - ➢ matter in path does not affect $\nu_\mu \leftrightarrow \nu_\tau$
  - ν_μ interacts with matter via NC
  - ν_S does not interact at all by definition

For $\Delta m^2 \sim 3\text{x}10^{-3}$ eV^2 (SK best-fit), neutrinos with $E_\nu > \sim 15$ GeV will have oscillation probability suppressed if mode is $\nu_\mu \leftrightarrow \nu_S$

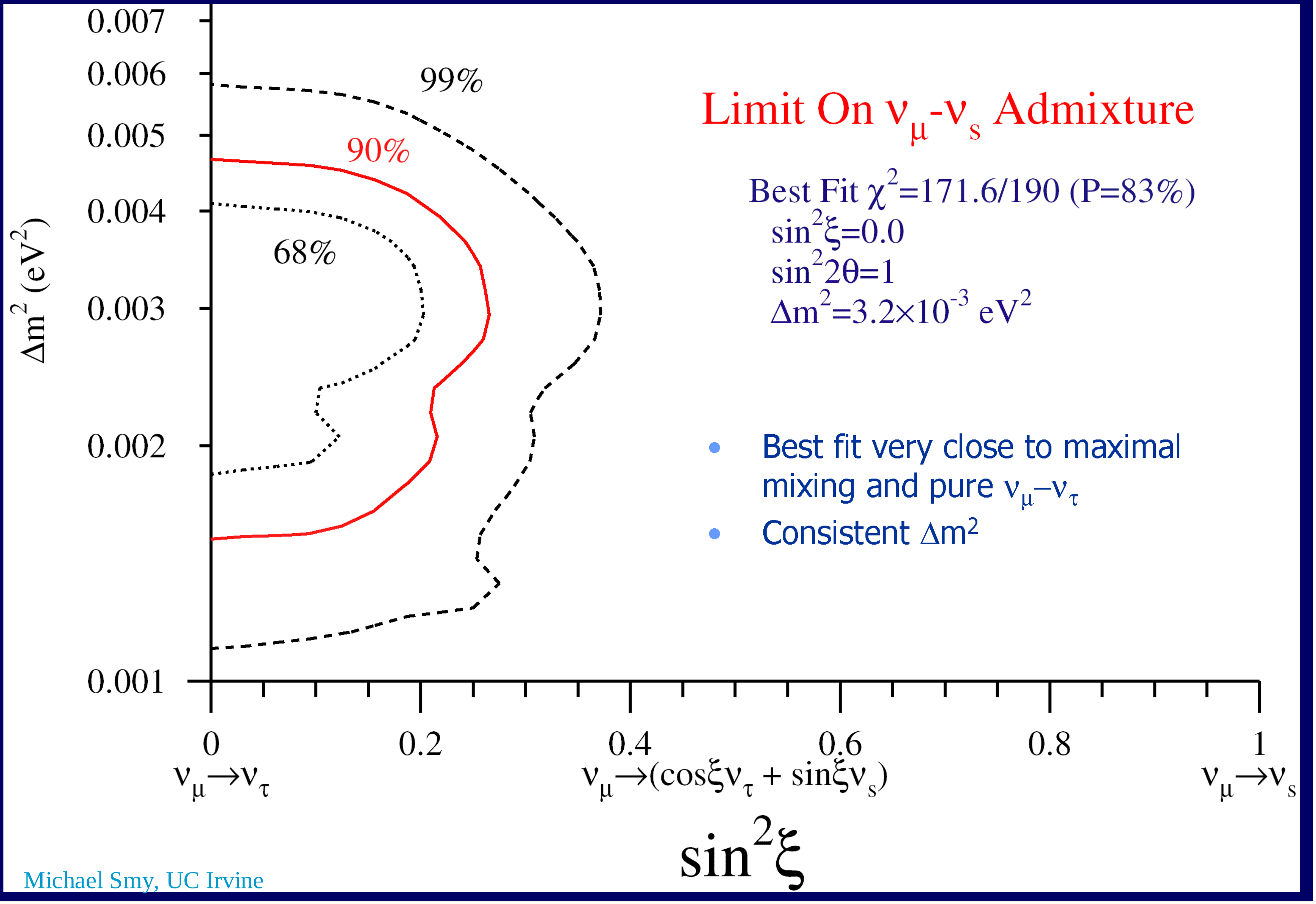


Matter matters: Upward muon up/horizontal ratio

Expectation for: $\nu_\mu \rightarrow \nu_S$ vs $\nu_\mu \rightarrow \nu_\tau$



Limit on Sterile Content

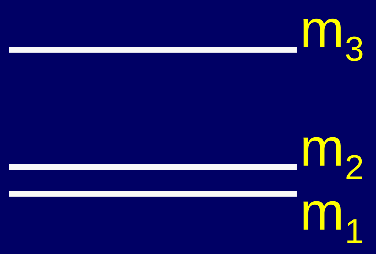


Limit On ν_μ-ν_s Admixture

Best Fit χ^2=171.6/190 (P=83%)
$\sin^2\xi=0.0$
$\sin^2 2\theta=1$
$\Delta m^2=3.2\times10^{-3}$ eV^2

- Best fit very close to maximal mixing and pure ν_μ–ν_τ
- Consistent Δm^2

3 flavor oscillations analysis



- Assume
  $\Delta m^2_{23} = \Delta m^2_{atm} \sim O(10^{-3})\ eV^2$
  $\Delta m^2_{12} = \Delta m^2_{solar} < O(10^{-4})\ eV^2 << \Delta m^2_{atm}$

- Vacuum oscillations can then be described in a simplified way:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_{13}) \bullet \sin^2\theta_{23} \bullet \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4(\theta_{13}) \bullet \sin^2(2\theta_{23}) \bullet \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\tau \rightarrow \nu_e) = \sin^2(2\theta_{13}) \bullet \cos^2\theta_{23} \bullet \sin^2(1.27\Delta m^2 L/E)$$

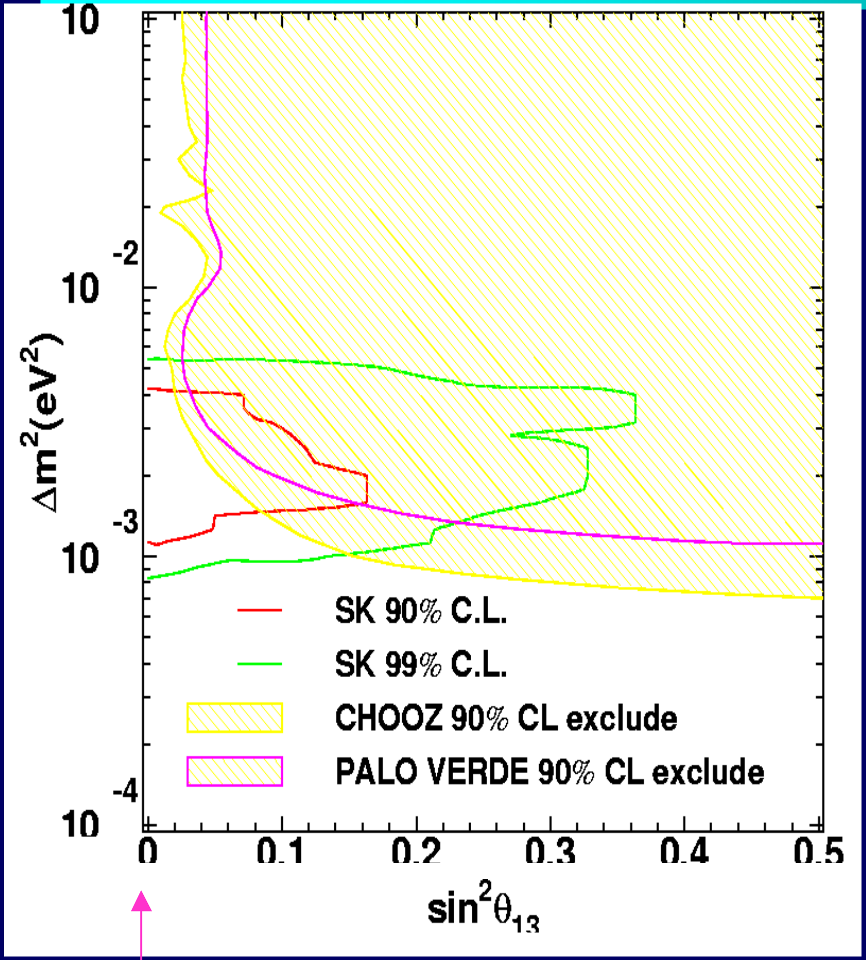
So only 3 parameters: $\Delta m^2 (= m^2_3 - m^2_2)$, θ_{13}, θ_{23}

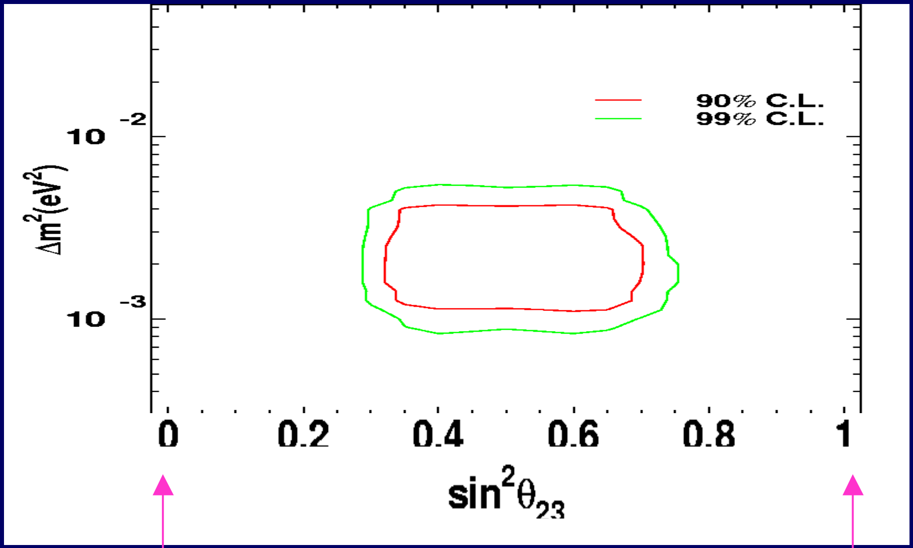
- From SK atmospheric neutrino results, we know that we have:
  - large $\nu_\mu - \nu_\tau$ mixing: $\theta_{23} \sim \pi/4$
  - No ν_e disappearance: θ_{13} is not large
  - CHOOZ tells us: $\sin^2\theta_{13} < 0.026$ for $\Delta m^2 > 2 \times 10^{-3} eV^2$

So analysis of ν_e events can estimate θ_{13}

thanx to M. Shiozawa, ICRR

SK allowed region for active 3-flavor oscillations





Pure $\nu_\mu \rightarrow \nu_\tau$

$\nu_e \rightarrow \nu_\tau$

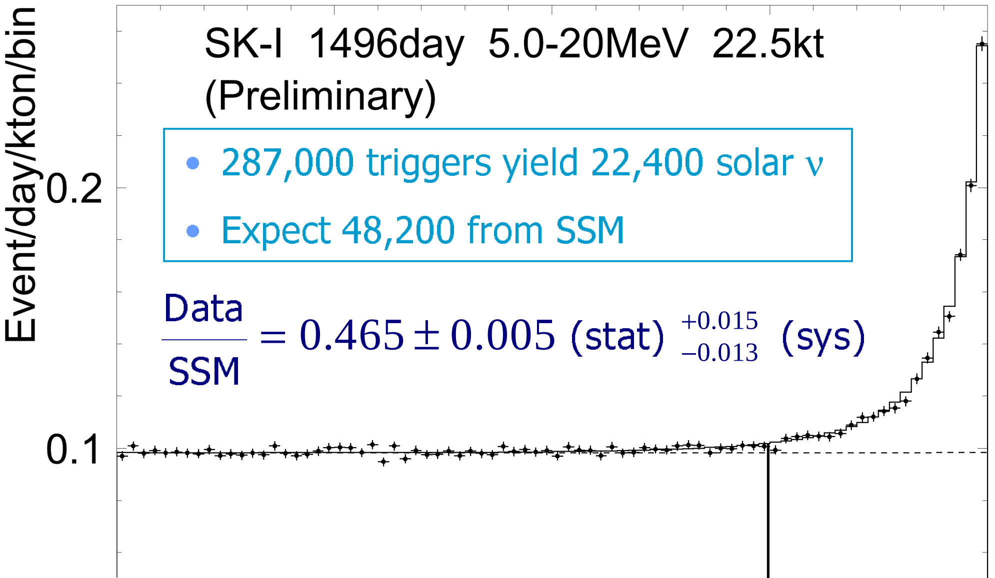
$\nu_e \rightarrow \nu_\mu$

Atmospheric neutrino puzzle is resolved

- Atmospheric anomaly is due to neutrino flavor oscillations
- μ neutrinos oscillate predominantly into τ neutrinos, with no sterile neutrino needed
  - SK observes evidence for appearance of τ neutrinos
- Mixing is large, possibly maximal
- The Δm^2 is a few times 10^{-3} eV^2
- No hint of positive θ_{13}, SK can set limit

Solar neutrino flux

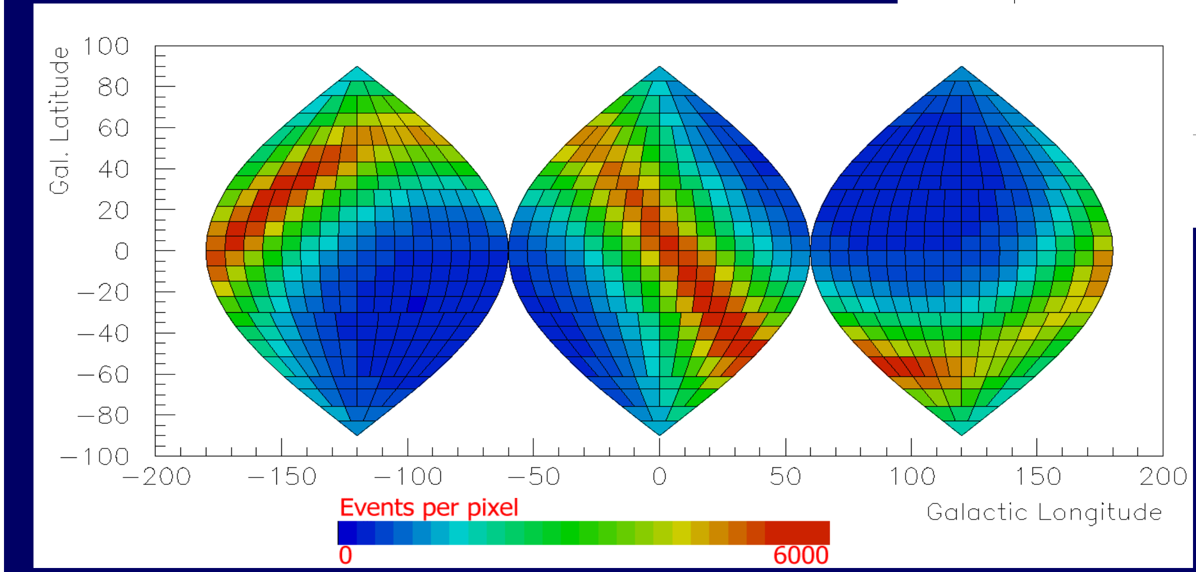
Solar neutrinos defined as events above background and from solar direction:



- 287,000 triggers yield 22,400 solar ν
- Expect 48,200 from SSM

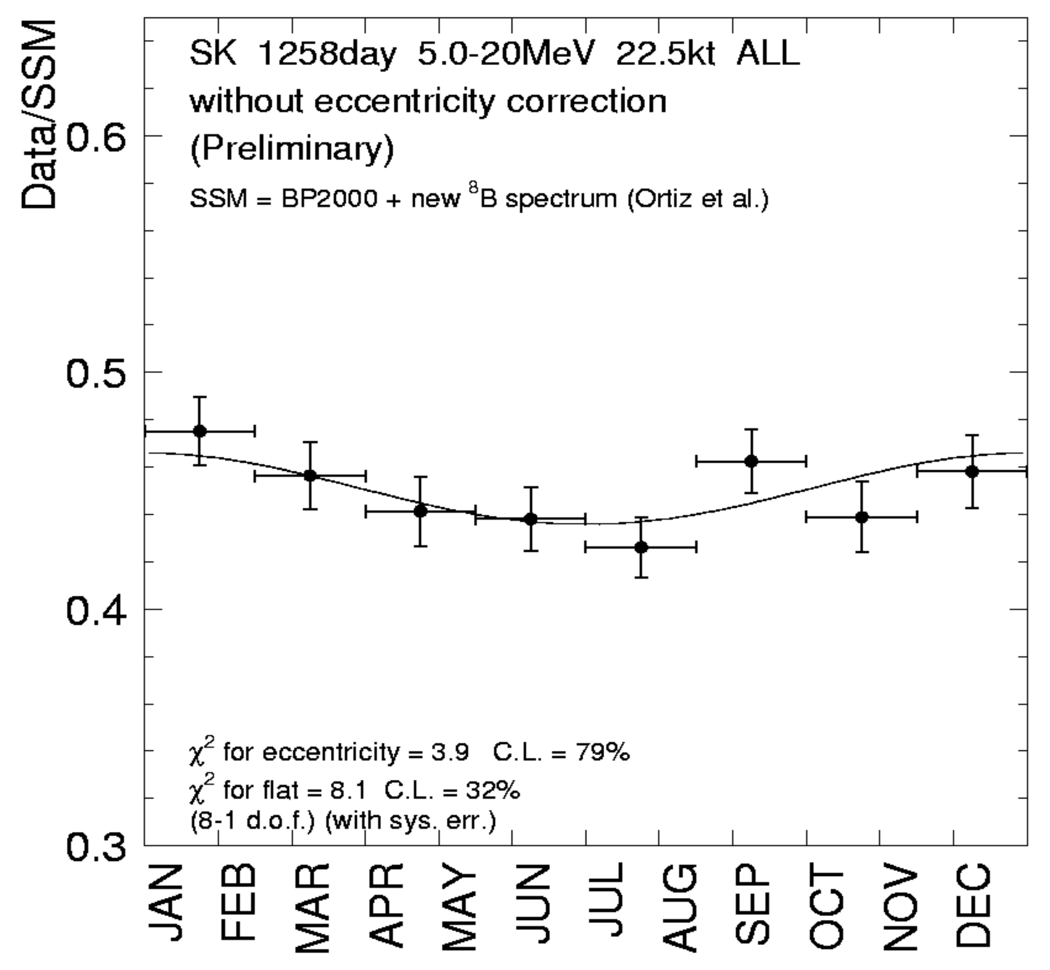
$$\frac{\text{Data}}{\text{SSM}} = 0.465 \pm 0.005\ (\text{stat})\ ^{+0.015}_{-0.013}\ (\text{sys})$$

SK sees the ecliptic in neutrinos…

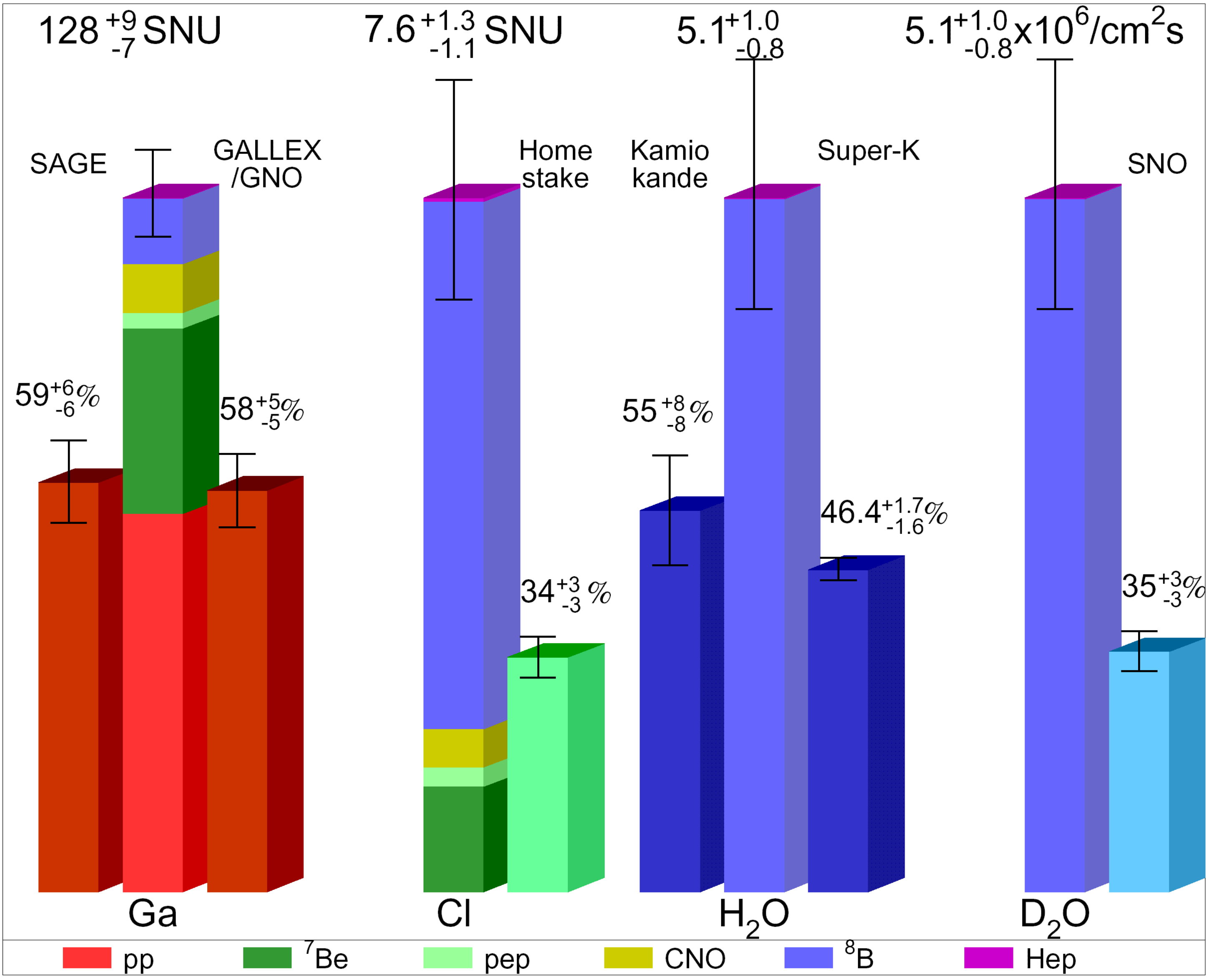


Seasonal variation of solar neutrino flux

- Consistent with variation expected from eccentricity of Earth’s orbit

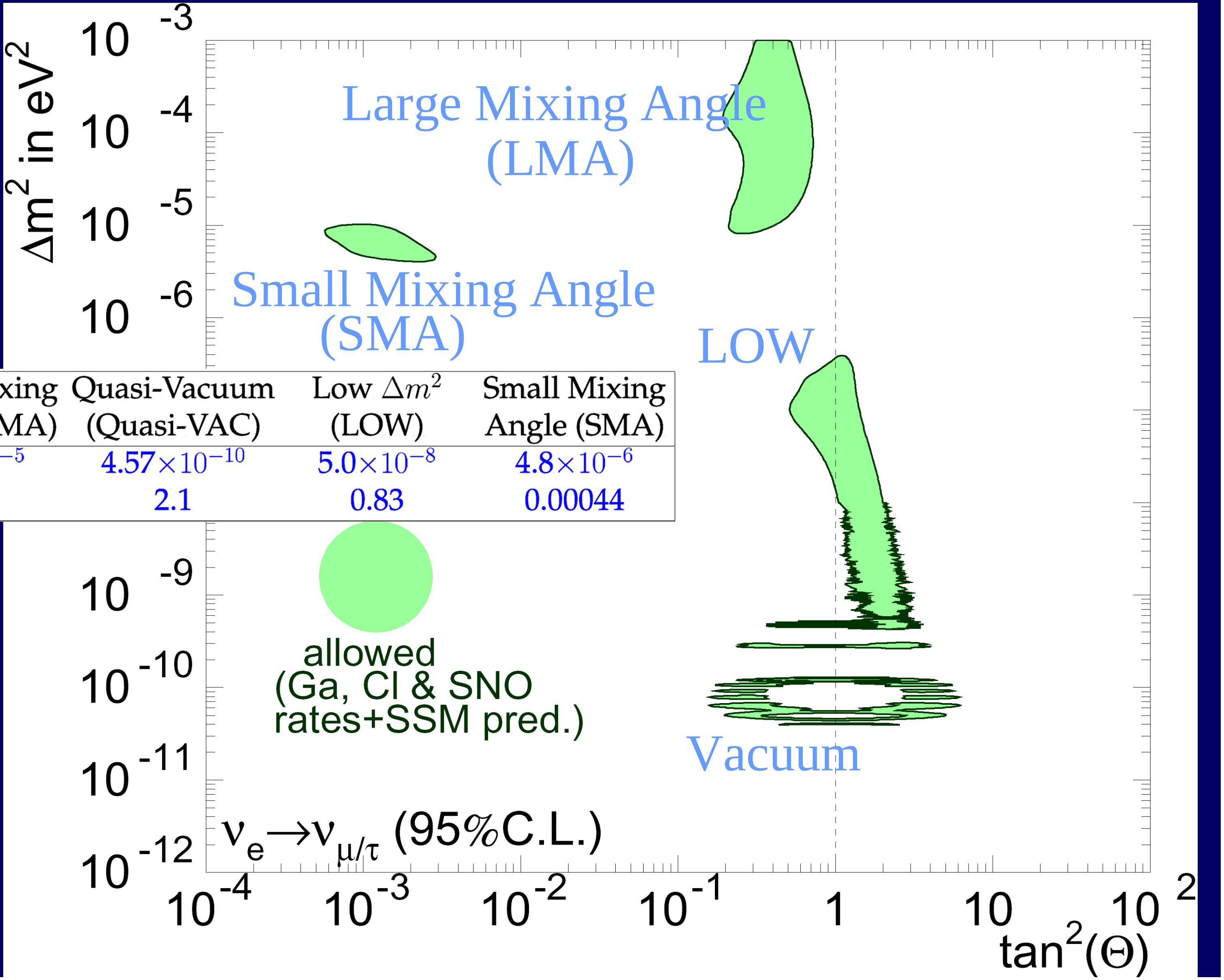


Solar ν puzzle:
Predictions of Standard Solar Model (BP2001) vs data



thanx to Michael Smy, UC Irvine

ν oscillations:
Allowed regions for SK 2-flavor analysis

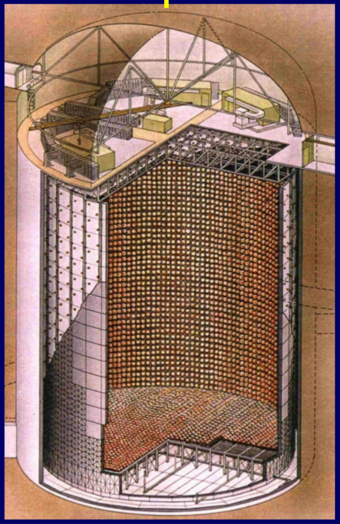


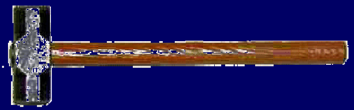
Solution	Large Mixing Angle (LMA)	Quasi-Vacuum (Quasi-VAC)	Low Δm^2 (LOW)	Small Mixing Angle (SMA)
Δm^2	6.0×10^{-5}	4.57×10^{-10}	5.0×10^{-8}	4.8×10^{-6}
$\tan^2\theta$	0.35	2.1	0.83	0.00044

Super-K + SNO

- Sudbury Neutrino Observatory (SNO) added another piece to the solar neutrino puzzle last year:
  - Super-K only measures ν_e and ν_μ combined
  - SNO can measure ν_e alone
- SNO results added to earlier Super-K results = solution !
  - Sun's expected ν_e output can be accounted for via effects of oscillations

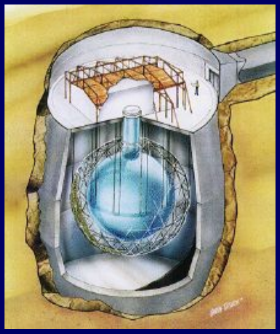
Super-K

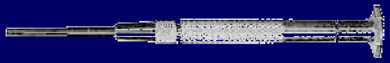




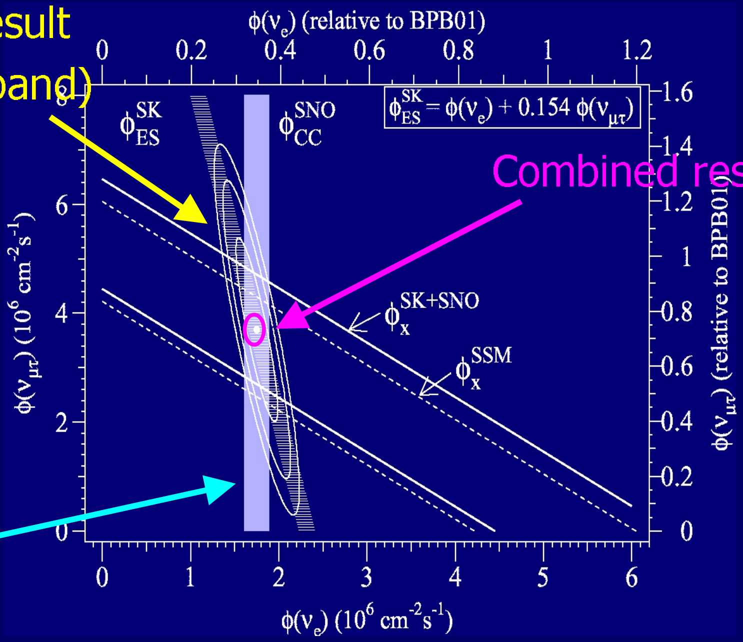
+

SNO





Super-K result (diagonal band)



Combined result

SNO result (vertical band)

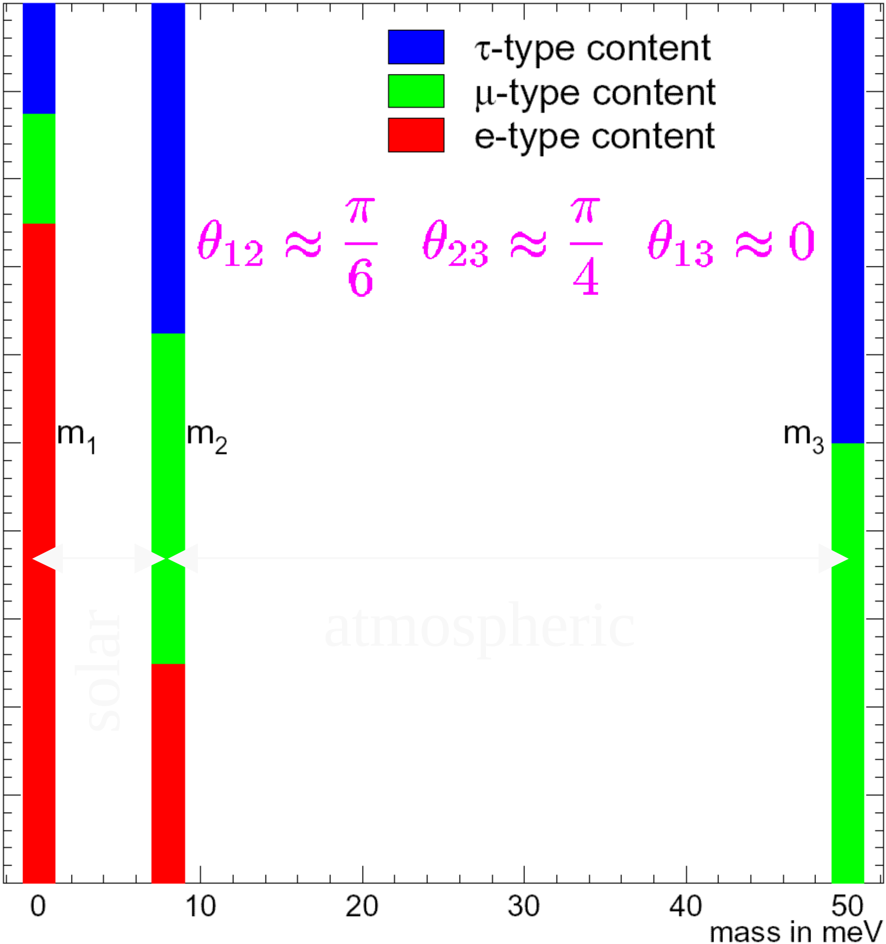
Solar neutrino puzzle is resolved

- Anomoly is due to neutrino flavor oscillations
- ν_e oscillate into μ/τ neutrinos: no sterile neutrino needed
  - SK observes some evidence for appearance of ν_μ
- LMA solution is most likely, but quasi-VAC is still a (remote) possibility
- Mixing is large, but not quite maximal
- $\Delta m^2 = 3 \sim 23 \times 10^{-5} eV^2$

Combining SK results on solar and atmospheric neutrinos...

- Large mixing angles preferred
- 3 neutrinos are enough: no evidence anywhere in SK data for sterile neutrinos
- $\Delta m^2_{atm} = 0.0025 eV^2$
- $\Delta m^2_{solar} = 0.00006 eV^2$
- Mass hierarchy scheme
  - Assume $m_1 = 0$
  - Assume $\theta_{13} = 0$
  - Neglect CP phase

$$U \approx \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{1}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$



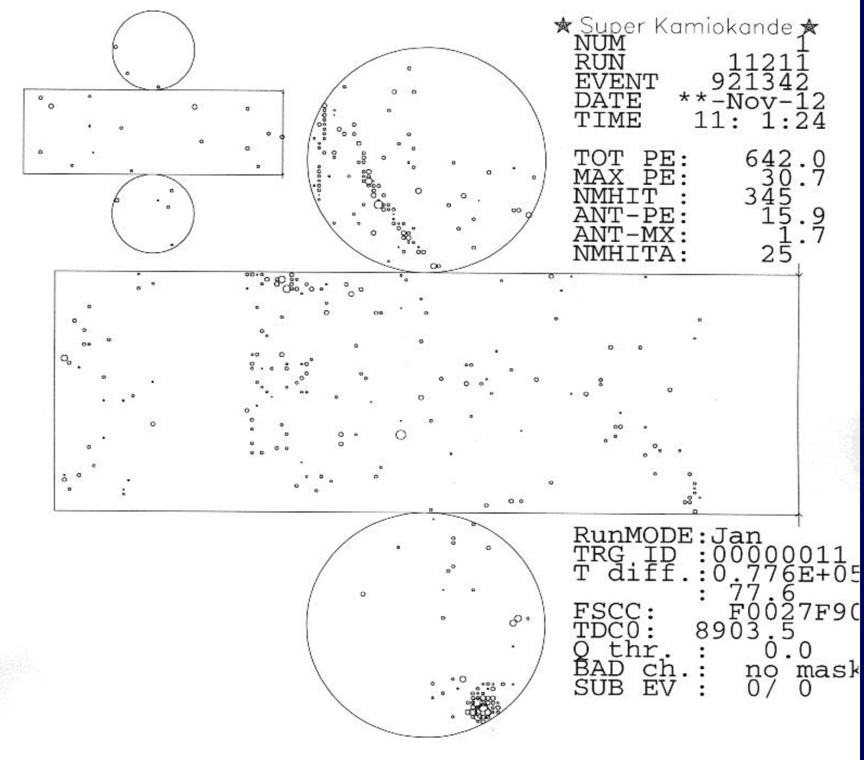
thanx to Michael Smy, UC Irvine

Before the disaster: Super-K Upgrade, Summer 2001

- Drained tank
- Replaced several hundred dead PMTs in both ID and OD while water level drops
- Revised water circulation plumbing to try to push radon level even lower

Super-K disaster 11/12/01

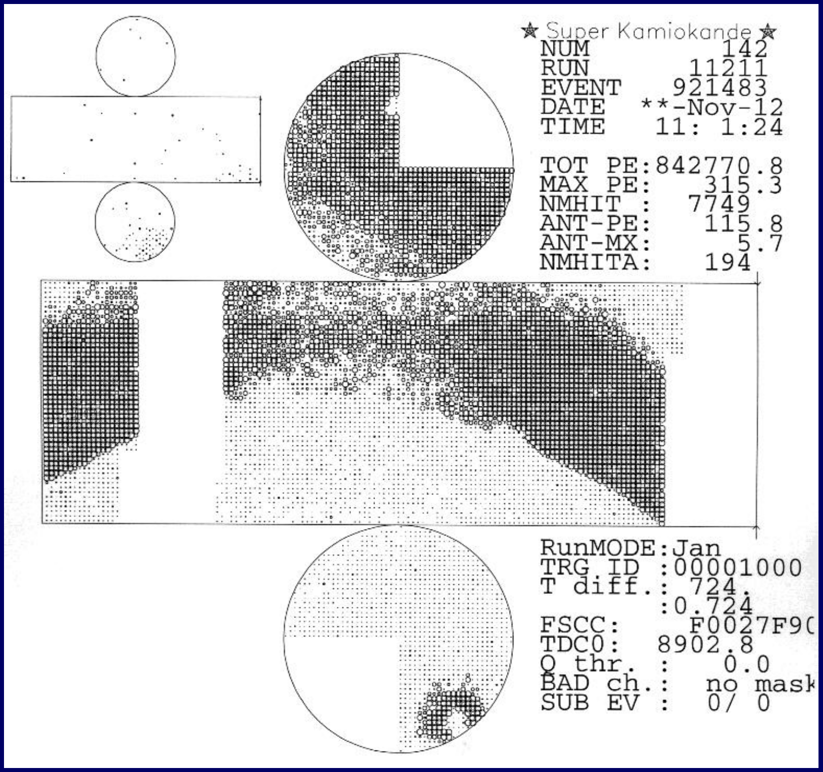
- 11/12/01: ~7000 ID PMTs and ~1000 OD PMTs were destroyed
- Refill under way, ~75% full at time of disaster
- Detector was operating (for SN watch): recorded sequential demise of PMTs
  - could watch it happen in the data files



```
★ Super Kamiokande ★
NUM             1
RUN         11211
EVENT      921342
DATE    **-Nov-12
TIME     11: 1:24

TOT PE:     642.0
MAX PE:      30.7
NMHIT :     345
ANT-PE:      15.9
ANT-MX:       1.7
NMHITA:      25

RunMODE:Jan
TRG ID :00000011
T diff.:0.776E+05
       :  77.6
FSCC:     F0027F9C
TDC0:    8903.5
Q thr.  :    0.0
BAD ch. :  no mask
SUB EV  :  0/ 0
```



```
★ Super Kamiokande ★
NUM           142
RUN         11211
EVENT      921483
DATE    **-Nov-12
TIME     11: 1:24

TOT PE:842770.8
MAX PE:   315.3
NMHIT :  7749
ANT-PE:   115.8
ANT-MX:     5.7
NMHITA:   194

RunMODE:Jan
TRG ID :00001000
T diff.:  724.
       :0.724
FSCC:      F0027F9C
TDC0:   8902.8
Q thr.  :   0.0
BAD ch. :  no mask
SUB EV  :  0/ 0
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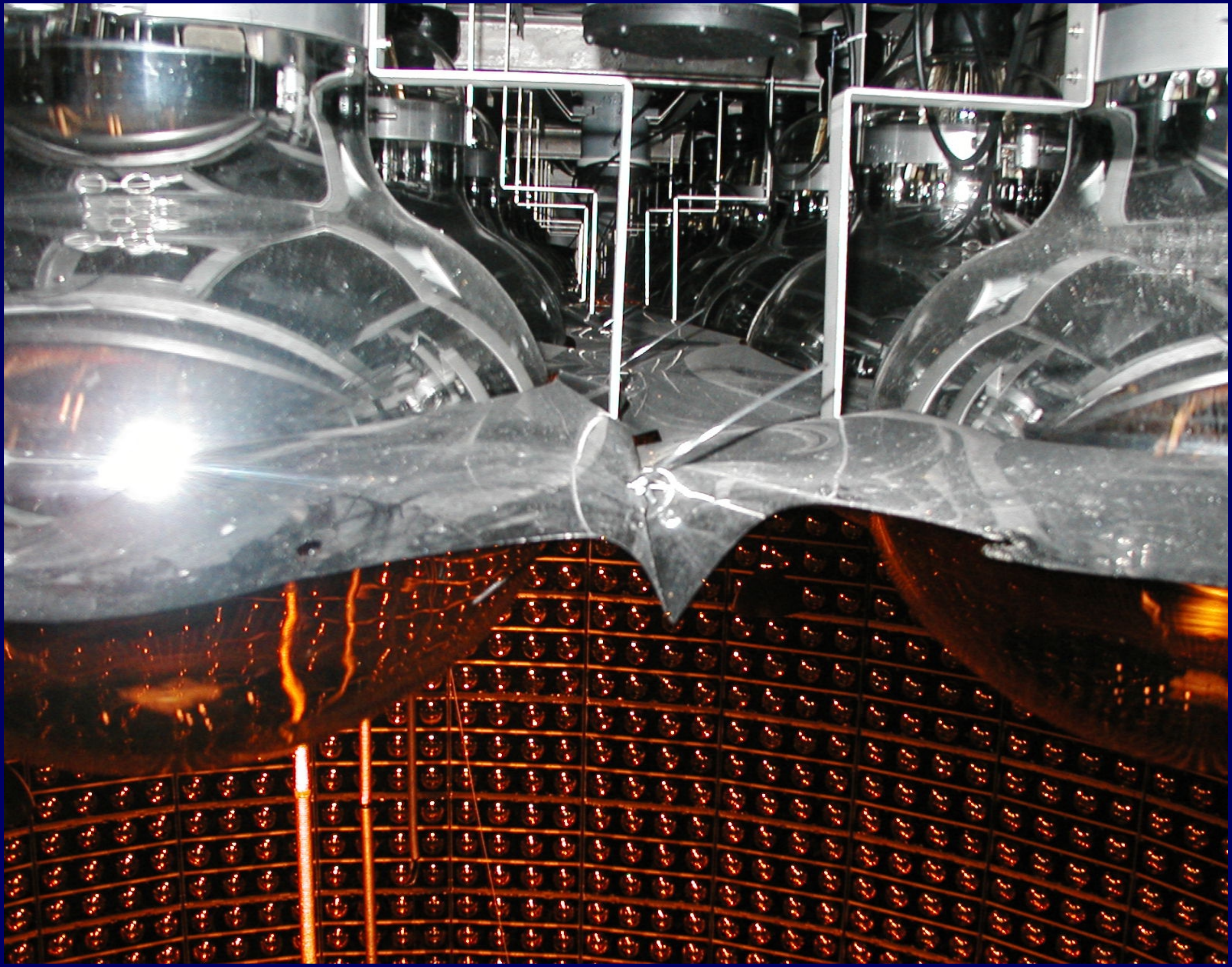
Before: View into Super-K from tank top (1996)



After…

- Photo from ha

Underwater photos of damage

- Photos shortly after disaster with underwater camera and ROV

- 5000 undamaged PMTs remain

Recovery Plans

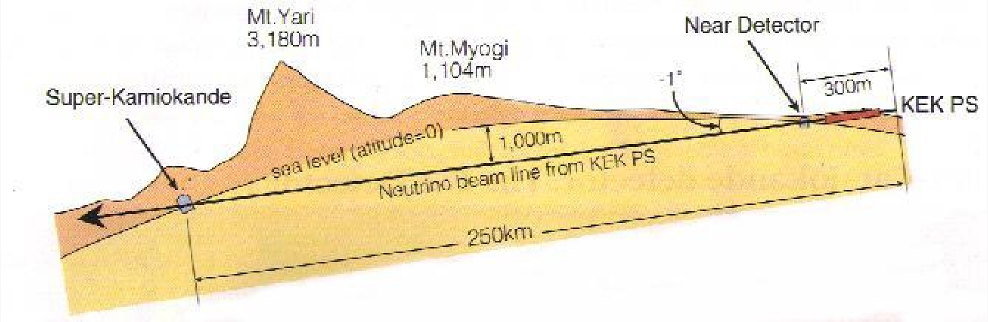
- Massive effort this year for recovery:
  - Drain tank and remove debris (completed)
  - Repair damaged tank structures and prepare for PMT replacement (April-June)
  - Rearrange surviving tubes to provide ~50% of original coverage (July-Sept)
    - Sufficient for for K2K and atmospheric neutrinos
    - Hamamatsu can supply ~1000 new PMTs this year, 6000 more in 3 years
  - Install protection against cascade failure
    - Acrylic domes to cover PMTs
      - Does not interfere with light collection
      - Slows down implosion effects to eliminate cascade failure

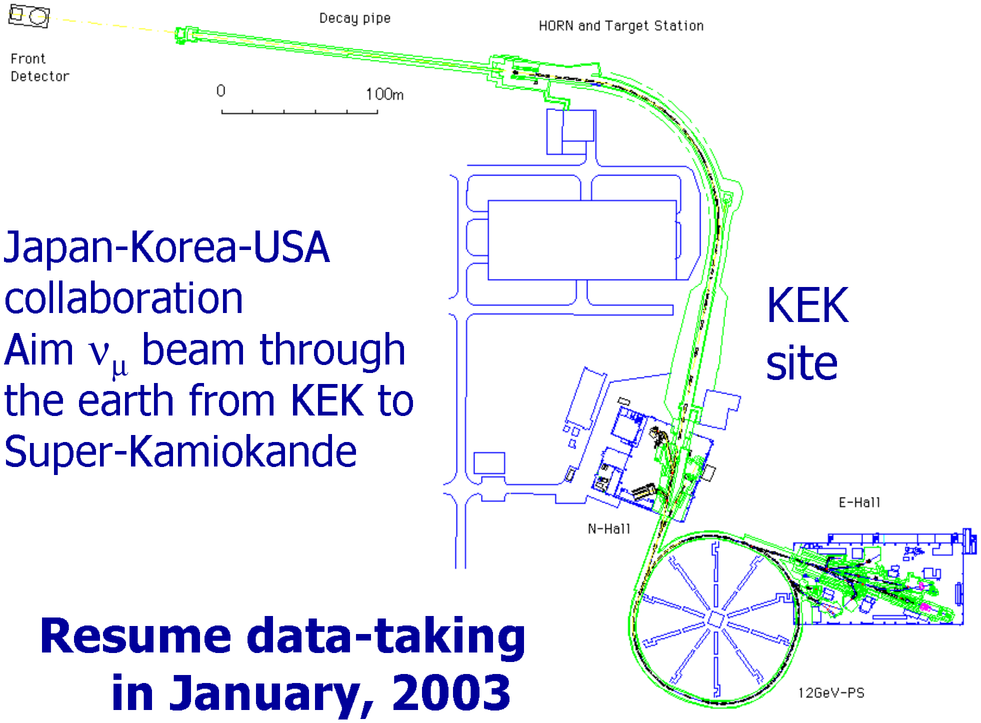
  - Start data taking by end of 2002
    - Restore supernova watch ASAP
    - K2K run Jan-June 2003
- Upgrade to full complement of PMTs in 2005, prepare for JHF2K

K2K: Long Baseline Neutrino Experiment (KEK E362)

- 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-intensity spill
- Background: 5 atmospheric neutrino events/day in SK
  - → $P(BG)=6\times10^{-11}$ per spill





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

KEK site

Resume data-taking in January, 2003

The K2K Collaboration

Japan

- High Energy Accelerator Research Organization(KEK)
- ICRR, University of Tokyo
- Kobe University
- Kyoto University
- Niigata University
- Okayama University
- Tokyo University of Science
- Tohoku University

Korea

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

Poland

- Warsaw University

USA

- Boston University
- University of California, Irvine
- University of Hawaii, Manoa
- Massachusetts Institute of Technology
- State University of New York at Stony Brook
- University of Washington, Seattle

KEK ν beam

Extracted 12 GeV p beamline
Target Station
Decay pipe
N
Neutrino Hall
(K2K near detectors)
to SK

What's new since last year...

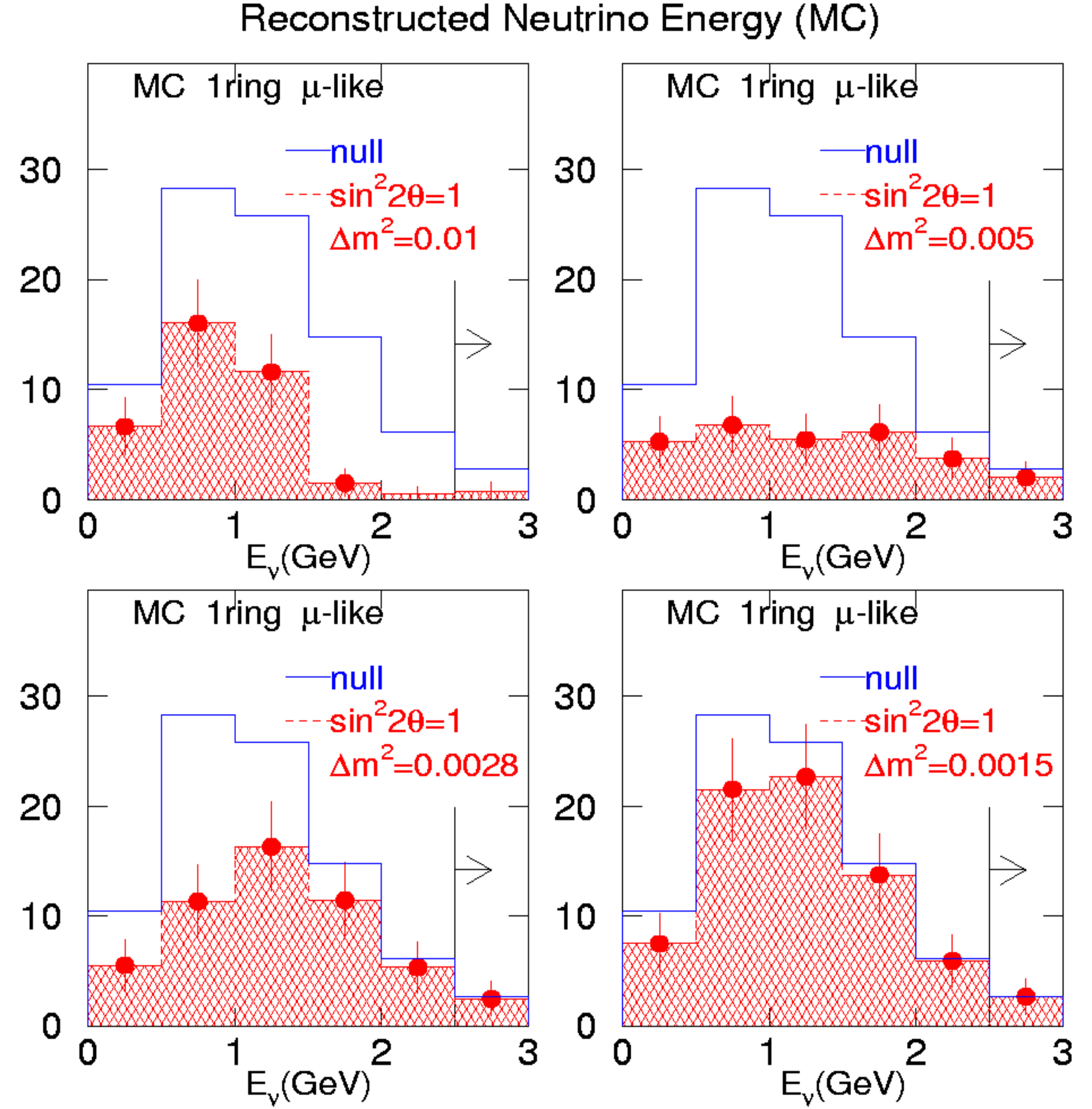
- No new data, for obvious reasons!
  - 2002 run cancelled, next run begins January 2003
- Used unanticipated "spare time" to improve analysis
  - Full treatment of systematic errors
  - Recalibration of near detector elements
  - Spectrum shape analysis
    - No-oscillations probability limits updated
    - Allowed-region contours

Oscillation effects clearly visible in E spectrum

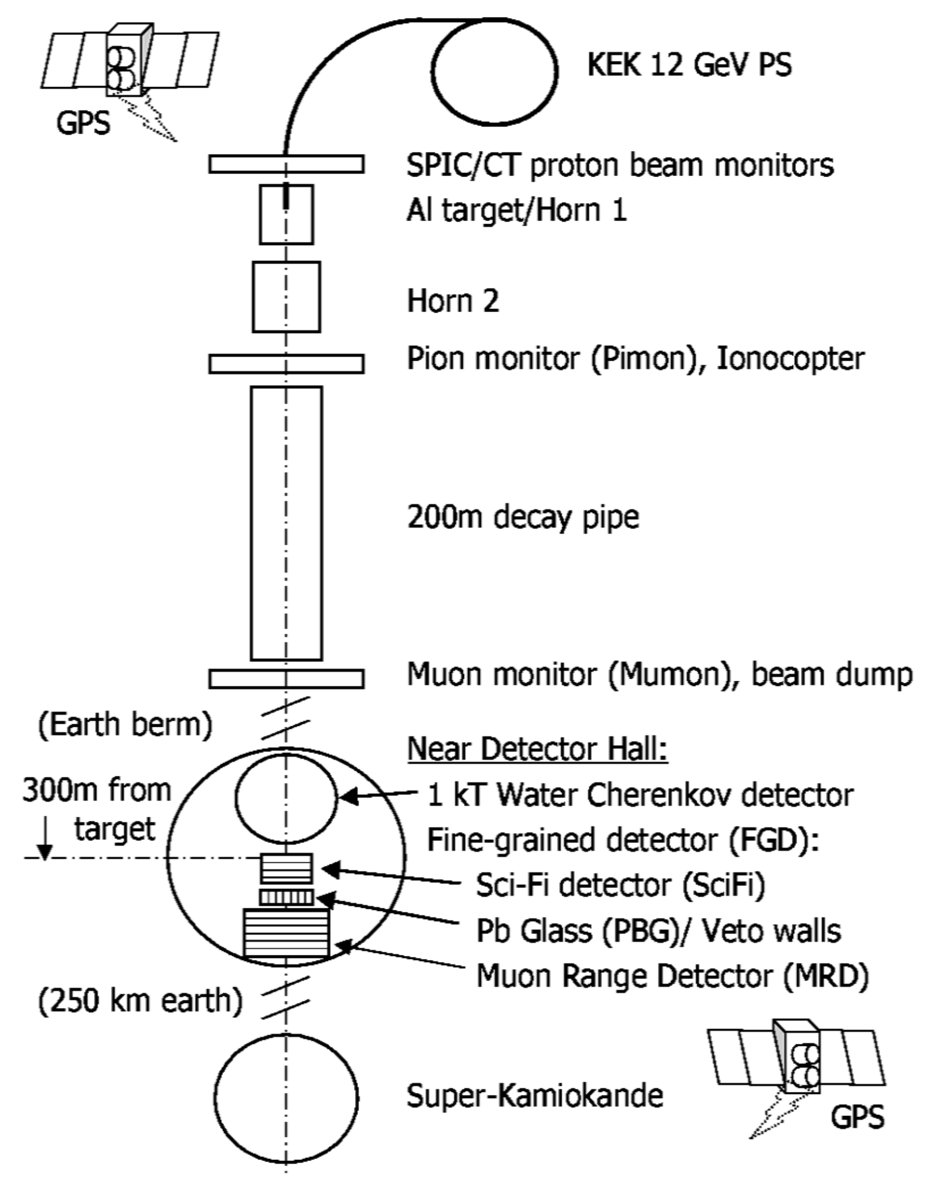
- Predicted far-detector E_ν spectra from beam Monte Carlo
  - ▬ = no oscillations

    (10^{20} pot → 190 events @ SK)

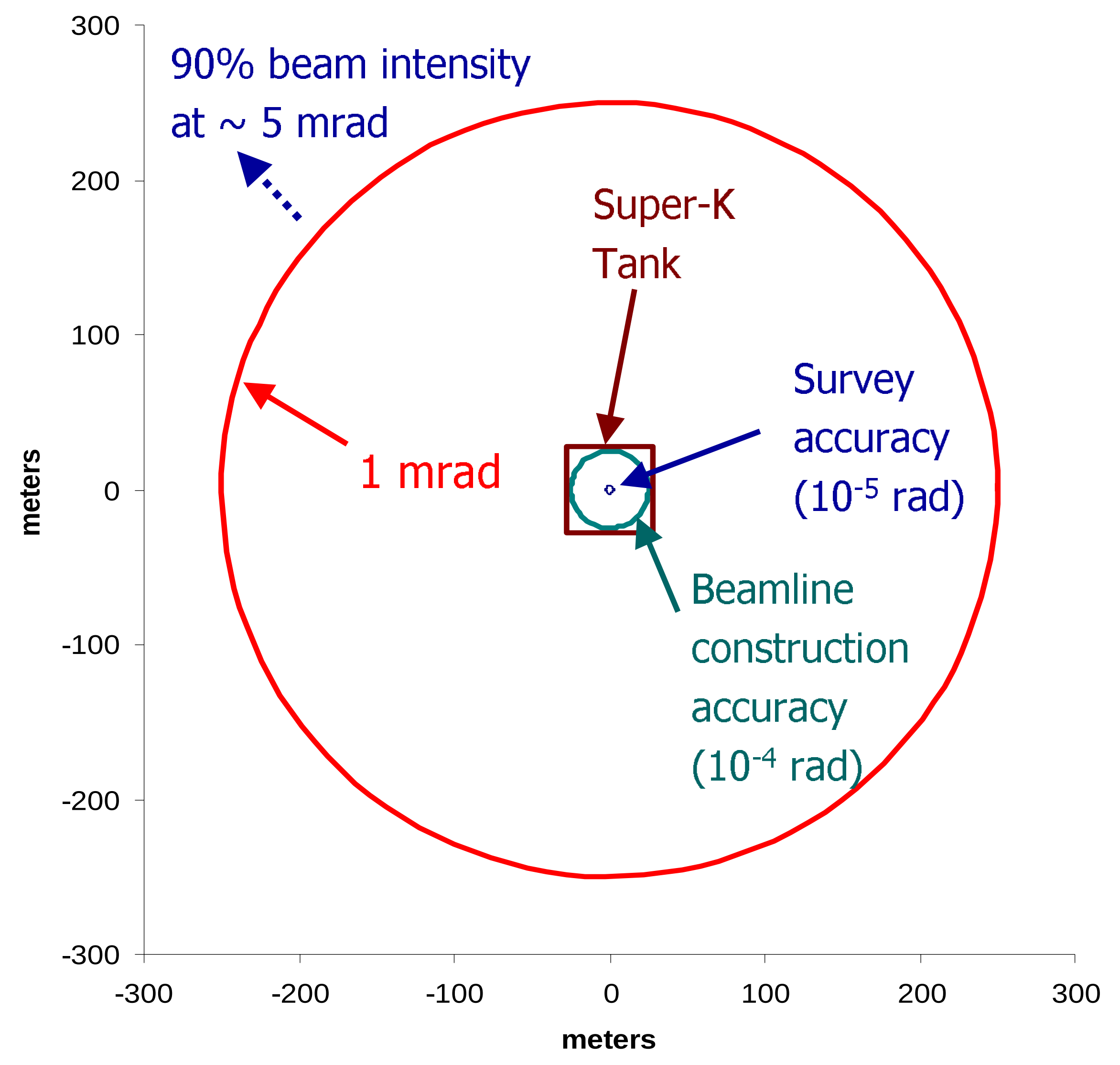
- ▨● = full $\nu_\tau - \nu_\mu$ mixing, various Δm^2 values



Functional overview of K2K

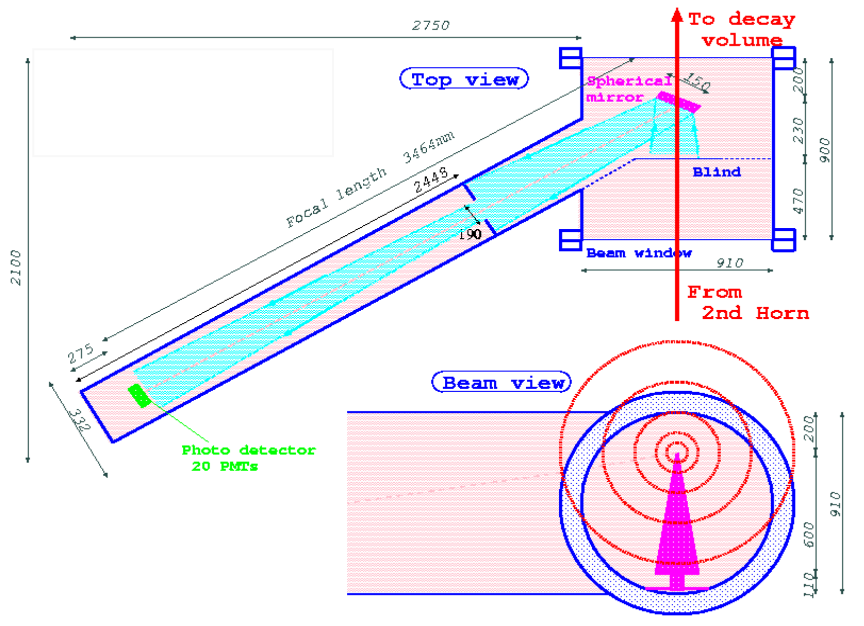


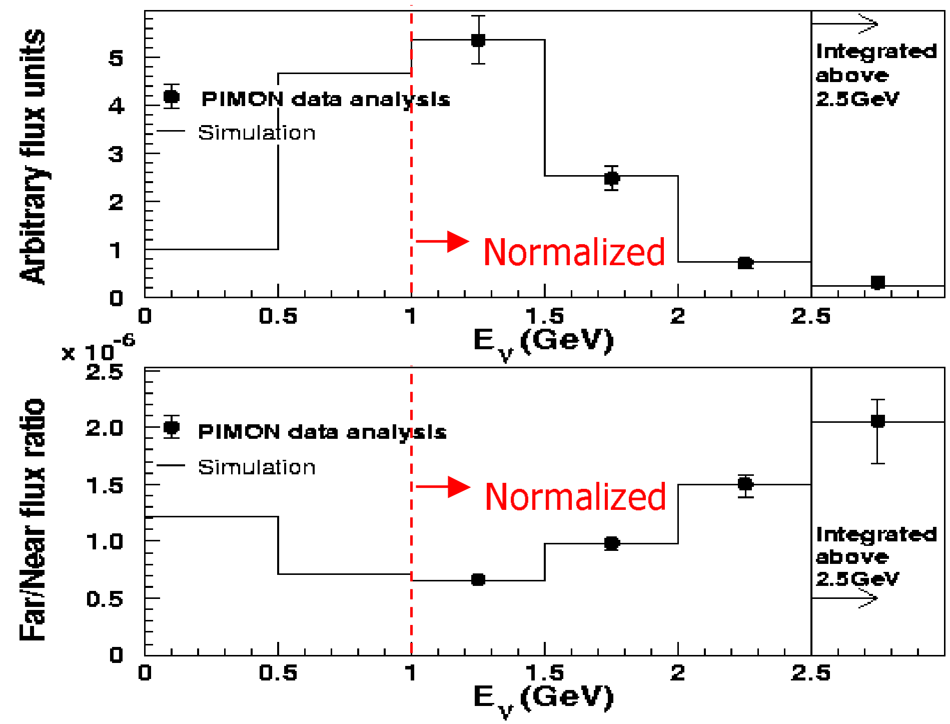
K2K beam aiming accuracy at Super-K

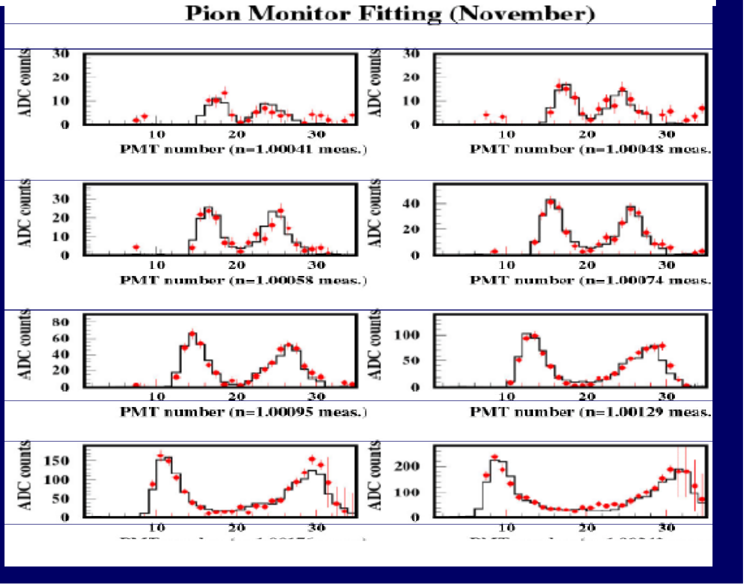


Pion monitor data vs beam MC

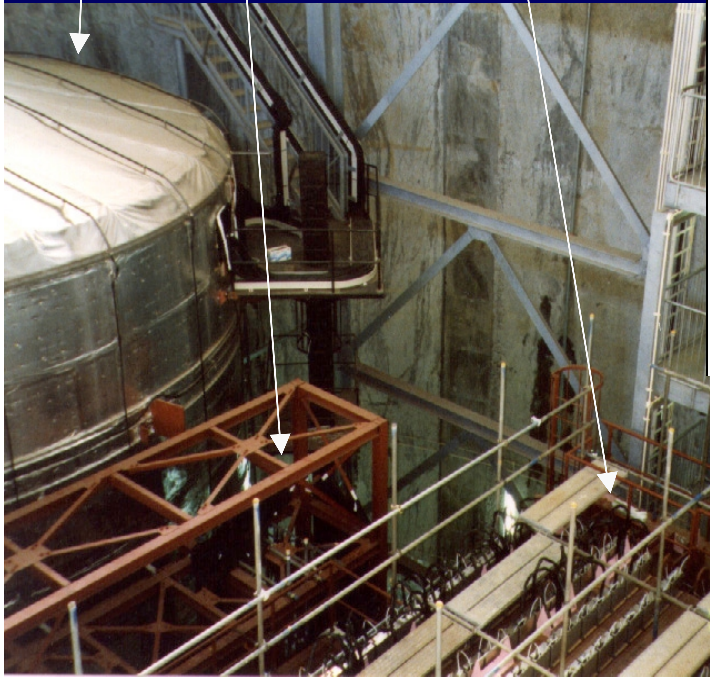
- PiMon: Gas Cherenkov detector
  - Samples p vs θ_{BEAM} in target hall
  - Novel design with wedge reflector in beam
  - Normally retracted, special calibration runs
- PiMon data vs beam MC: input for
  - Near detector spectrum
  - Far/near ratio






Pion Monitor Fitting (November)

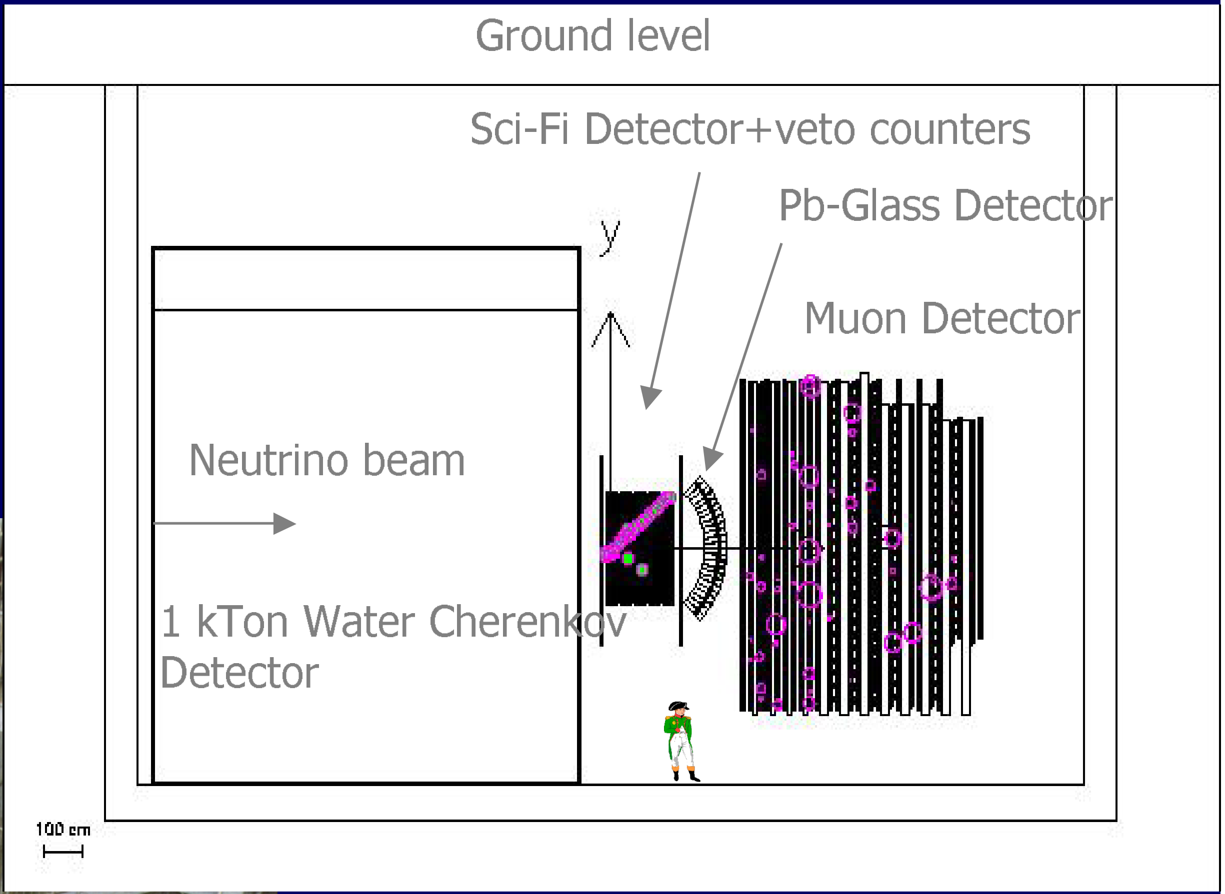
K2K Near Detector Hall



1 kT

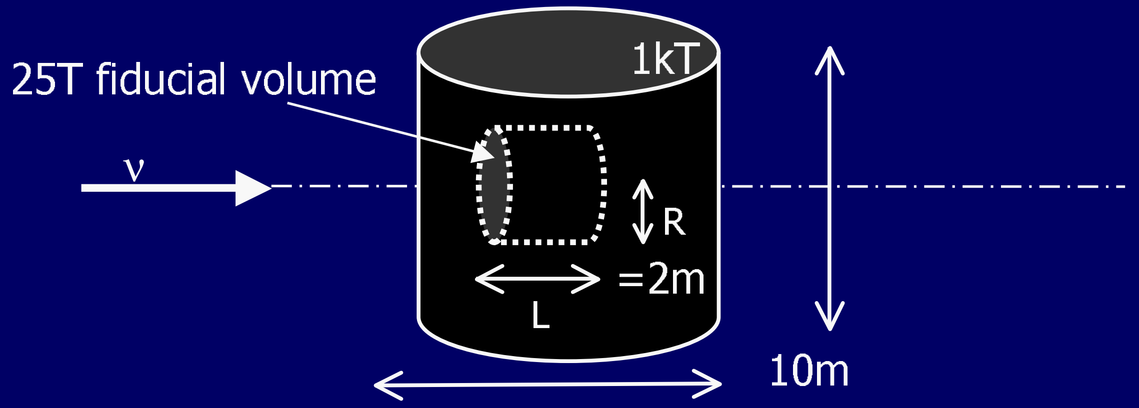
Sci-Fi

Muon Detector



...and six flights of stairs - very healthy!

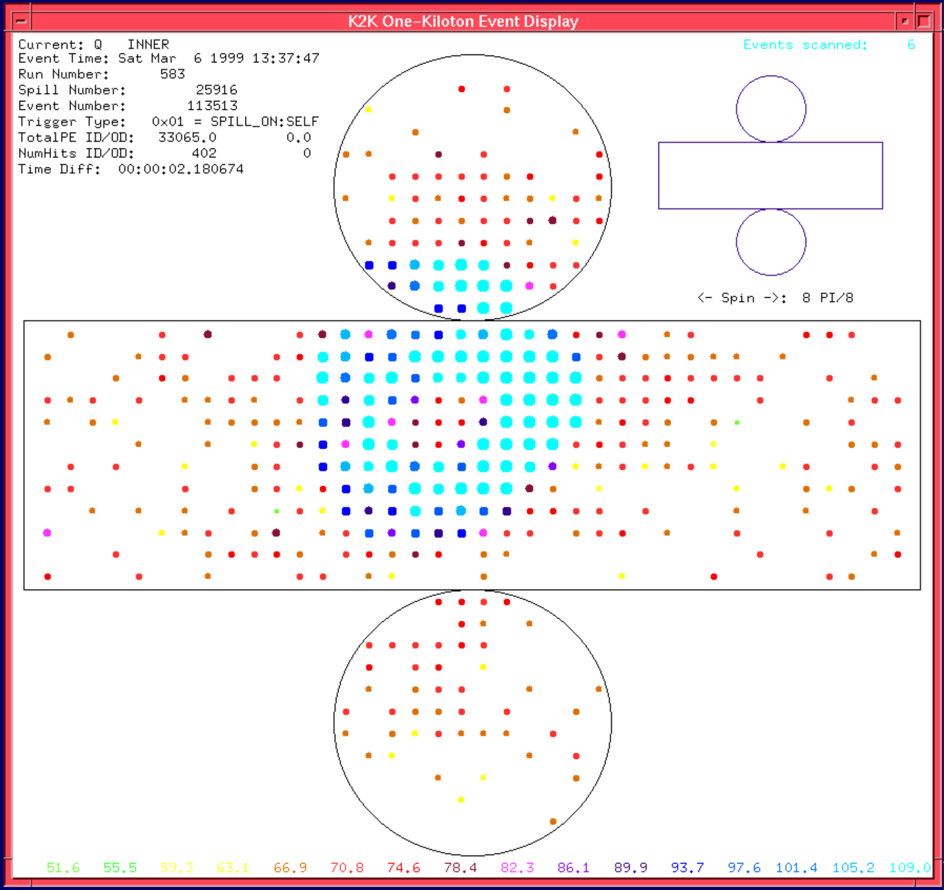
1kT Water Cerenkov Detector



- 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
- Neutrino event selection:
  - No 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
- Event rate:
  - $<\nu_\mu$ events per pot$> = 3.2\times10^{-15}$
  - Corrected for spills with >1 event

1 kT event displays

Neutrino event

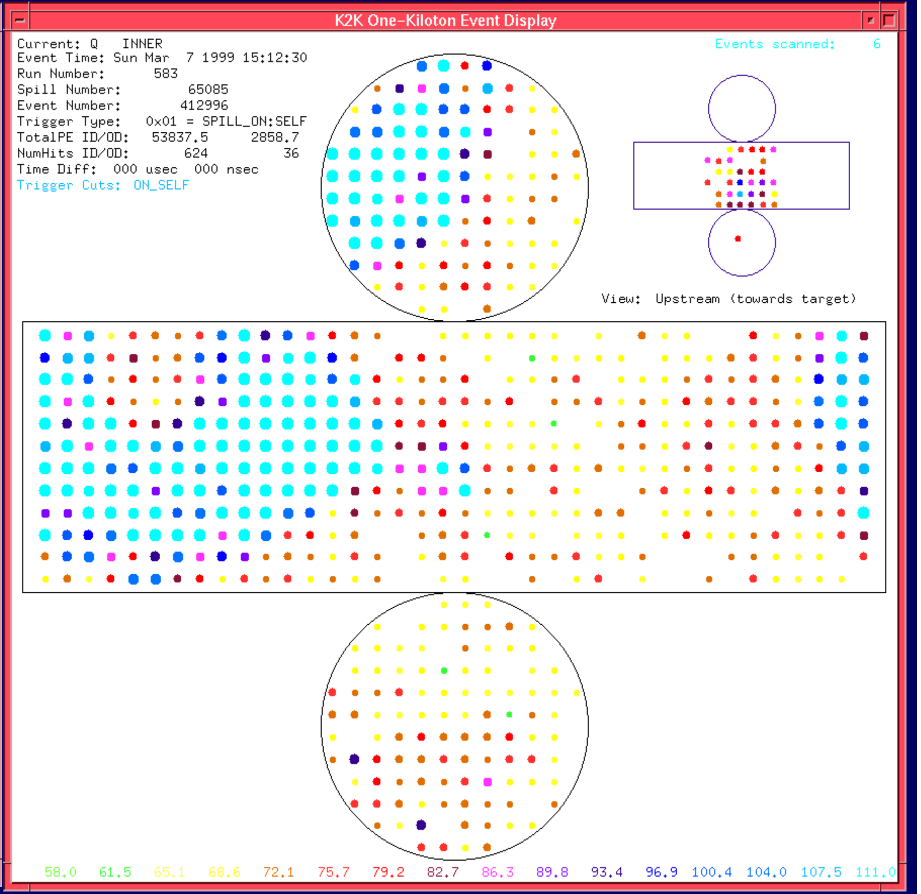


```
Current: Q   INNER
Event Time: Sat Mar  6 1999 13:37:47
Run Number:      583
Spill Number:         25916
Event Number:       113513
Trigger Type:   0x01 = SPILL_ON:SELF
TotalPE ID/OD:   33065.0          0.0
NumHits ID/OD:        402           0
Time Diff:  00:00:02.180674
```

Events scanned: 6

<- Spin ->: 8 PI/8

Beam induced muon

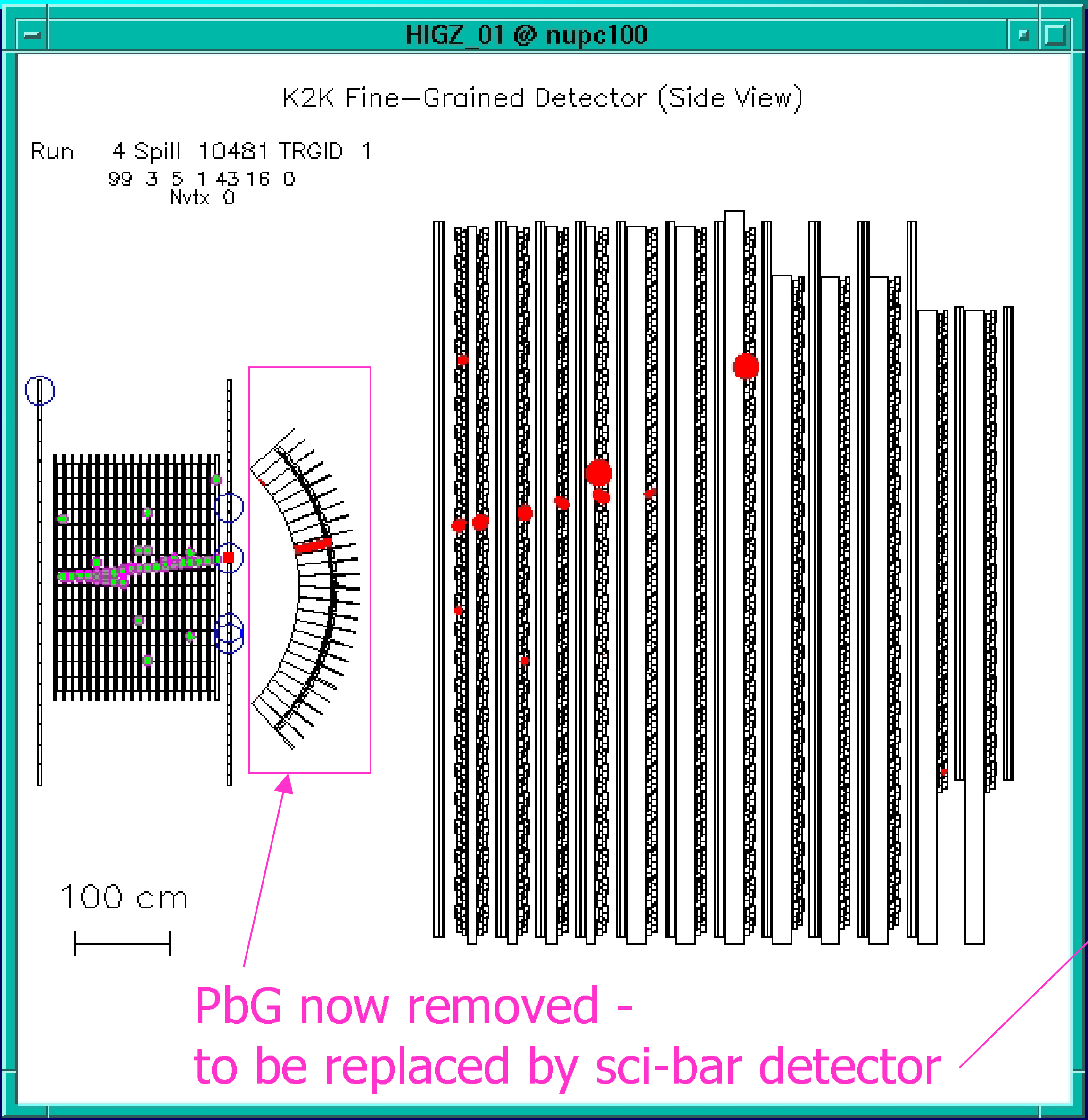


```
Current: Q   INNER
Event Time: Sun Mar  7 1999 15:12:30
Run Number:      583
Spill Number:         65085
Event Number:       412996
Trigger Type:   0x01 = SPILL_ON:SELF
TotalPE ID/OD:   53837.5      2858.7
NumHits ID/OD:        624          36
Time Diff:  000 usec  000 nsec
Trigger Cuts:  ON_SELF
```

Events scanned: 6

View: Upstream (towards target)

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

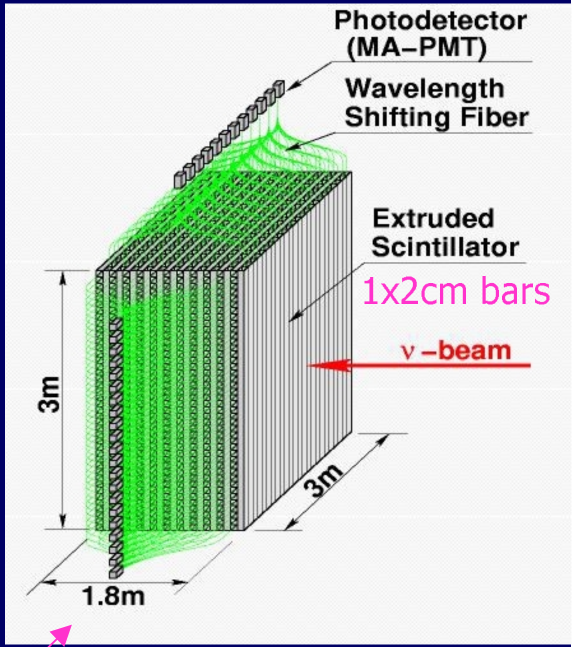


HIGZ_01 @ nupc100

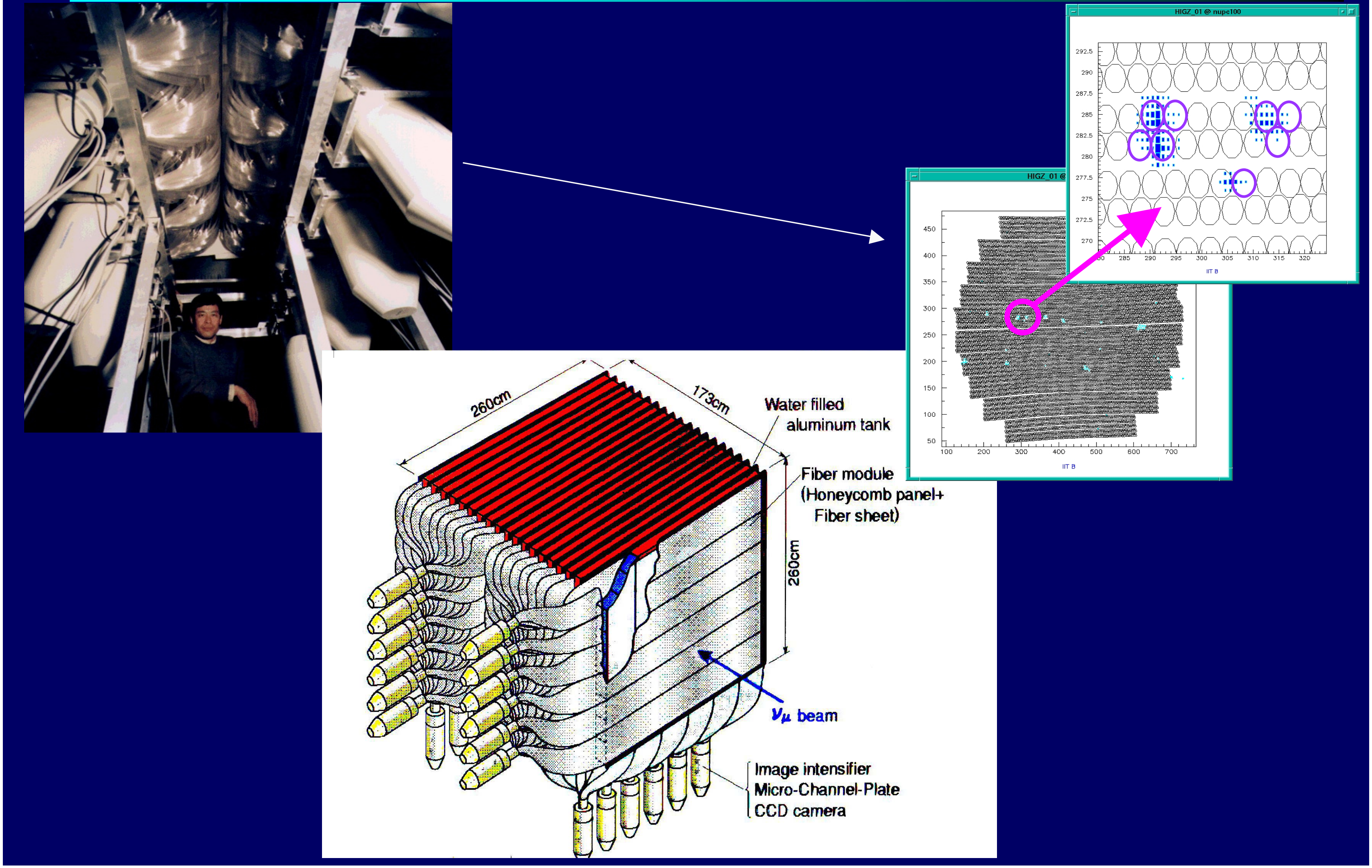
K2K Fine-Grained Detector (Side View)

```
Run     4 Spill  10481 TRGID  1
          99  3  5  1 43 16  0
                Nvtx  0
```

PbG now removed -
to be replaced by sci-bar detector



K2K scintillating fiber detector

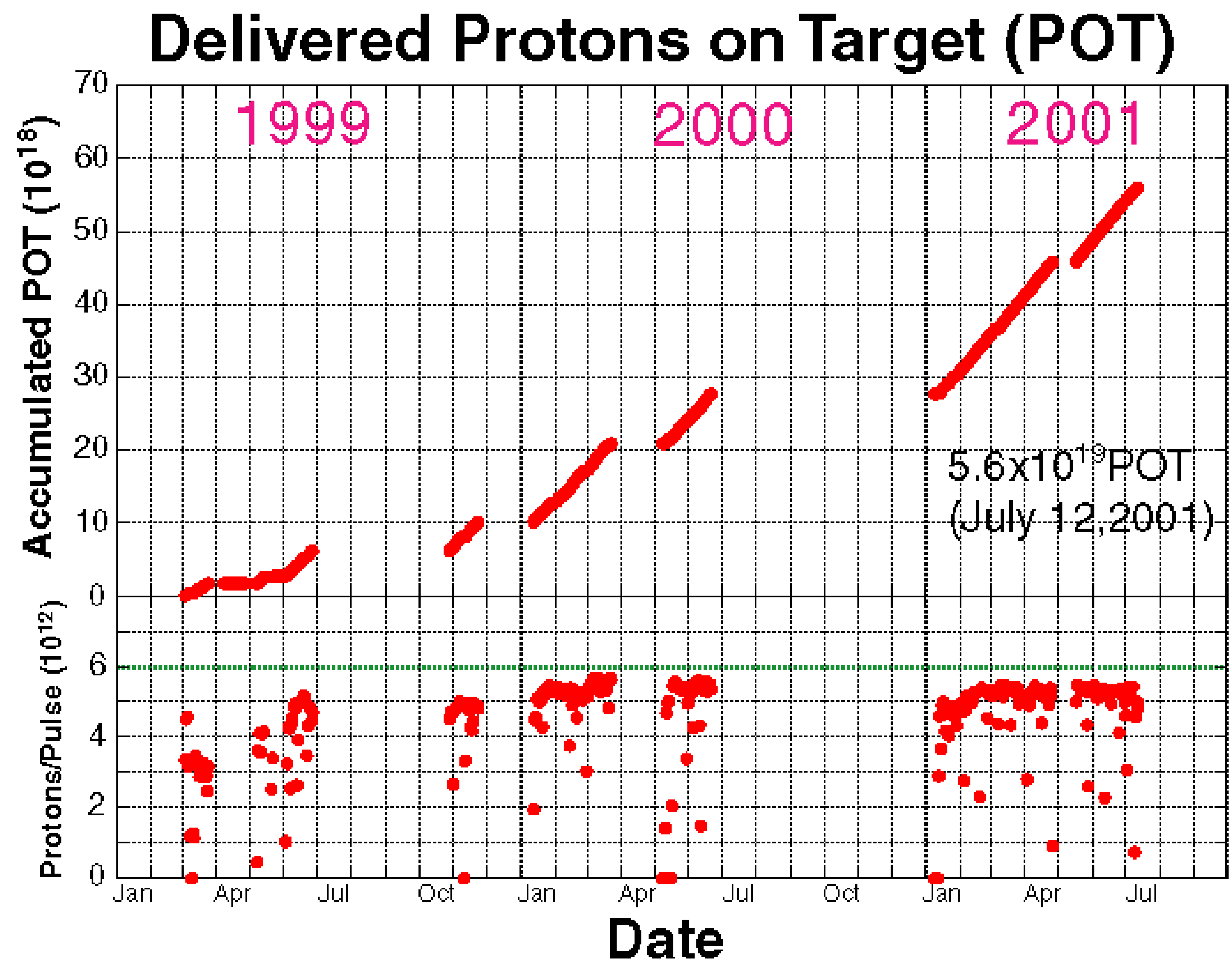


K2K Protons on Target (POT) vs time

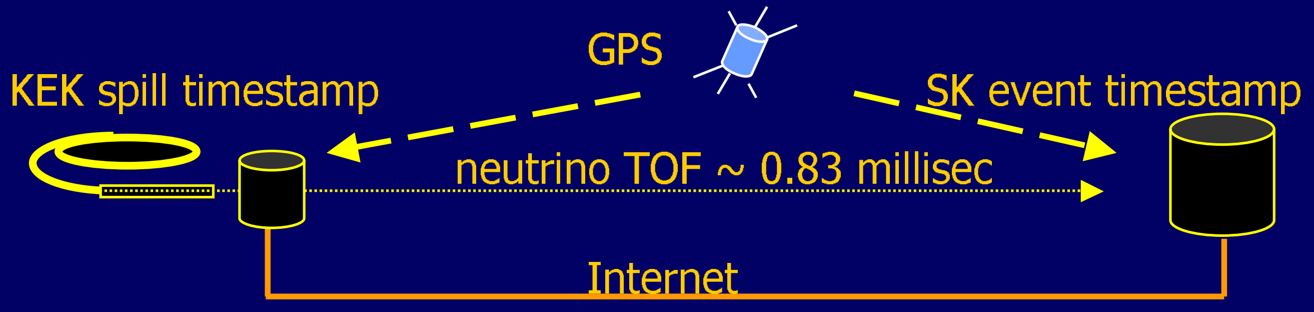
- Intermittent and varying beam current in 1999 =

"engineering run"

- Stable running in 2000 and 2001
- Net 5.6×10^{19} pot as of 7/01 (last run)



Finding K2K events at SK

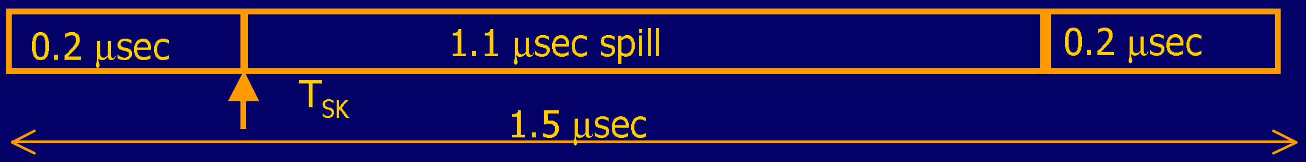


- Event selection criteria:

  Expected arrival time at SK:

$$\begin{aligned} T_{SK} &= T_{SPILL} + TOF \\ TOF &= 830\ \mu\text{sec} \\ \Delta T_{SPILL} &= 1.1\ \mu\text{sec} \\ \sigma_{GPS} &\approx 0.1\ \mu\text{sec} \end{aligned}$$

  So use 1.5 μsec acceptance window:



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

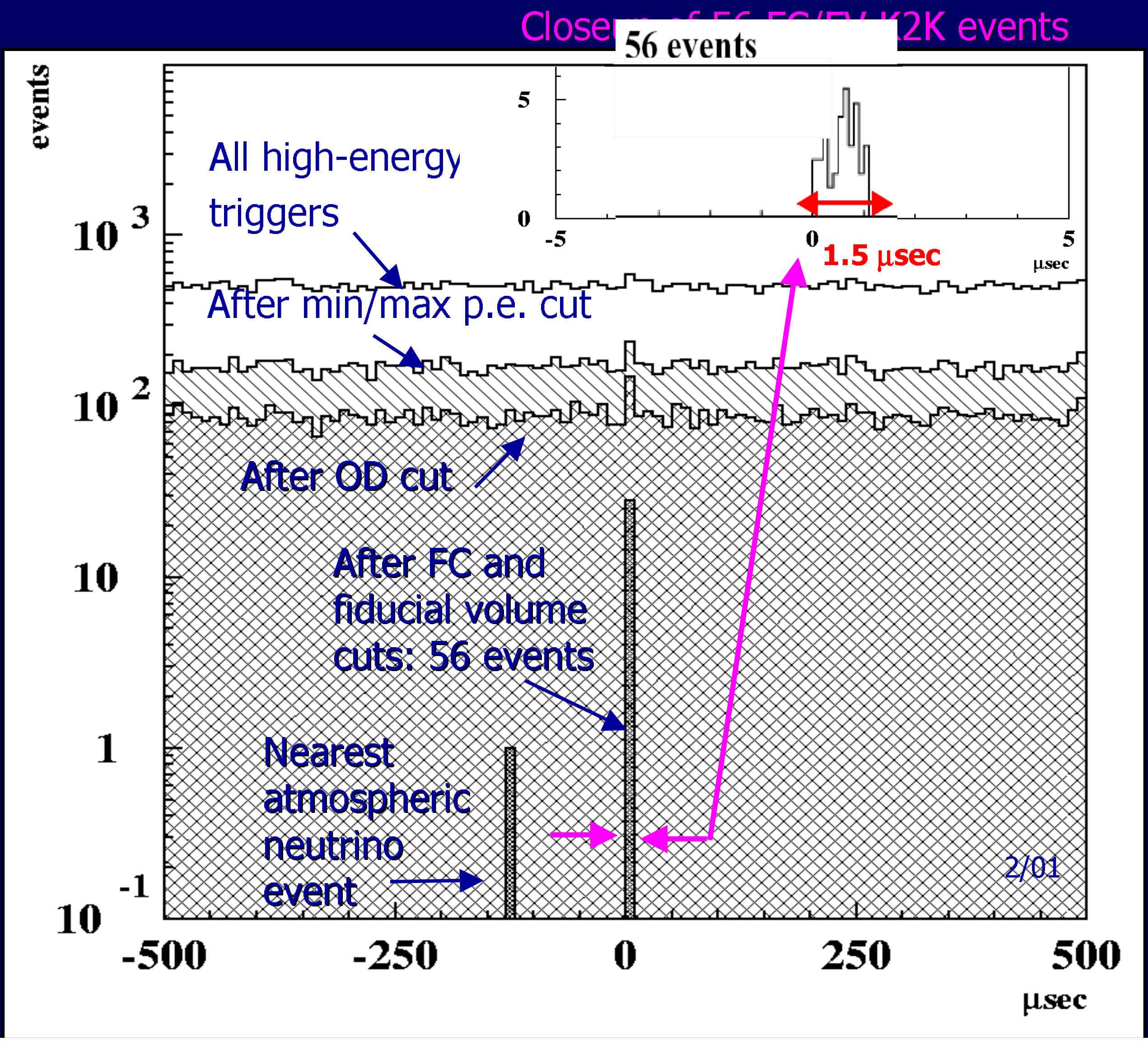
$$\Delta T_{SK} = T_{SK}{}^{+1.3\mu\text{sec}}_{-0.2\mu\text{sec}}$$

Δt 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)
- Atmospheric neutrino background: <10^{-3} events within 1.5 μsec



Data sets used for analysis

- Running conditions
  - June 1999 (6.5% of total livetime)
    - 2 cm diameter Al target, horn current 200 kA
    - larger systematic errors in near-detector data
  - November 1999 - July 2001
    - 3 cm target, horn current 250 kA
    - full analysis of systematic errors performed
- SK data sets
  - June '99 - July '01 (full set)
    - analysis limited to number of events observed:
      - 56 fully contained, in fid.vol. (FC/FV) events with E_{vis}> 30 MeV
      - Expected (no-osc): 80 events (+6.2 / -5.4)
  - November '99 - July '01
    - E_ν spectrum shape analysis
    - 29 1-ring mu-like, FC/FV events

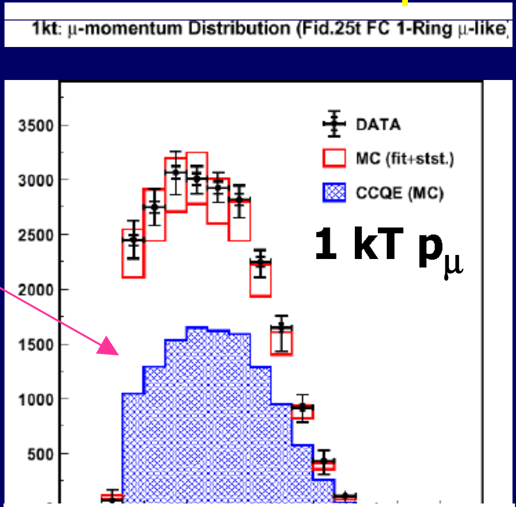
Oscillation analysis

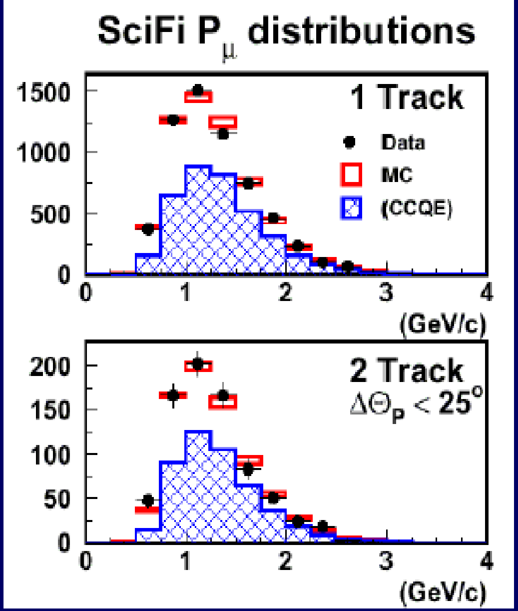
- Analysis procedure
  - Observe (p_μ,θ_μ) spectra in near detectors
  - Unfold near spectrum $\phi_{near}(E_\nu)$ using neutrino interaction model
  - Extrapolate to far detector: near/far ratio $R_{FN}(E_\nu)$
  - Predict far spectrum $\phi_{SK}(E_\nu)$ assuming no oscillations
    - Number of events for no-osc (N_{SK}) using interaction model
      - all event types
    - Max Likelihood fit to spectral shape to get $\{\Delta m^2, \sin^2(2\theta)\}$ allowed region
      - event sample with best-known systematics (1-ring, mu-like FC/FV)
- Systematic errors analyzed
  - Beam flux
  - Quasi-elastic/non-QE ratio
  - Near/Far ratio
  - SK reconstruction efficiency
  - SK energy scale
  - Normalizations (for 6/99 and 11/99~7/01)

Near and far

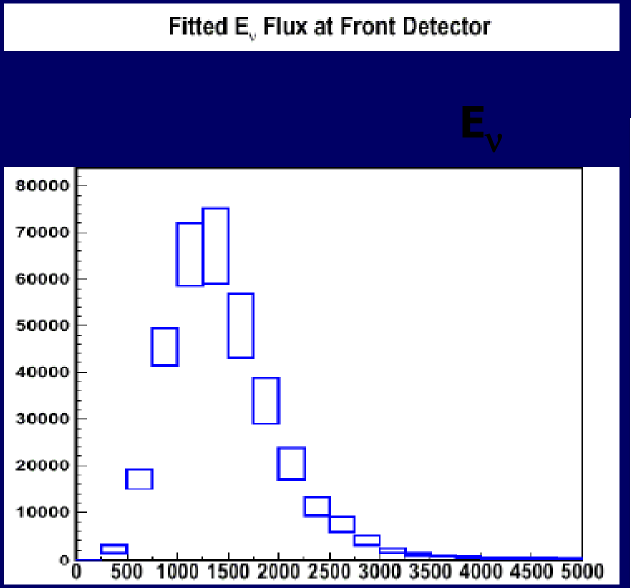
Near detector spectra

shaded = quasi-elastics (from MC)

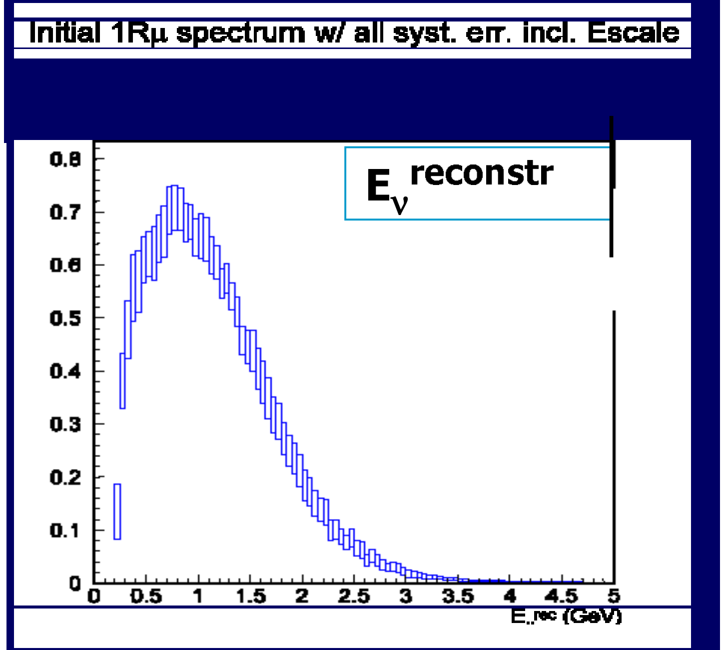




Near flux

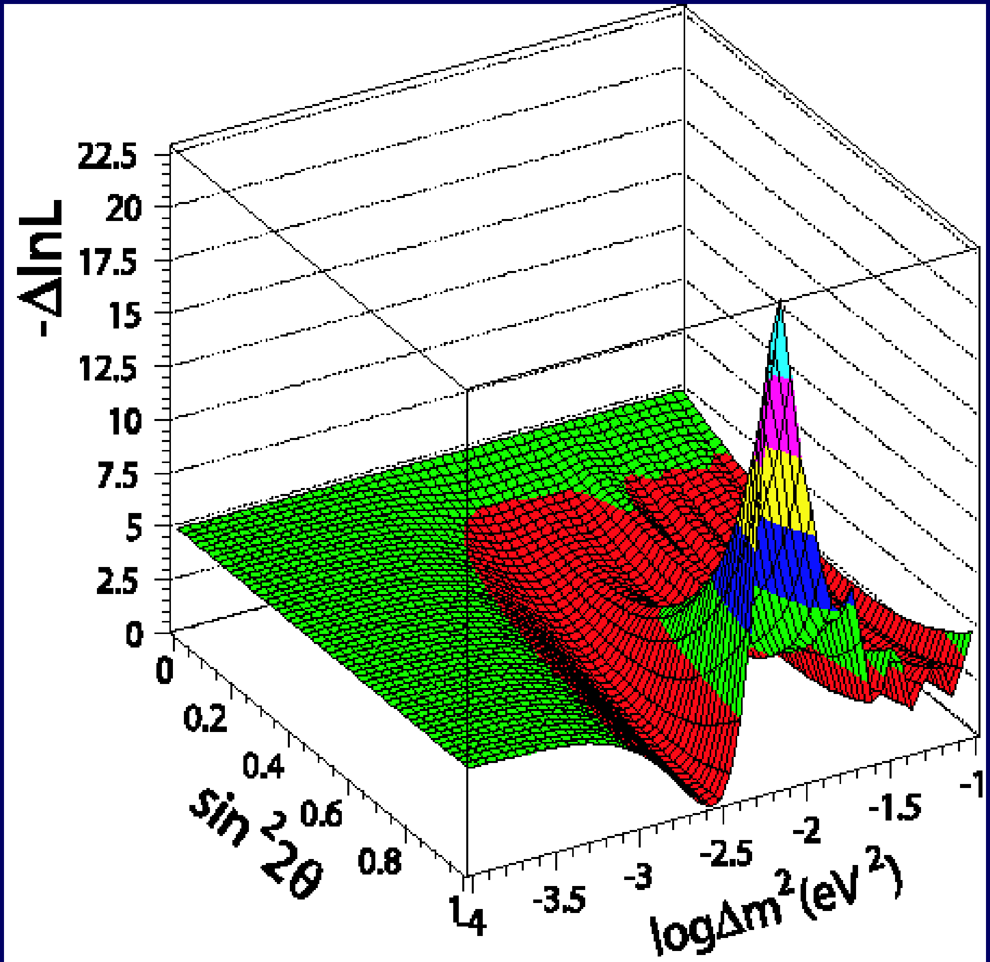


Predicted far flux



Likelihood vs Δm^2, $\sin^2(2\theta)$

- likelihood surface for spectrum shape + normalization



$$L_{tot} = L_{norm}(f)\, L_{shape}(f)\, L_{syst}(f)$$

Normalization:

$$N_{exp} = 80.1^{+6.2}_{-5.4}$$

Spectrum shape

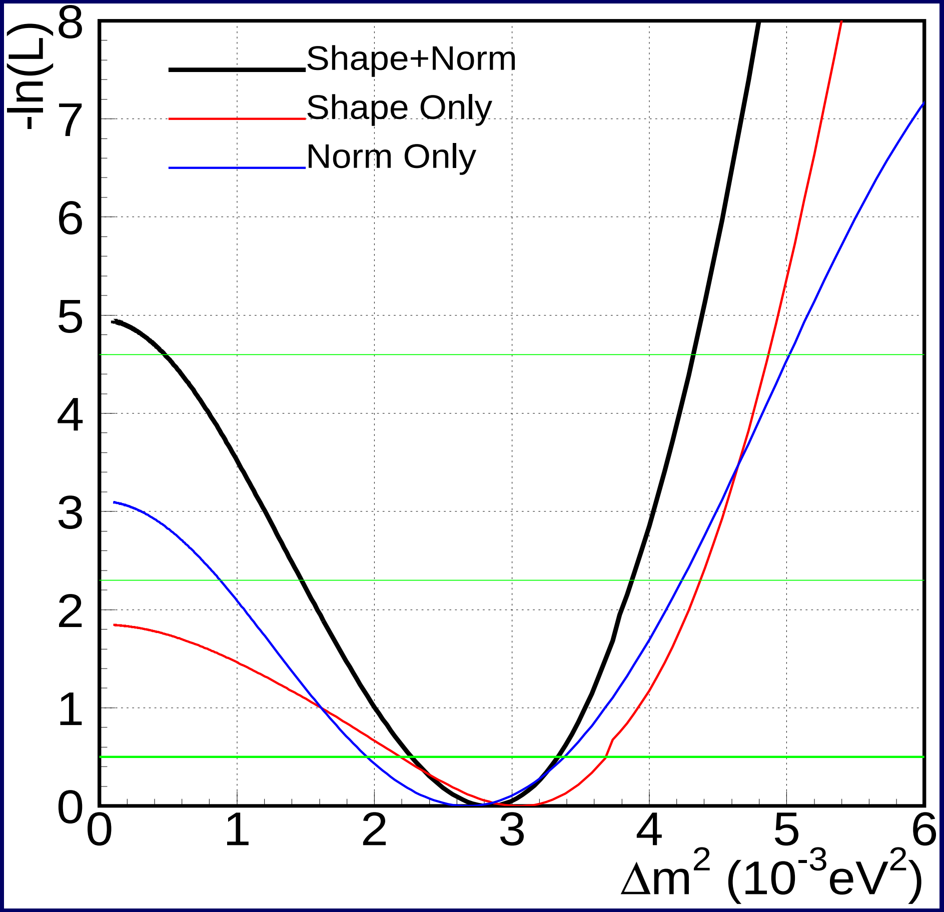
Constraint term for systematic parameters (error matrices)

Allowed-Δm² scan in likelihood for full mixing

N_{SK}+Shape

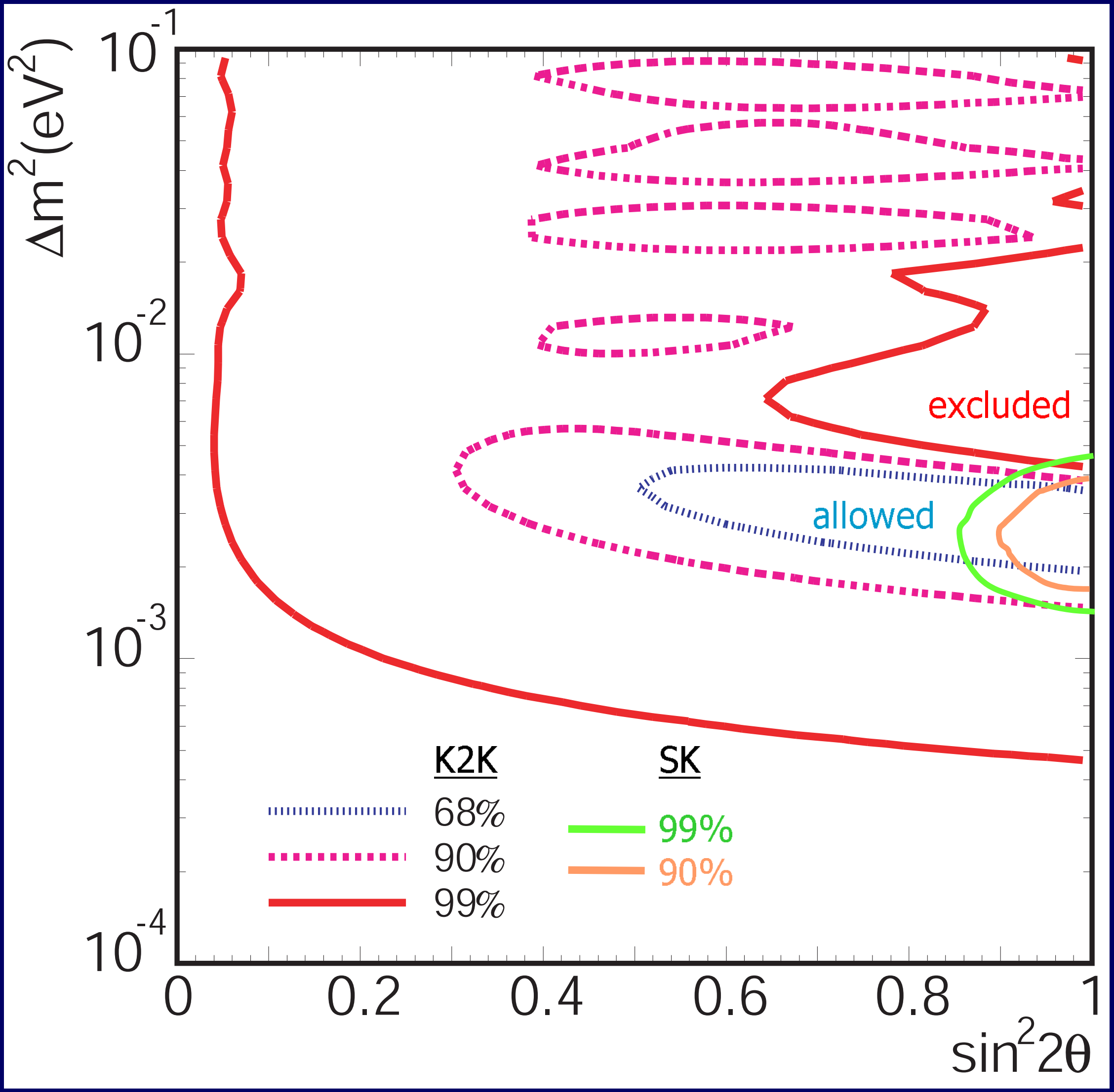
Number of Events only

Spectrum Shape only



Normalization and shape analysis consistent

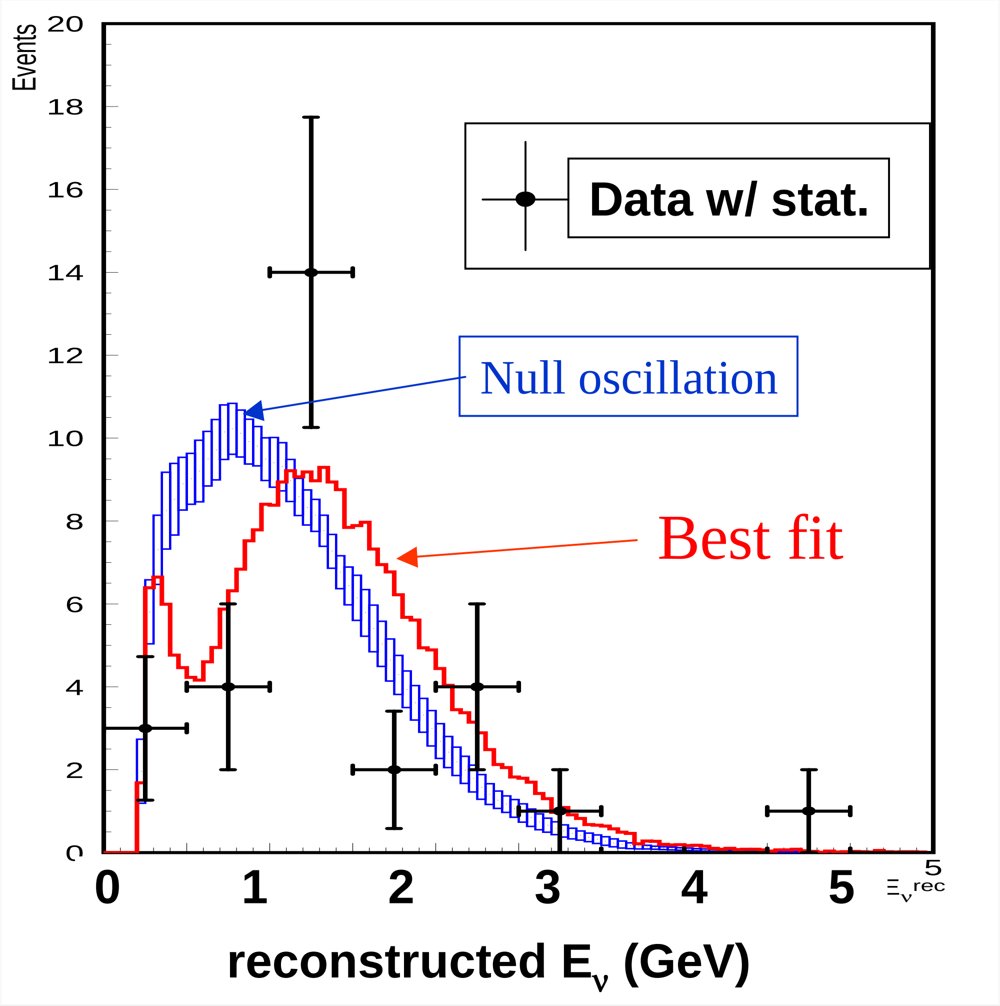
K2K allowed region (combined fit)



$1.5 \sim 3.9 \times 10^{-3}$ eV^2
at $\sin^2 2\theta=1$ (90%CL)

Consistent with SK
atmospheric ν results:
$\Delta m^2=(1.6\sim3.9)$x10-3 eV^2
for $\sin^2 2\theta=1.0$

Best-fit values



- Probability of no oscillations:

N_{SK}only	1.3%
Shape only	15.7%
N_{SK}+Shape	0.7%

- N_{SK} prediction = 54
  (obs: 56)
- Best fit oscillation parameters
  ($\sin^2 2\theta$, Δm^2) =

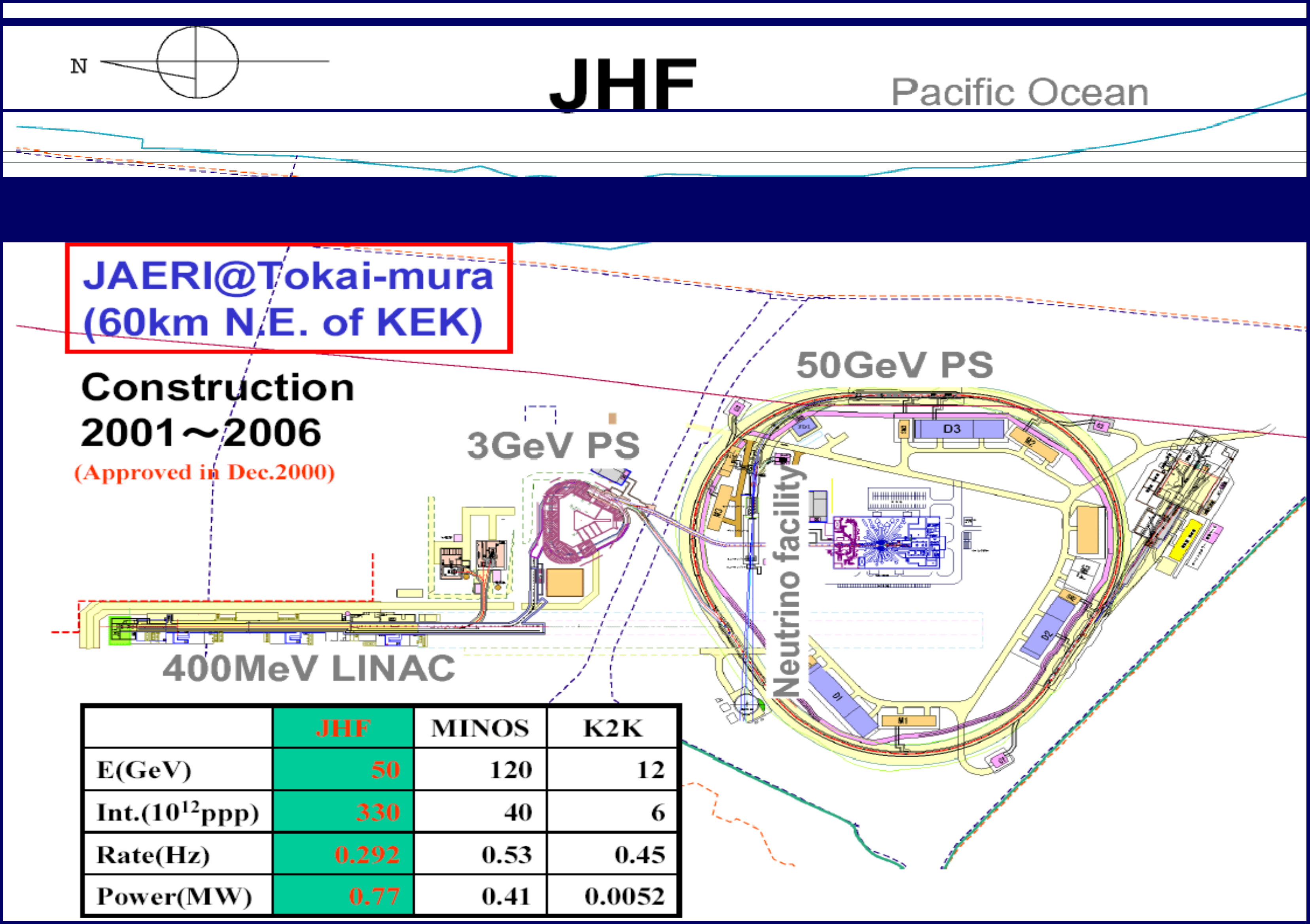
Shape only: $(1.09, 3.0\mathrm{x}10^{-3}\mathrm{eV}^2)$
N_{SK} +Shape: $(1.03, 2.8\mathrm{x}10^{-3}\mathrm{eV}^2)$
Spectrum shape fit has $P_{K\text{-}S}$ = 79%

Future plans

- “JHF2K”
  - 50 GeV accelerator to be built 100 km N of Tokyo
    - JAERI (Japanese Atomic Energy Research Institute, Tokai-Mura)
  - Neutrino beam included in approved plans
    - High intensity: 3.3×10^{14} ppp/3.4 sec
    - ~20x increased sensitivity for oscillation effects
    - *Narrow* band beam: ~1 GeV
  - Far detector will be Super-Kamiokande
    - Baseline 295 km
    - Upgrade Super-K from 50% PMT coverage to 100% by 2007

  See http:://neutrino.kek.jp/jhfnu
- Will allow:
  - Δm_{mx}^2 to be determined to 1×10^{-4} eV^2 in one year; 1% measurement of $\sin^2 2\theta_{\mu \to x}$ in five years, $\sin^2 2\theta_{\mu e}$ to be measured down to 6×10^{-3}.
  - improved limits on possible sterile neutrino contributions in ν_μ disappearance.
  - Measurement of CP violation in the lepton sector may be feasible, but will require new far detector with mass ~1 Mton. (No fundamental engineering showstoppers)

JHF accelerator: first beam in late 2006



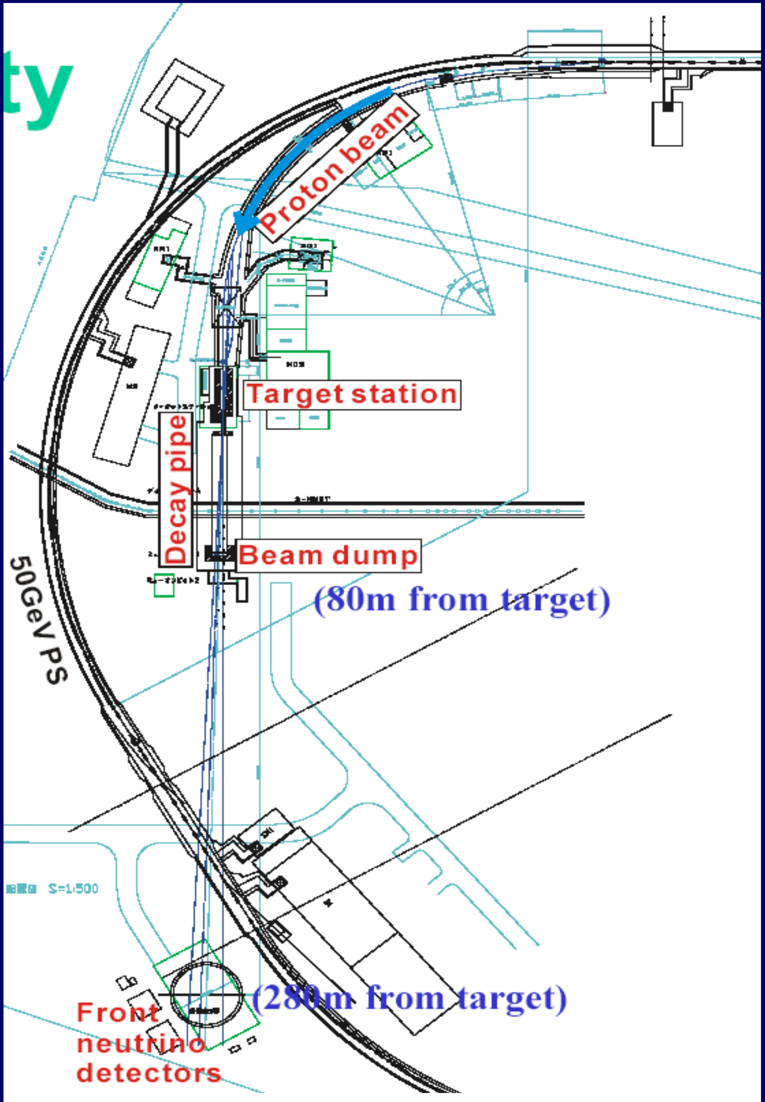
JAERI@Tokai-mura (60km N.E. of KEK)

Construction 2001～2006

(Approved in Dec.2000)

	JHF	MINOS	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.292	0.53	0.45
Power(MW)	0.77	0.41	0.0052

Neutrino beam area at JHF

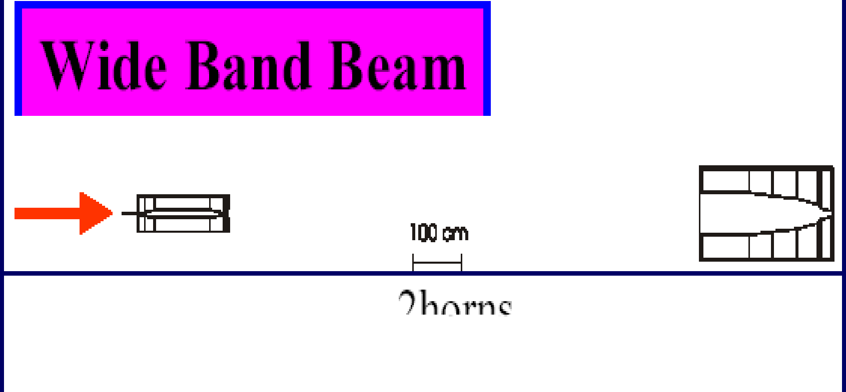


- Comparison of high intensity proton accelerators:

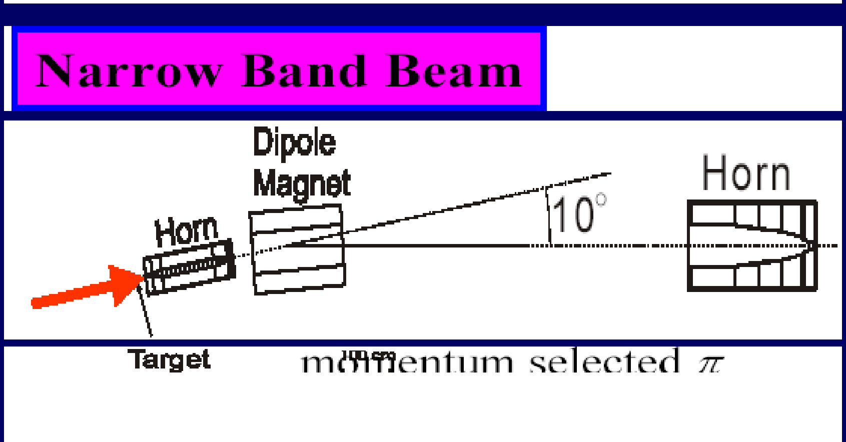
	Power, MW	Energy, GeV	Intensity, 10^{12} ppp	Rep Rate, Hz
KEK-PS	0.005	12	6	0.45
FNAL-MI	0.41	120	40	0.53
JHF-I	0.77	50	330	0.29
JHF-II	4	50		

- Near detector at 280 m from production target
- Intermediate detector at 2 km an option
  - Large water Cherenkov detector
  - Excavation will be expensive...

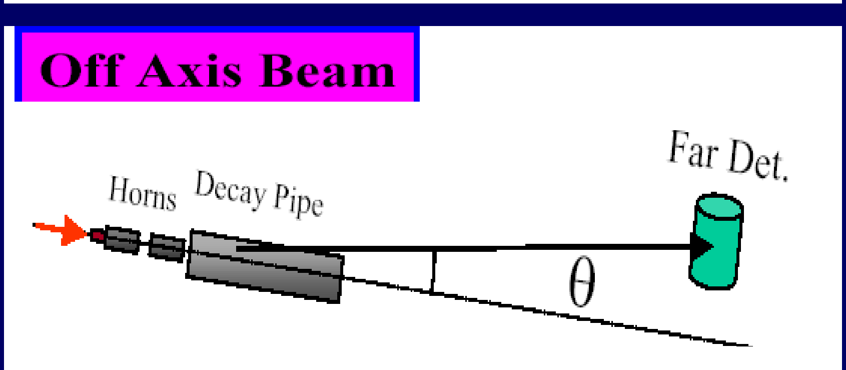
JHF neutrino beam options



- Highest intensity
- Widest reach in Δm^2
- Background from HE tail
- Systematic error from spectrum extrapolation

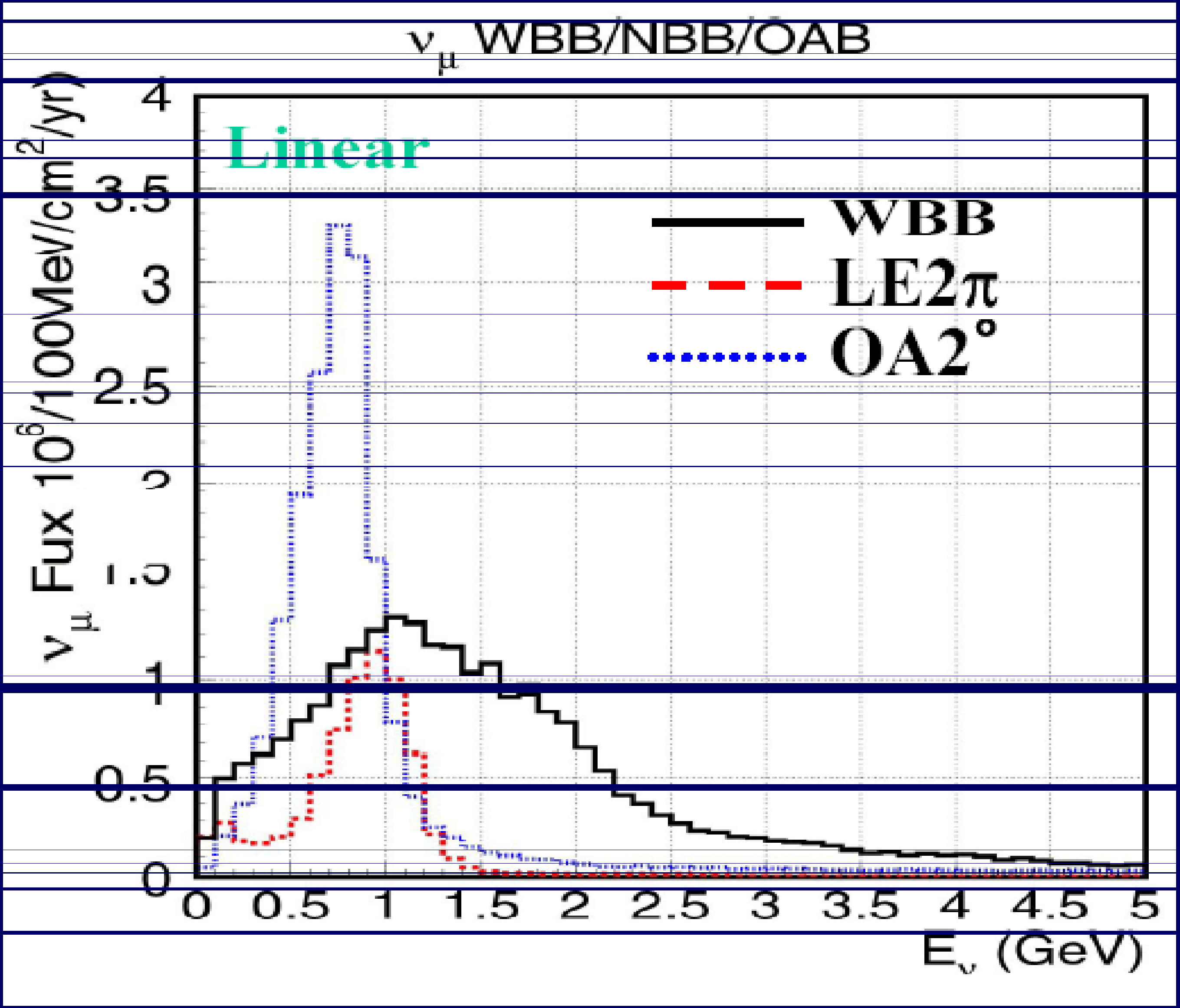


- No HE tail
- Less systematic error on spectrum
- Easy to tune energy

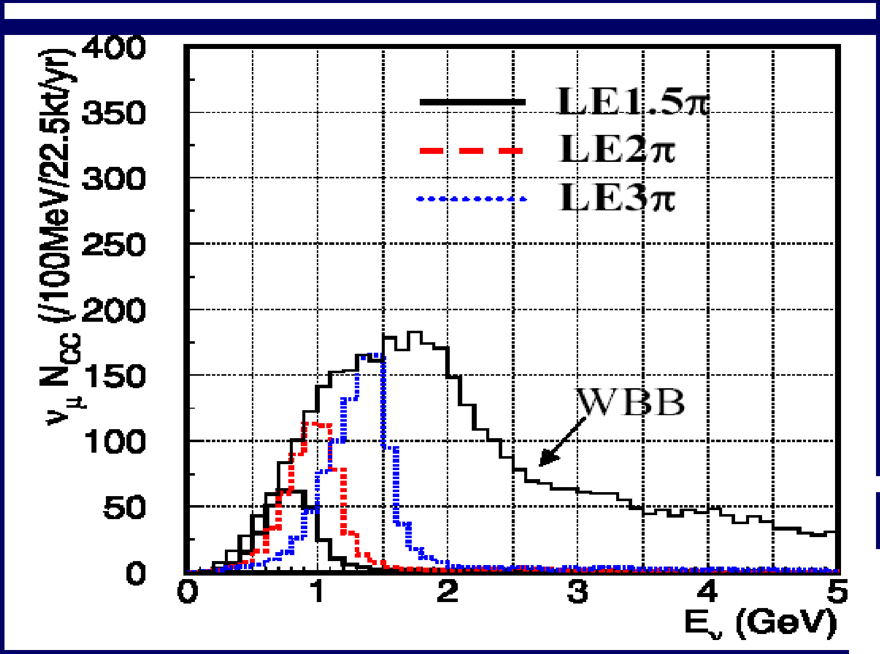


- High intensity, narrow band
- More HE tail than NB beam
- Hard to tune energy

Neutrino beam energy spectra

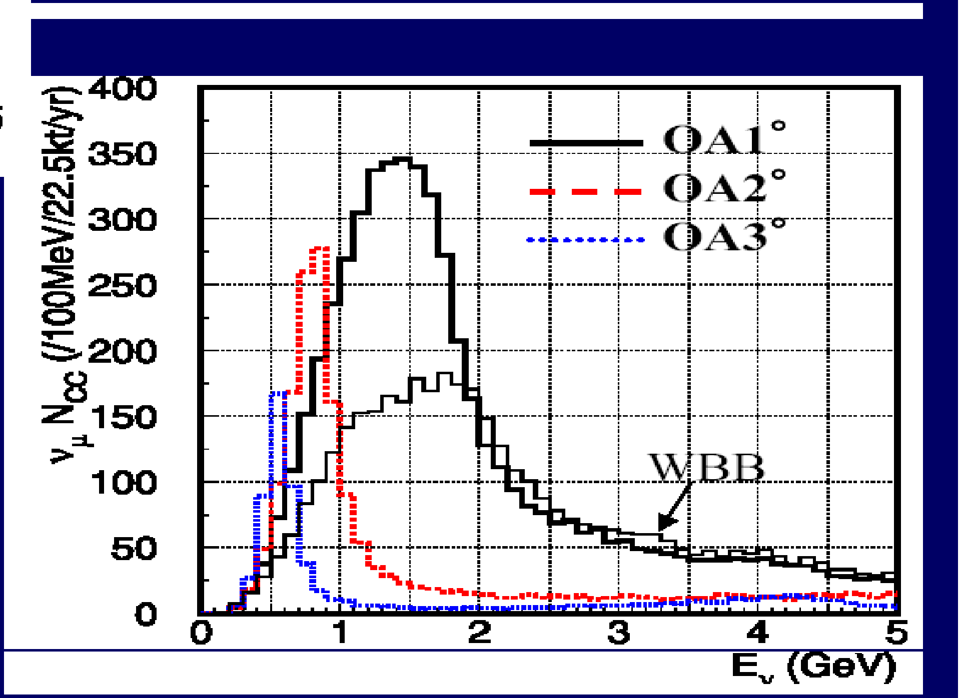


Spectra for narrow band and off-axis options



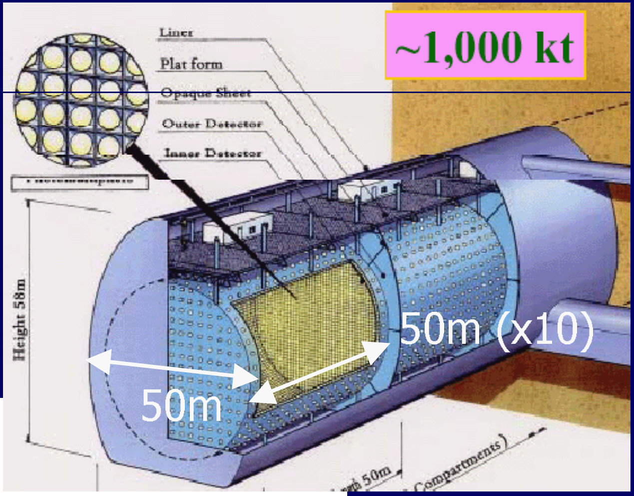
WB vs NB beam spectra

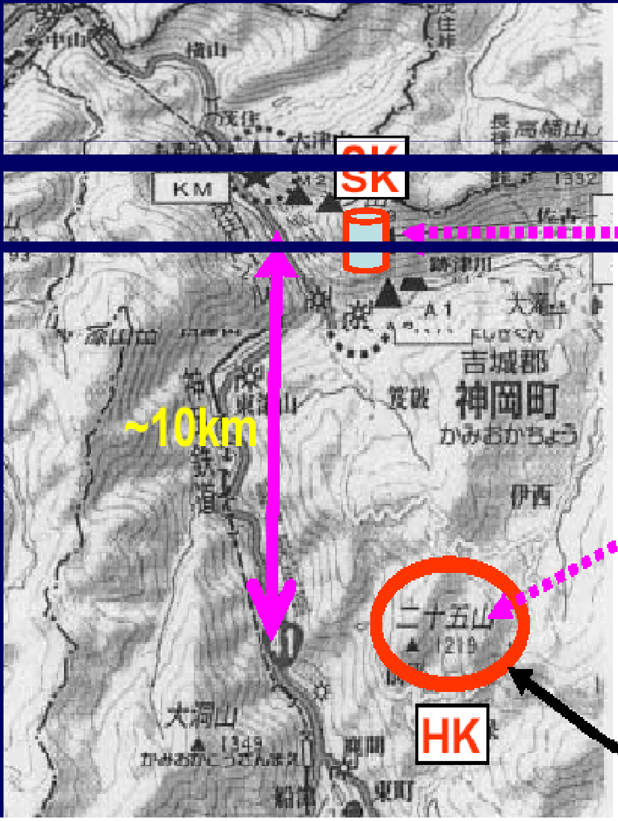
Off-axis beam spectra

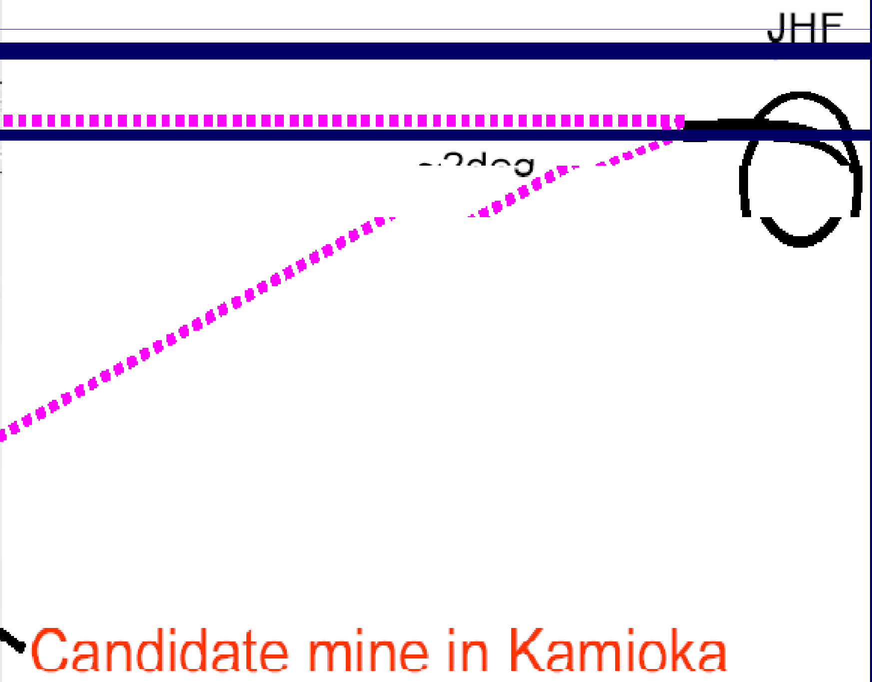


Super-K follow-up: Hyper-K?

- Hyper-Kamiokande = ~1 million tons of water (possibly several tanks)
- A good Hyper-K site is in another mine nearby (same mine company)
- JHF beam must be able to aim at both







Candidate mine in Kamioka

- Atmospheric neutrinos
- Nucleon decay
- LBL experiments

Summary

- Consensus exists that neutrino oscillations explain the long-standing solar neutrino and atmospheric neutrino anomalies
- Super-K made (and will continue to make) essential contributions to our understanding of neutrino oscillations, in addition to nucleon decay and astrophysical studies
- K2K has proven the viability of LBL neutrino experiments
- Additional LBL beam studies are needed to clarify scenarios
- Super-K suffered a disastrous loss of photomultiplier tubes last year
- Thanks to prompt response by Japanese and US agencies, recovery is well underway
  - Expect to be taking data in time for scheduled KEK neutrino beam run in January, 2003
  - Plan to completely restore detector as soon as PMTs can be supplied, certainly in time for 2007 startup of new neutrino beam from JHF
- Plans include possibility that Super-K will be upgraded to Hyper-K still later

Implosion test videos: Bare tubes

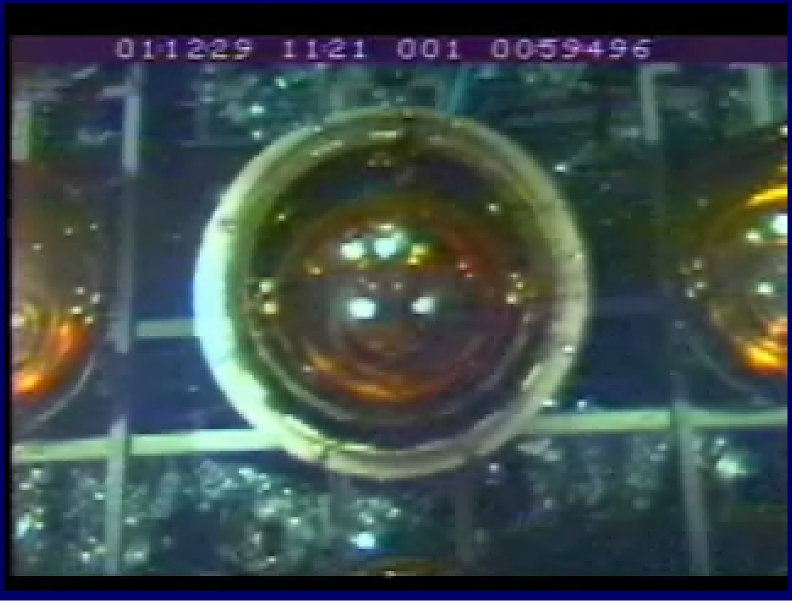
- realtime

- slow motion

Implosion tests: With acrylic shield

- realtime

- slow motion



Selected Super-K/K2K Publications

- Evidence for oscillation of atmospheric neutrinos, Phys.Rev.Lett. 81 (1998) 1562
- Flux and zenith-angle distribution of upward through-going muons, Phys.Rev.Lett. 82 (1999) 2644-2648
- Tau Neutrinos Favored over Sterile Neutrinos in Atmospheric Muon Neutrino Oscillations, Phys.Rev.Lett. 85 (2000) 3999-4003.
- Detection of Accelerator-Produced Neutrinos at a Distance of 250 km, The K2K collaboration, Phys.Lett. B511 (2001) 178-184.
- Constraints on Neutrino Oscillations Using 1258 Days of Super-Kamiokande Solar Neutrino Data, Phys.Rev.Lett. 86 (2001) 8656-8660.

See our website: http://www.phys.washington.edu/~superk/

- For additional details: see papers by M. Smy, M. Shiozawa, and K. Nishikawa at Neutrino 2002