Recent Results from Super-Kamiokande

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INT Workshop on Neutrino Physics
7/27/99

Assume you already know...

SuperK atmospheric neutrino data provide evidence for neutrino oscillations

- Consistent picture from several independent analysis samples
- Inconsistent with standard model expectation at $4\sim8\sigma$ level
- Statistical errors already below systematic errors
- Cannot be explained by systematics
- Independent analyses within SK agree
- See Phys.Rev.Lett. 81 (1998) 1562

Superk-K Publications

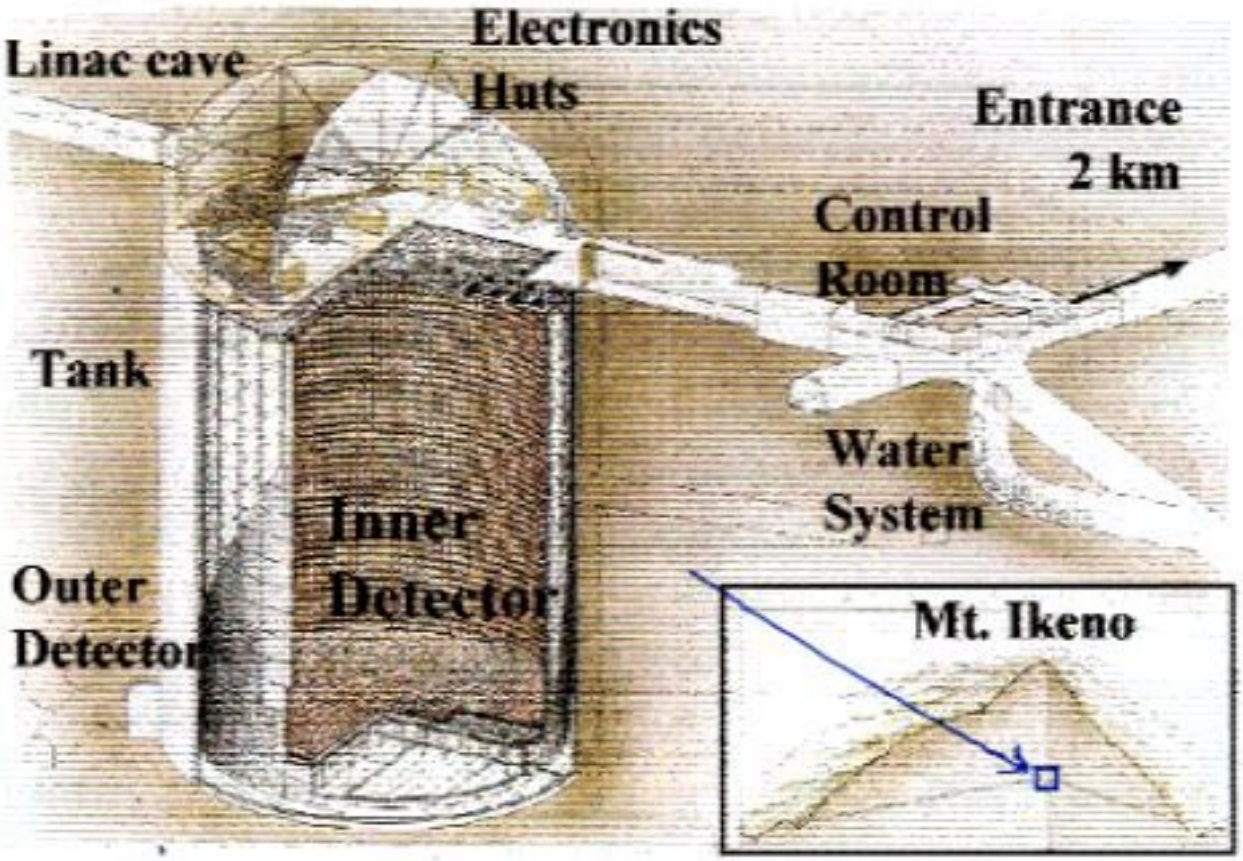
- Measurement of a small atmospheric ν_μ/ν_e ratio, Phys.Lett. B433 (1998) 9
- Study of the atmospheric neutrino flux in the multi-GeV energy range, Phys.Lett. B436 (1998) 33-41.
- Search for Proton Decay via p -> e+ pi0 in a Large Water Cherenkov Detector, Phys.Rev.Lett. 81 (1998) 3319-3323
- Measurements of the Solar Neutrino Flux from Super-Kamiokande's First 300 Days, Phys.Rev.Lett. 81 (1998) 1158-1162; Erratum-ibid. 81 (1998) 4279
- Evidence for oscillation of atmospheric neutrinos, Phys.Rev.Lett. 81 (1998) 1562
- Calibration of Super-Kamiokande Using an Electron Linac, Nucl.Instrum.Meth. A421 (1999) 113-129
- Flux and zenith-angle distribution of upward through-going muons, Phys.Rev.Lett. 82 (1999) 2644-2648
- Constraints on neutrino oscillation parameters from the measurement of day-night solar neutrino fluxes, Phys.Rev.Lett. 82 (1999) 1810-1814.
- Measurement of the solar neutrino energy spectrum using neutrino-electron scattering, Phys.Rev.Lett. 82 (1999) 2430-2434.
- Observation of the E-W anisotropy of the atmospheric neutrino flux, Phys.Rev.Lett. 82 (1999) 5194-5197.

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

Super-Kamiokande

- In Mozumi mine of Kamioka Mining Co.
- 1000 m rock (2,700 mwe) overburden
- Easy, continuous access for equipment and personnel via horizontal car tunnel
- Computer and dormitory facilities in Higashi-Mozumi village (10 min drive)

The Super-Kamiokande Detector



50,000 tonne water Cherenkov detector

ID: 11,146 50cm PMTs, non-reflective liner

OD: 1,885 20cm PMTs + wavelength shifters, reflective liner

Commissioned 4/1/96,

Taking data continuously since 5/31/96 with >500 days livetime

livetime efficiency 85% overall

now running >95%

Guide Bleu to SuperK data

*** Published results

Final approval by collaboration*

**translation*: those who bothered to download and read the paper draft...

** Official Plots

Preliminary approval by collaboration*, for use by any member

**trans*: those who were still awake when shown at the collaboration meeting...

- Usually (but not always) marked "preliminary".
- Subject to change before publication.
- Updated every collaboration meeting (twice/yr).

* "Very Preliminary" / Experts Only

Preliminary approval by collaboration, but only for use by experts in analysis subgroup*

**trans*: nobody else understands them...

Superk-K Publications

- Measurement of a small atmospheric ν_μ/ν_e ratio, Phys.Lett. B433 (1998) 9
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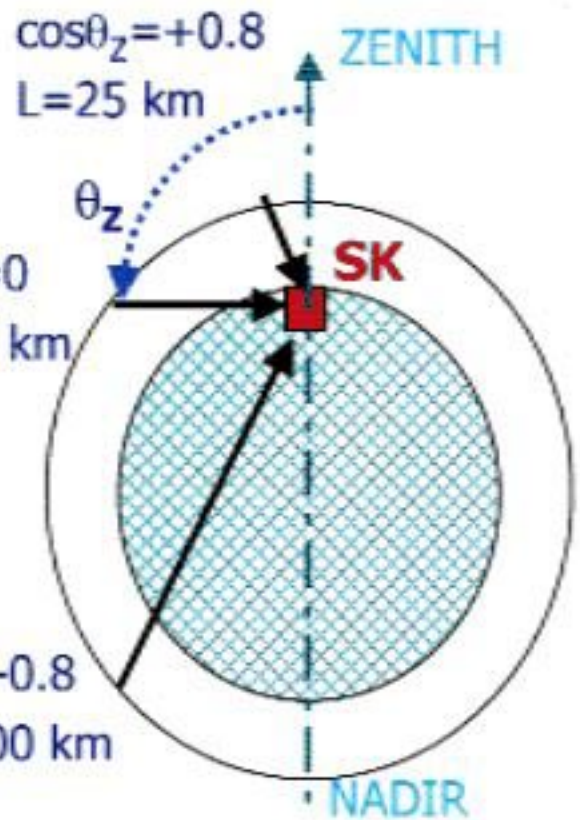
Atmospheric Neutrinos

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

  (cosmic ray)+(air nucleus) $\rightarrow \pi, K \rightarrow \nu$

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

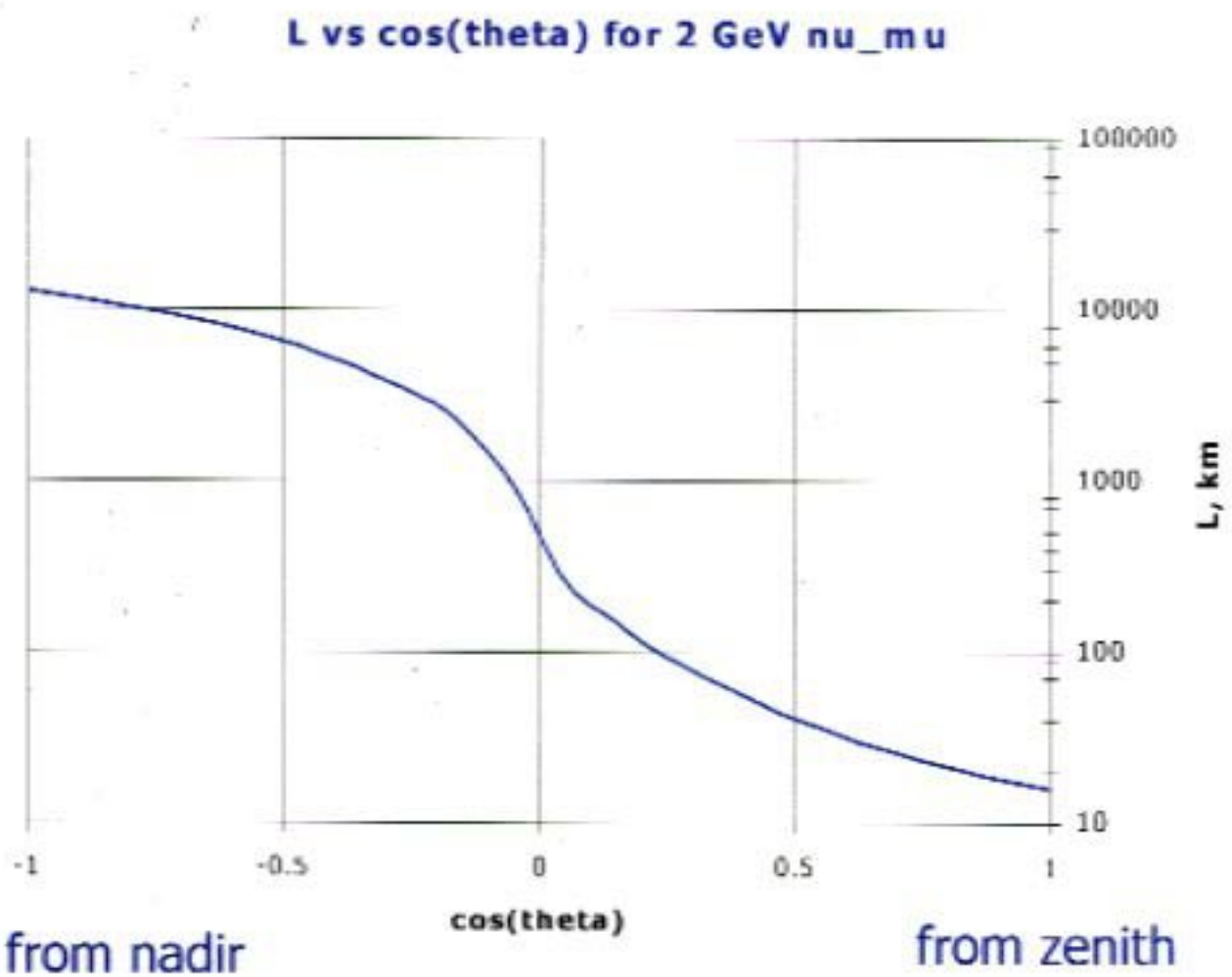
- Energy
  100 MeV $\rightarrow$
  ~100 GeV



Can't be solar:
E_{SOLAR}~20 MeV max

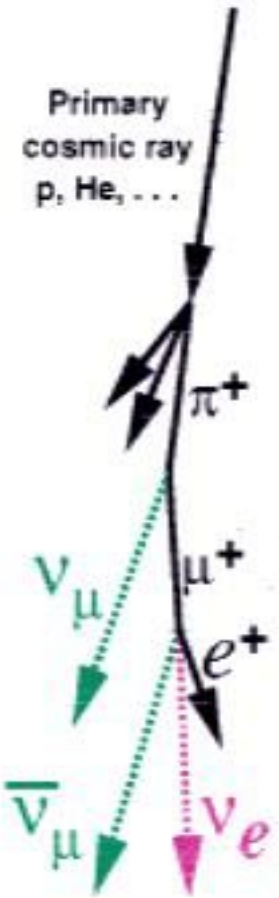
Can't be astrophysical:
flux << atmospheric ν
below ~10 TeV

L vs $\cos\theta_z$

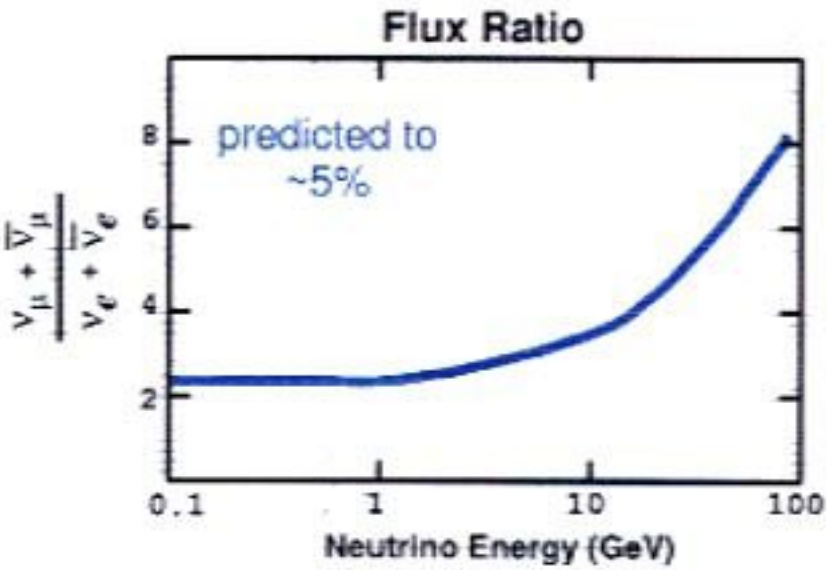


from nadir

from zenith



μ/e Double Ratio



$$R = \frac{(N\mu/Ne)_{DATA}}{(N\mu/Ne)_{M.C.}}$$

$$R(\text{sub-GeV}) = \frac{1852/1826}{2617.6/1754} = 0.68 \pm 0.02 \pm 0.05$$

$$R(\text{multi-GeV}) = \frac{821/439}{1143.4/414.3} = 0.68 \pm 0.04 \pm 0.08$$

52.3 kton-yrs, 40 yr M.C., Super-K preliminary

Possible explanation: Neutrino Oscillations

For, e.g, simple case of 2 neutrino generations with mixing angle θ:

ν_α , ν_β = observable states

ν_1 , ν_2 = mass eigenstates

$\nu_\alpha = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$

$\nu_\beta = -\sin\theta\ \nu_1 + \cos\theta\ \nu_2$

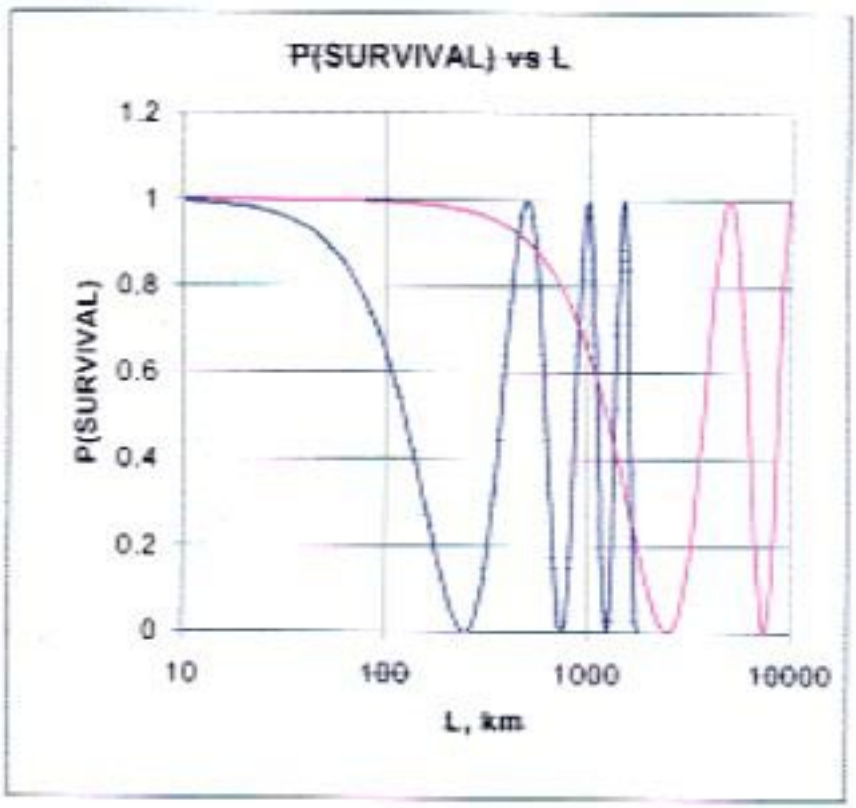
Probability of oscillation:

$P(L/E) = \sin^2 2\theta \sin^2(1.267 \Delta m^2 L/E)$

L= distance in km,

Δm^2 in eV^2,

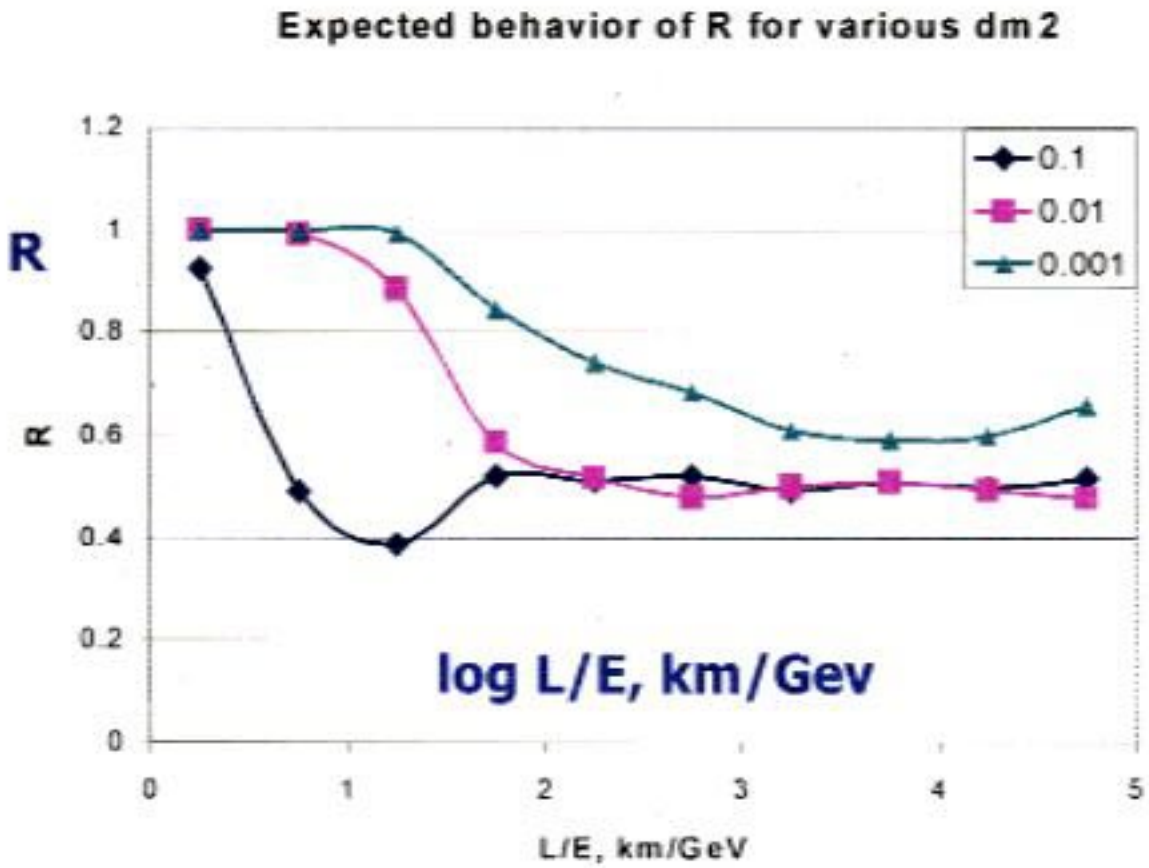
E_ν in GeV



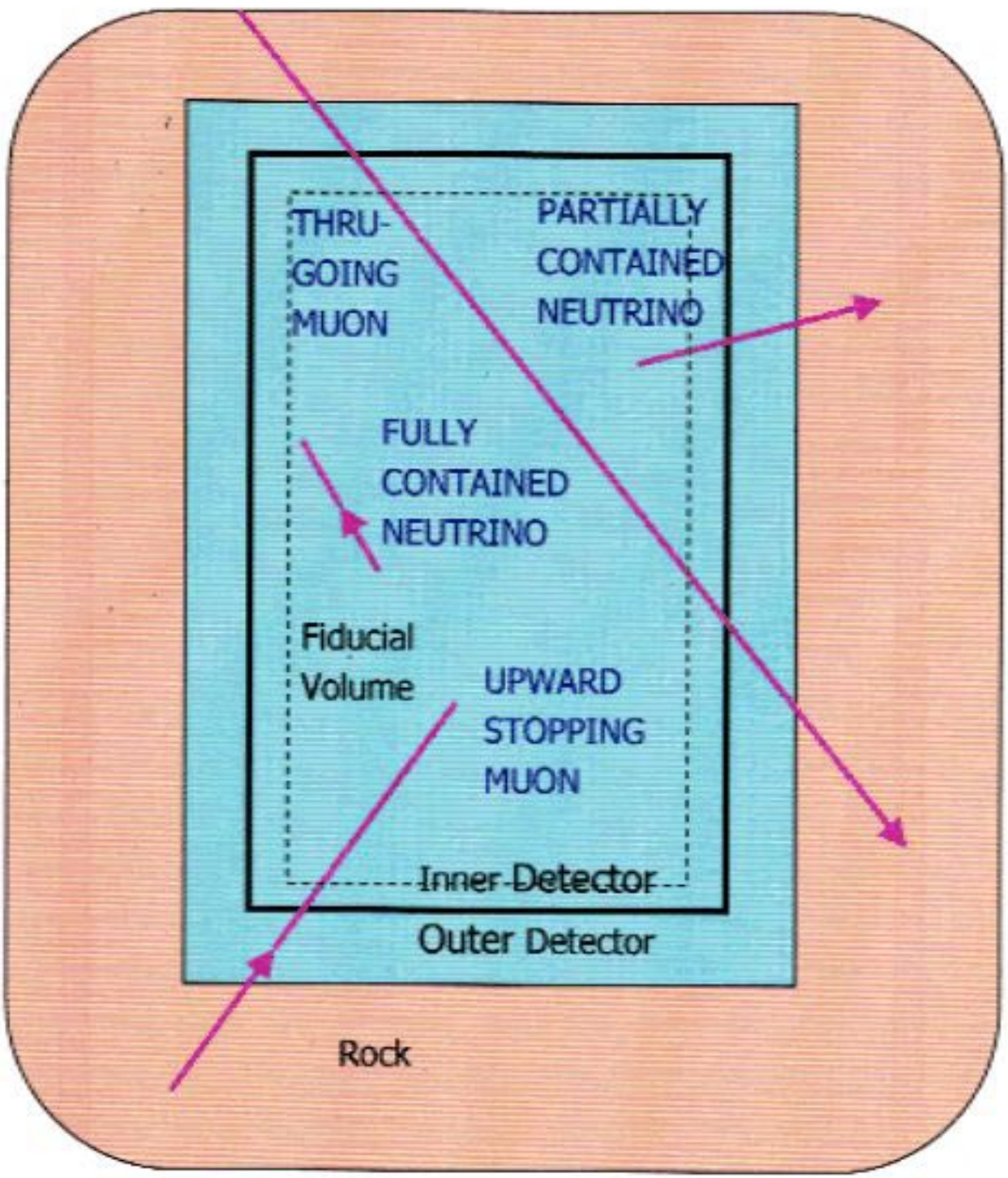
L/E distributions

Expected behavior of R for several Δm^2 values ($\sin^2(\theta)=1$):

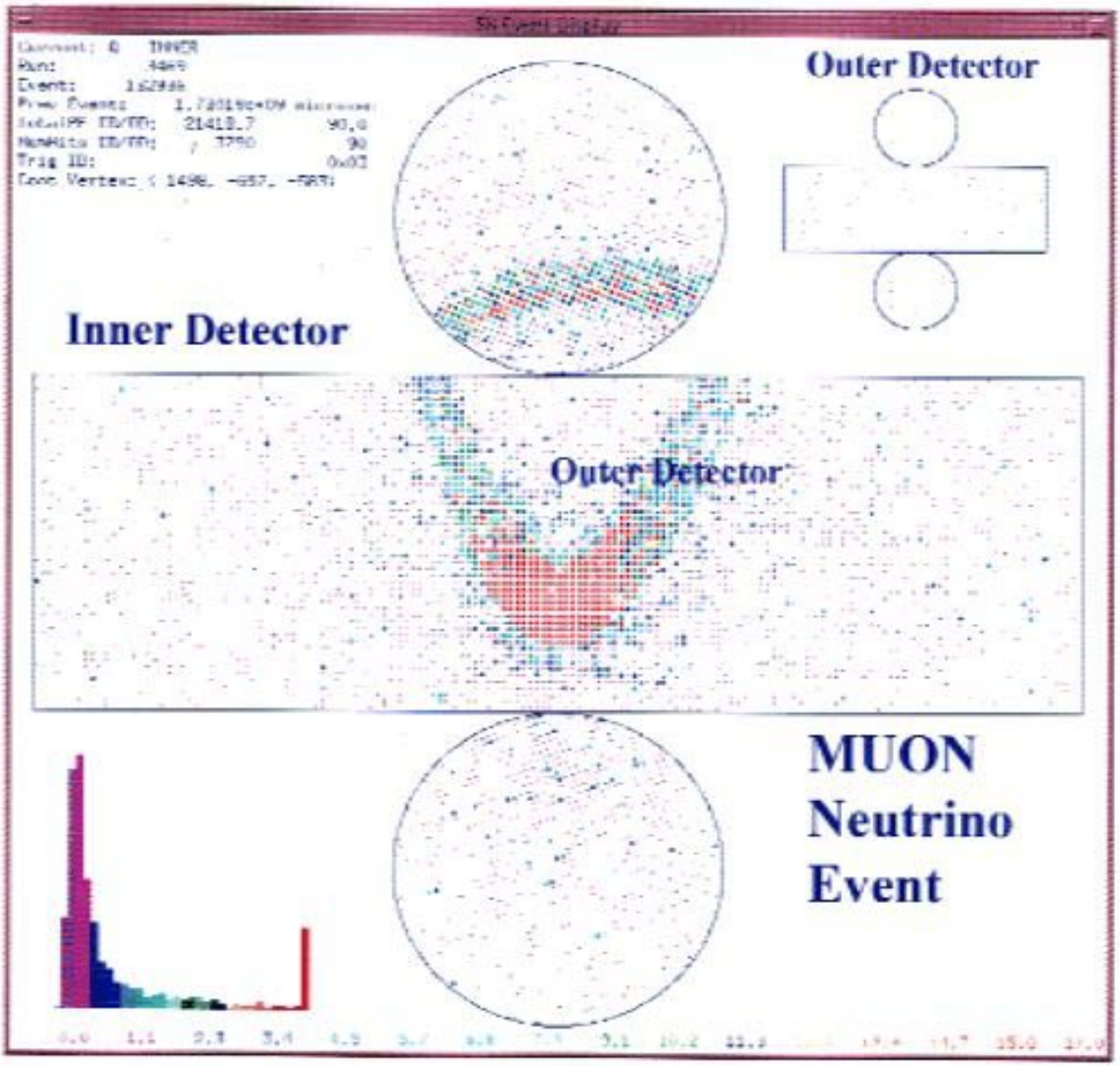
our angular resolution smears oscillations



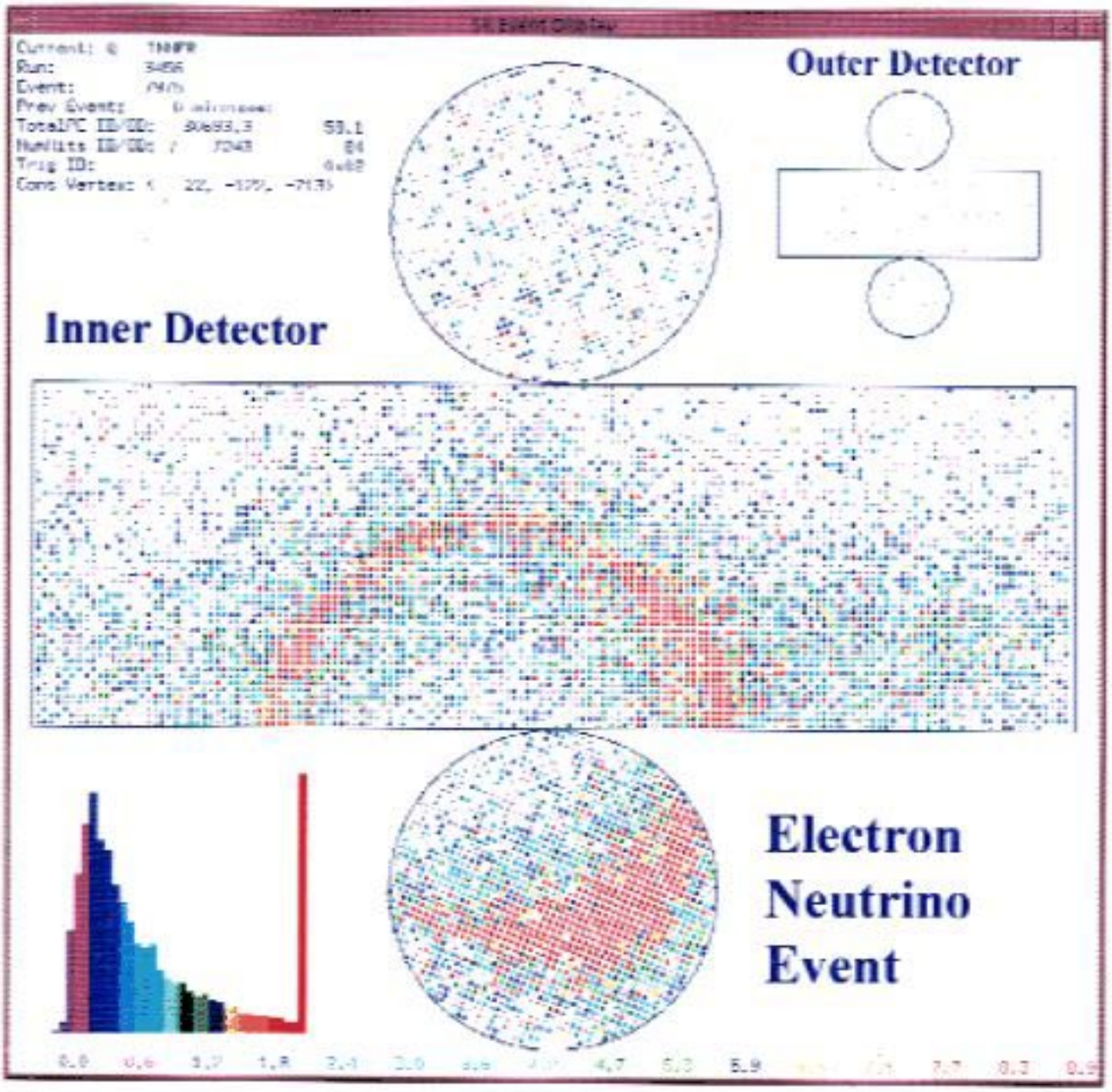
Super-K Event Types



Event Types: ν_μ

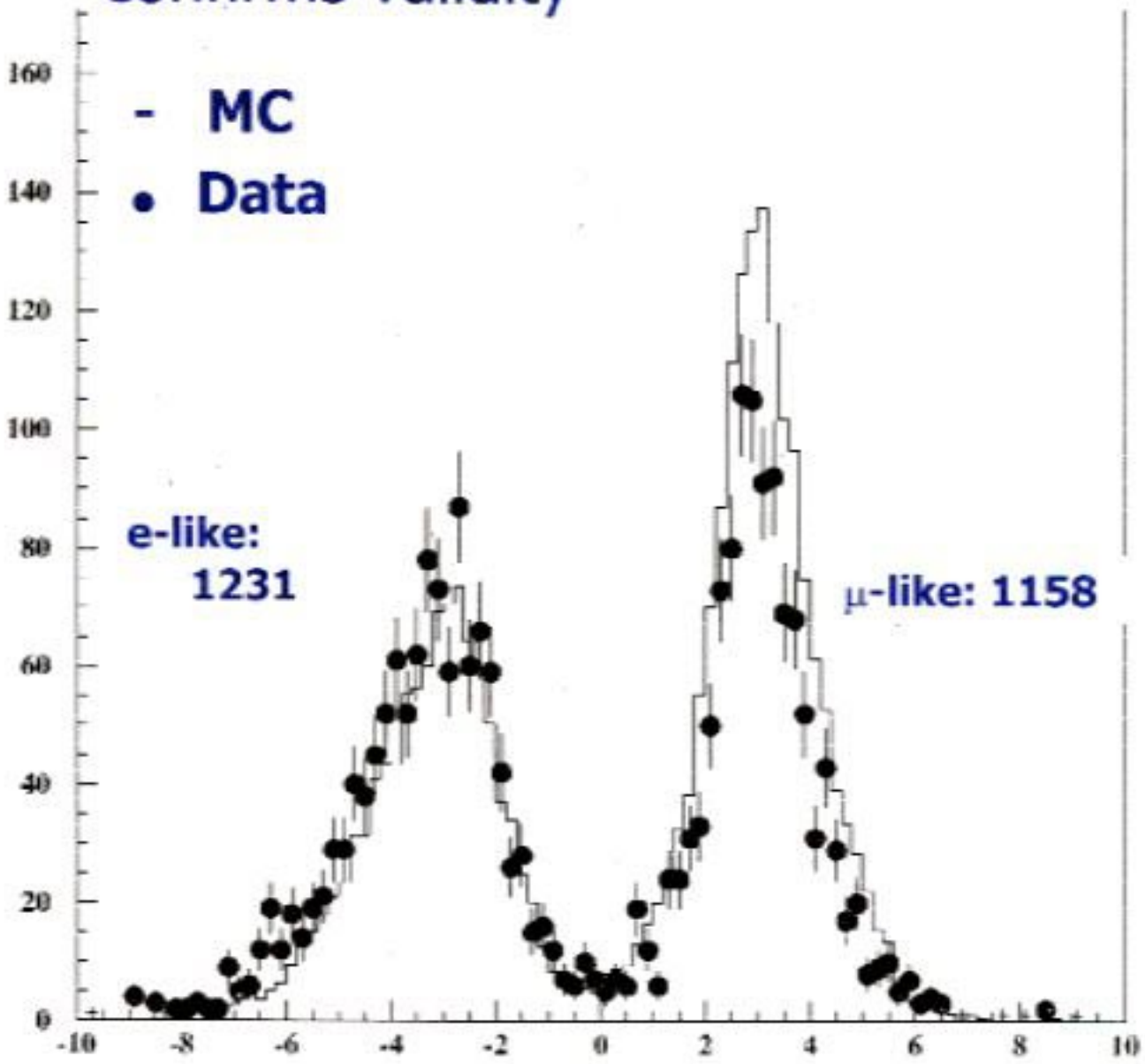


Event Types: ν_e



ν_μ/ν_e Particle Id (PID)

- Likelihood ratio parameter
- KEK beam test expt (E261A) confirms validity



PID likelihood, Sub-GeV, 1-ring event

Data reduction

- Simple online trigger
- Offline (realtime) reduction
  - thresholds, time windows
  - Super-Low-E (4.6 MeV)
- Offline analysis
  - clustering in time and position, Cherenkov ring fits, track fits, scanning (now minimal)
- Results (for each ring):
  - μ or e (PID)
  - estimates of E_ν
  - vertex position
  - lepton direction

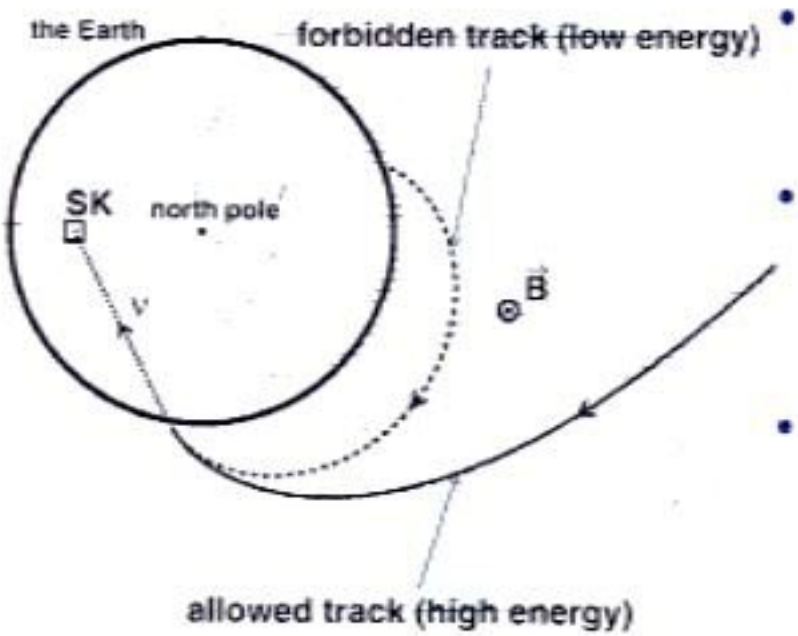
Data analysis

- Two independent subgroups reduced and analyzed first 300 days of data
  - Results were equivalent within errors
- Monte Carlo simulation provides expected distribution for no-oscillations
  - Integrates all detector effects and systematic errors
- Oscillations analysis: On a grid of $\{\Delta m^2, \sin^2(2\theta)\}$ values:
  - Find L/E for each MC event
  - Weight each event by $P_{osc}(L/E)$ to to produce "oscillated" MC
  - Find probability that data and MC_{osc} are consistent using standard statistical tests

Systematic Errors

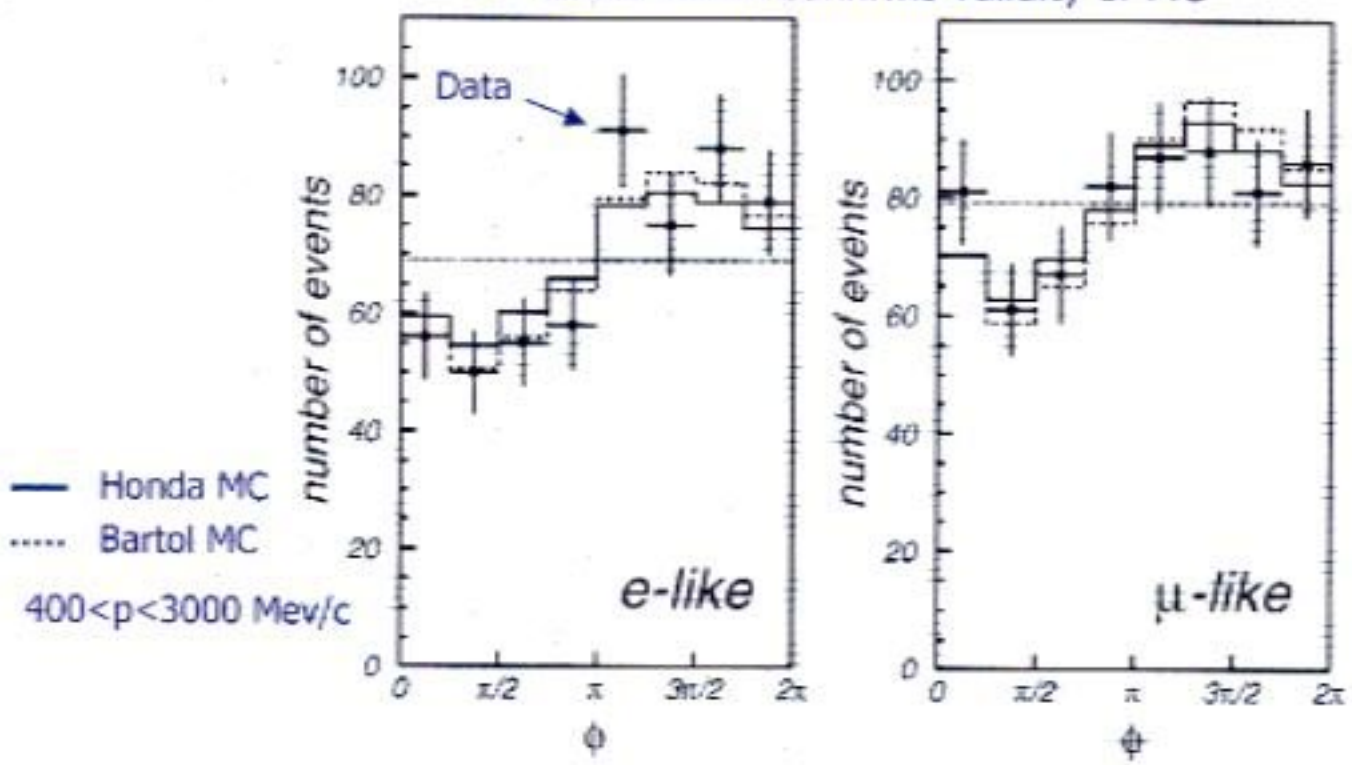
	Sub−GeV cut $P_e > 100$ MeV/c $P_\mu > 200$ MeV/c Evis < 1.33 GeV	Multi−GeV FC+PC
reduction	<< 1%	3%
$(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$	< 5%	< 5%
$E^{-\gamma}$	0.6%	1.6%
μ/e separation	2%	3%
1ring/2ring separation	3%	6%
vertex position	0.6%	2.4%
energy calibration	1.0%	4.1%
non neutrino back ground		
flasher	< 0.5%	<< 0.5%
cosmic μ	< 0.1%	1%
e−like background	< 0.1%	< 0.2%
CC cross section	3.5%	4.3%
NC cross section	3%	4%
hadron simulator	0.5%	1%
FC/PC separation	< 0.1%	0.5%
Total systematic error	7.8%	11.8%
M.C. statistics	1.5%	2.9%

East-West Effect



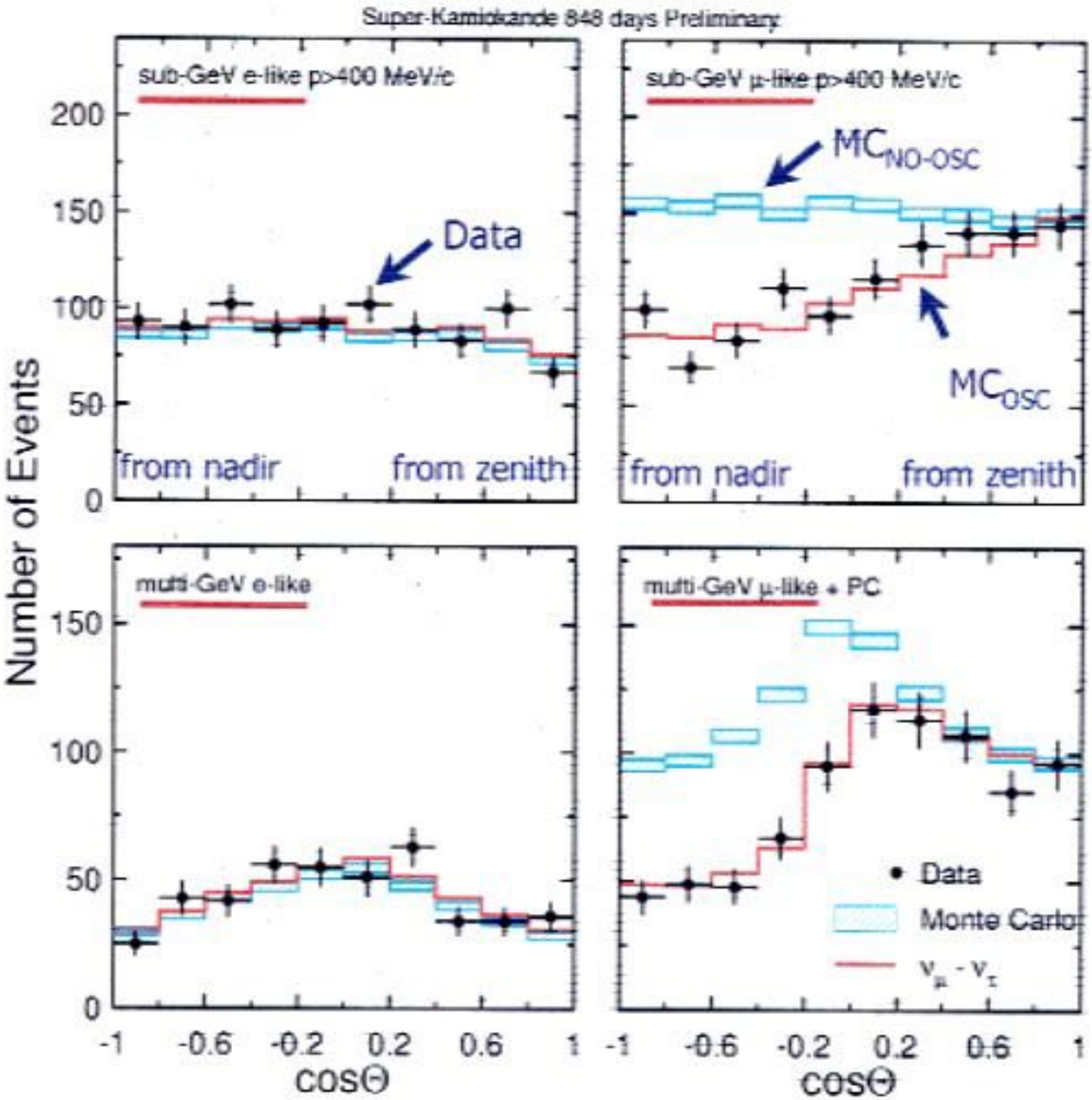
- Particles below cutoff energy cannot reach atmosphere from space
- Parent cosmic rays have + charge, so cutoff energy differs for arrival from E or W
- Cutoff energy depends upon geomagnetic latitude

- Observation confirms validity of MC



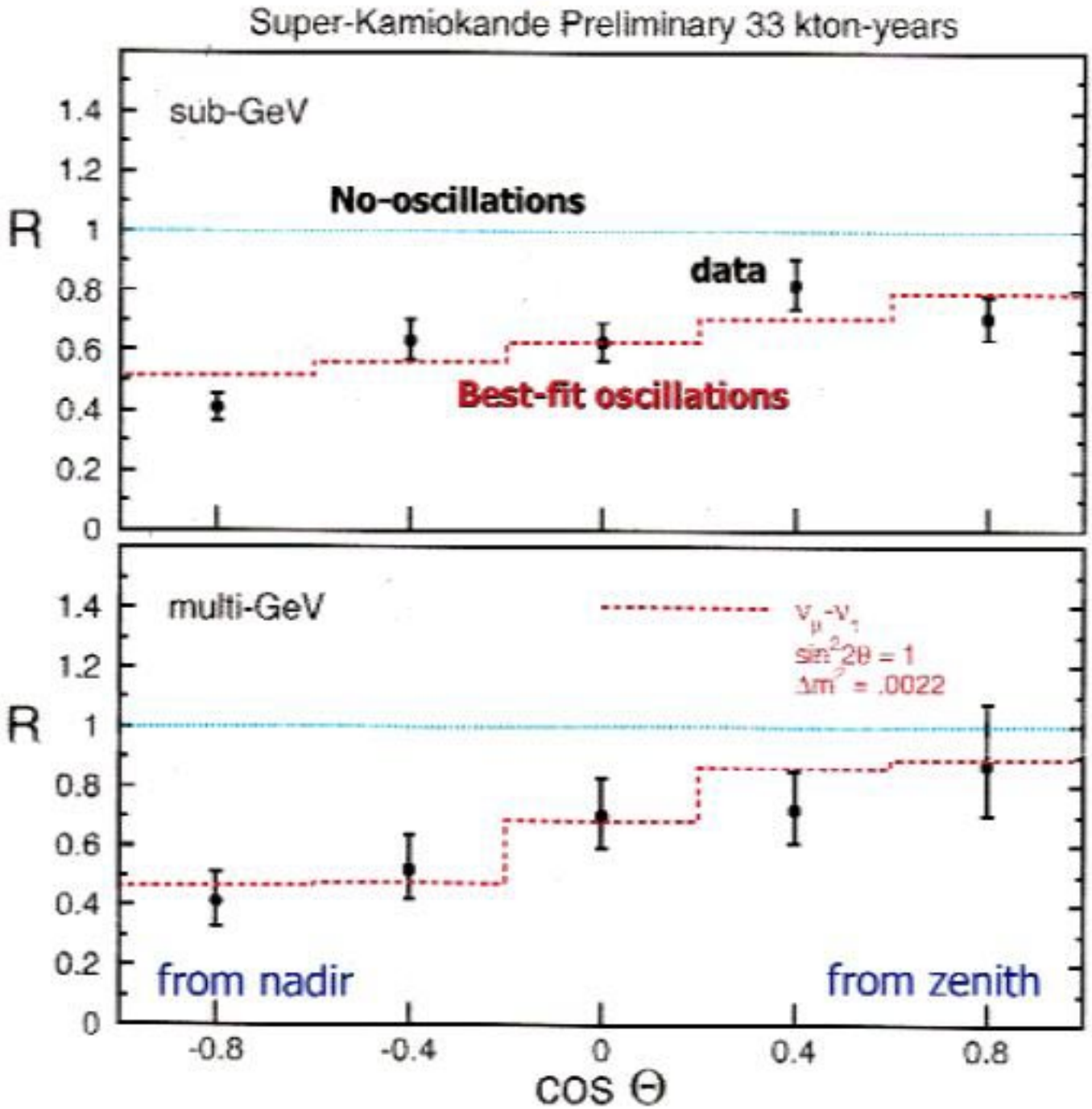
Zenith angle distributions

Data (+), MC_{OSC} (-), $MC_{NO\text{-}OSC}$(---)

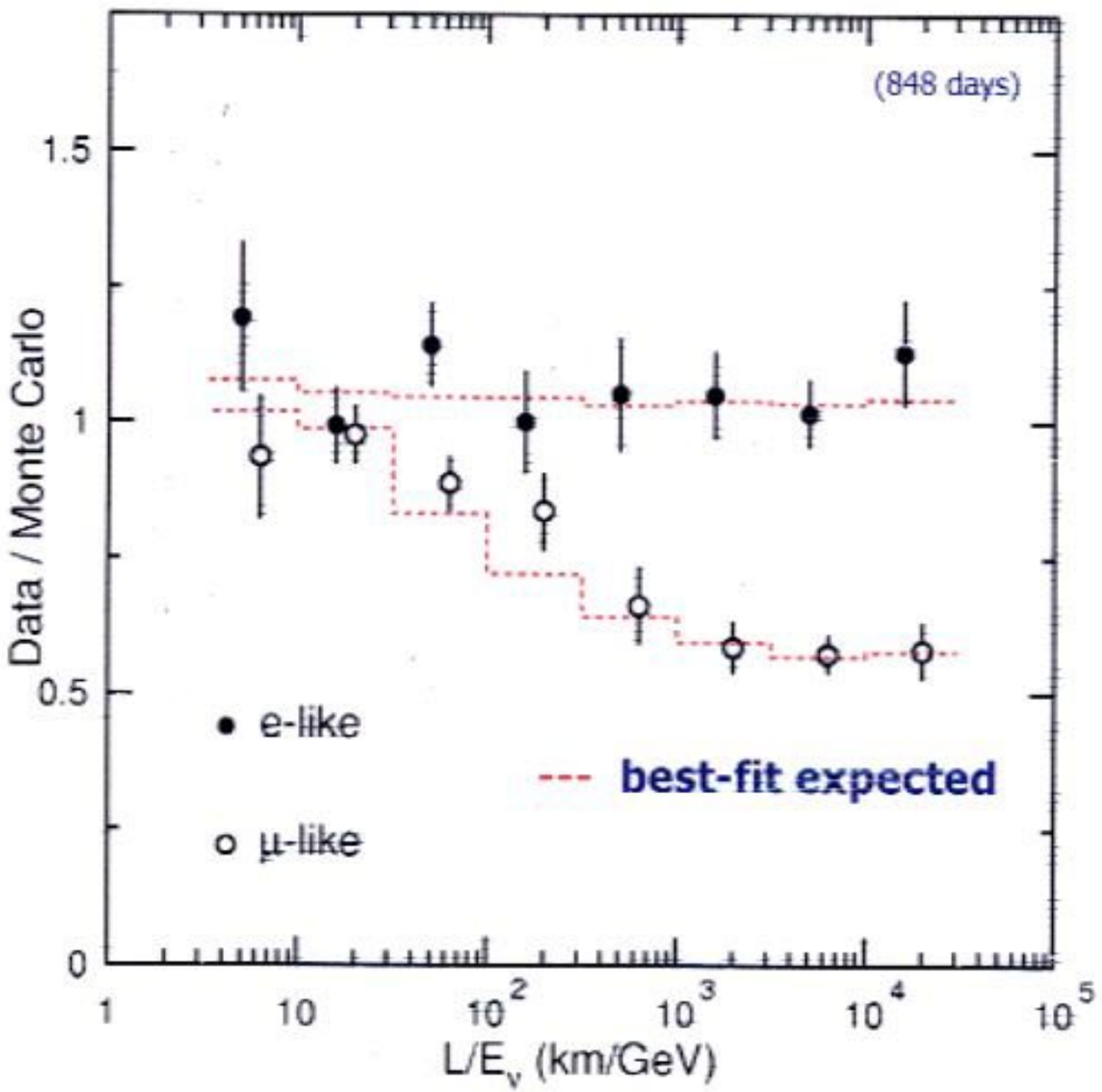


$R = (\mu/e)_{DATA} / (\mu/e)_{MC}$

... vs zenith angle



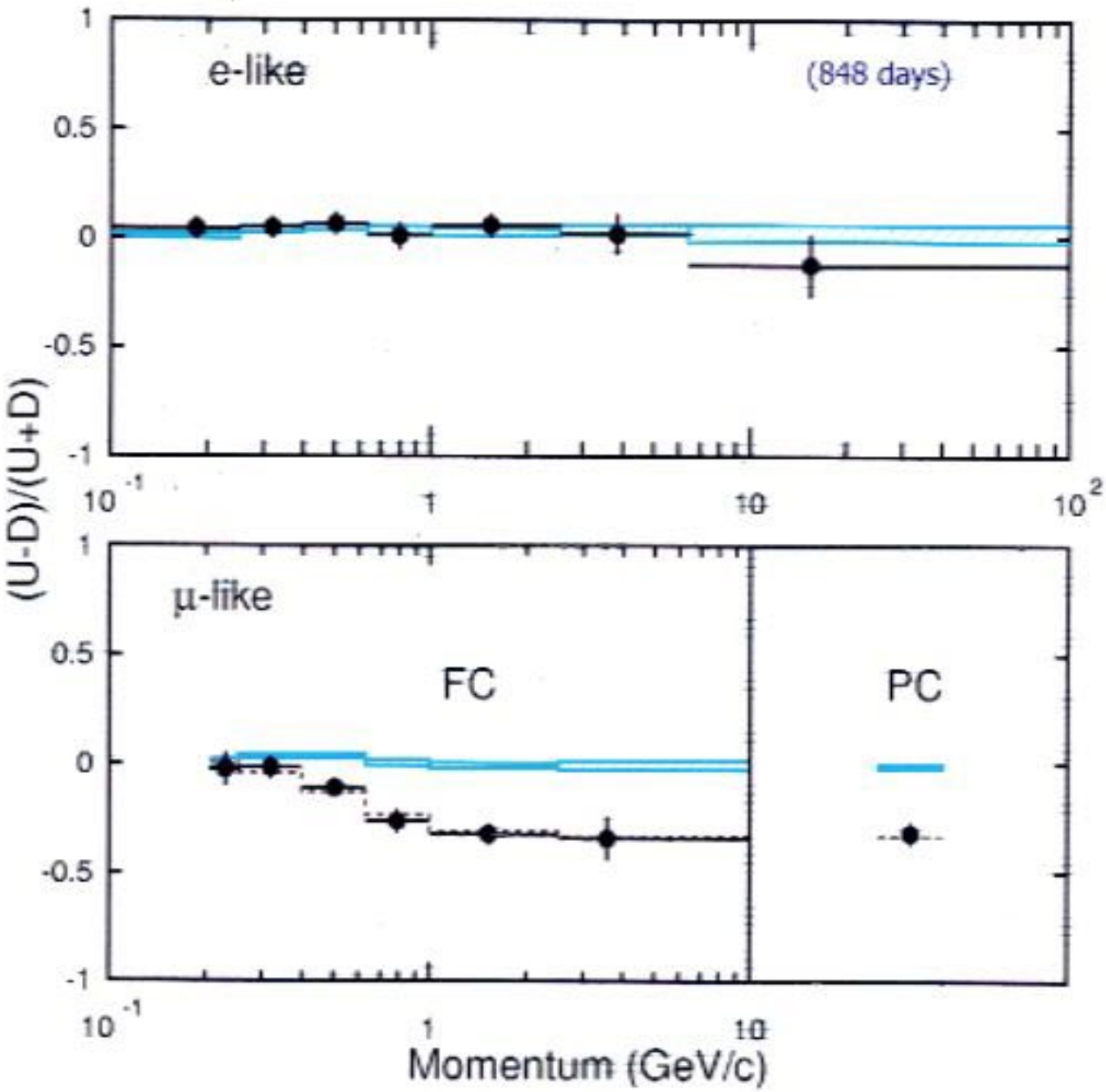
Data/MC vs L/E


(848 days)
1.5
1
0.5
0
Data / Monte Carlo
1
10
10^2
10^3
10^4
10^5
L/E_ν (km/GeV)
e-like
μ-like
best-fit expected

Up/Down Asymmetry

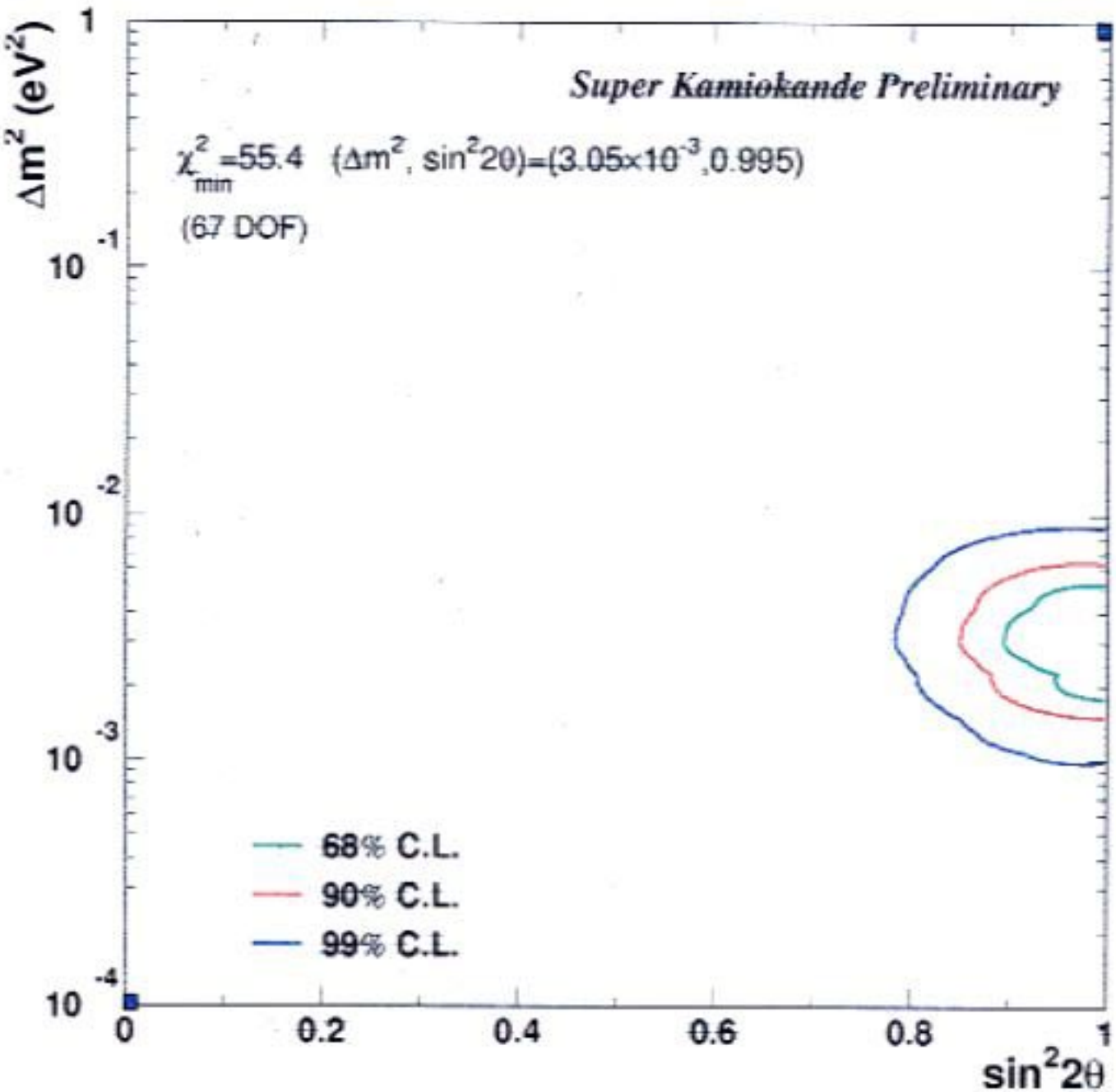
$A = (U-D) / (U+D)$ vs p_{lepton}

Expect $A = 0 (\pm 0.02)$ for no oscillations



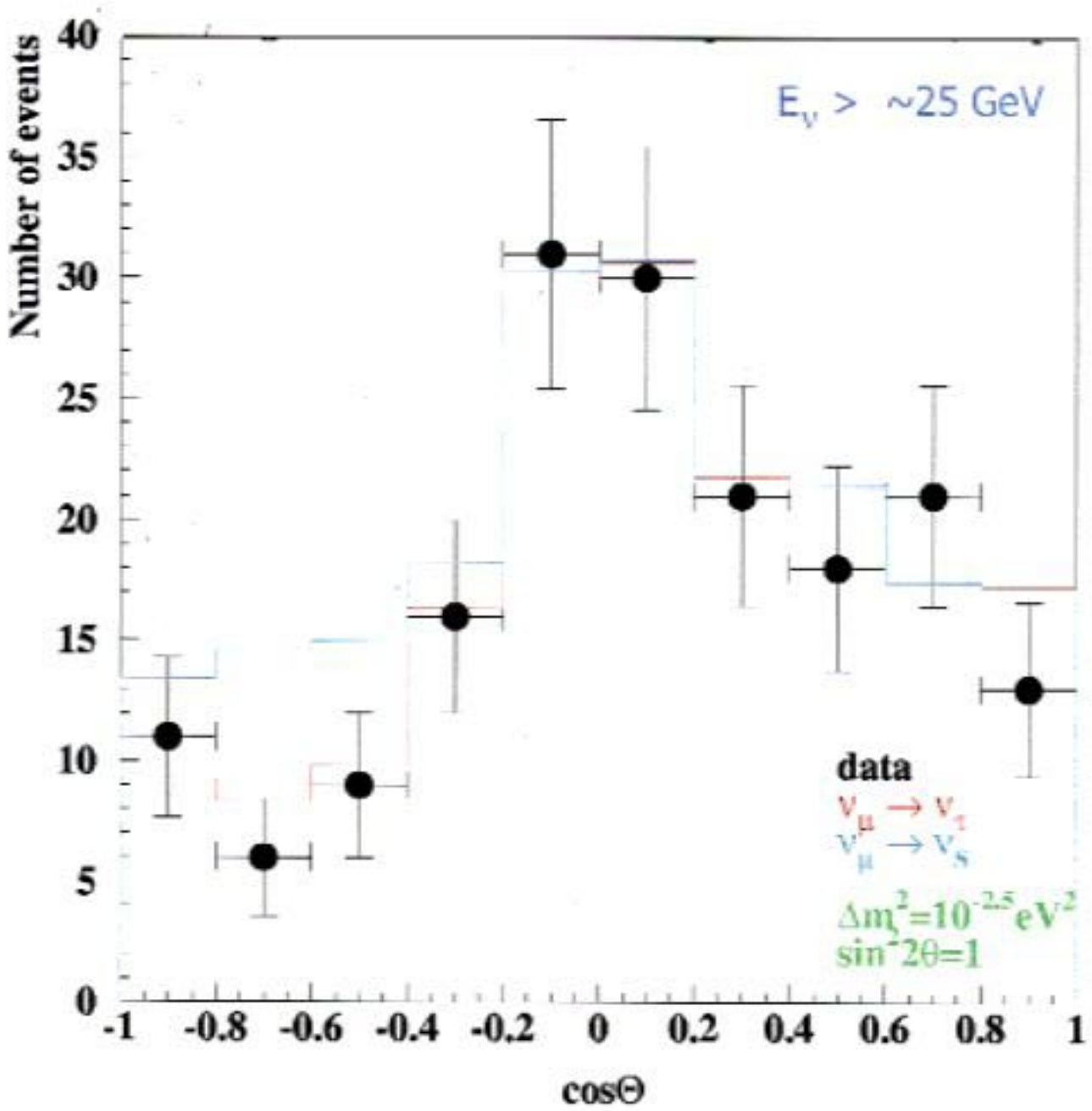
Allowed region for atmospheric neutrino data

Fully-contained + partially contained events



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

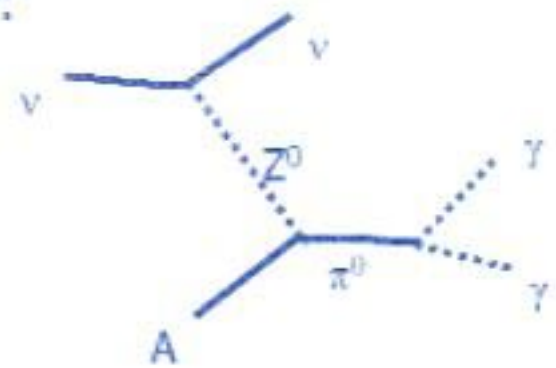
- High energy sample (partially contained and upward-muon) analysis disfavors ν_s



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

- Single-π^0 event analysis disfavors ν_s

  Neutral current (NC) interactions can produce a single π^0 -- identify by:
  - 2 rings
  - both rings e-like
  - no μ decay
  - E_{VIS}=90~190 MeV



- Events with a single π^0 are 80% NC interactions
- Full $\nu_\mu \leftrightarrow \nu_S$ mixing reduces NC by ~25%

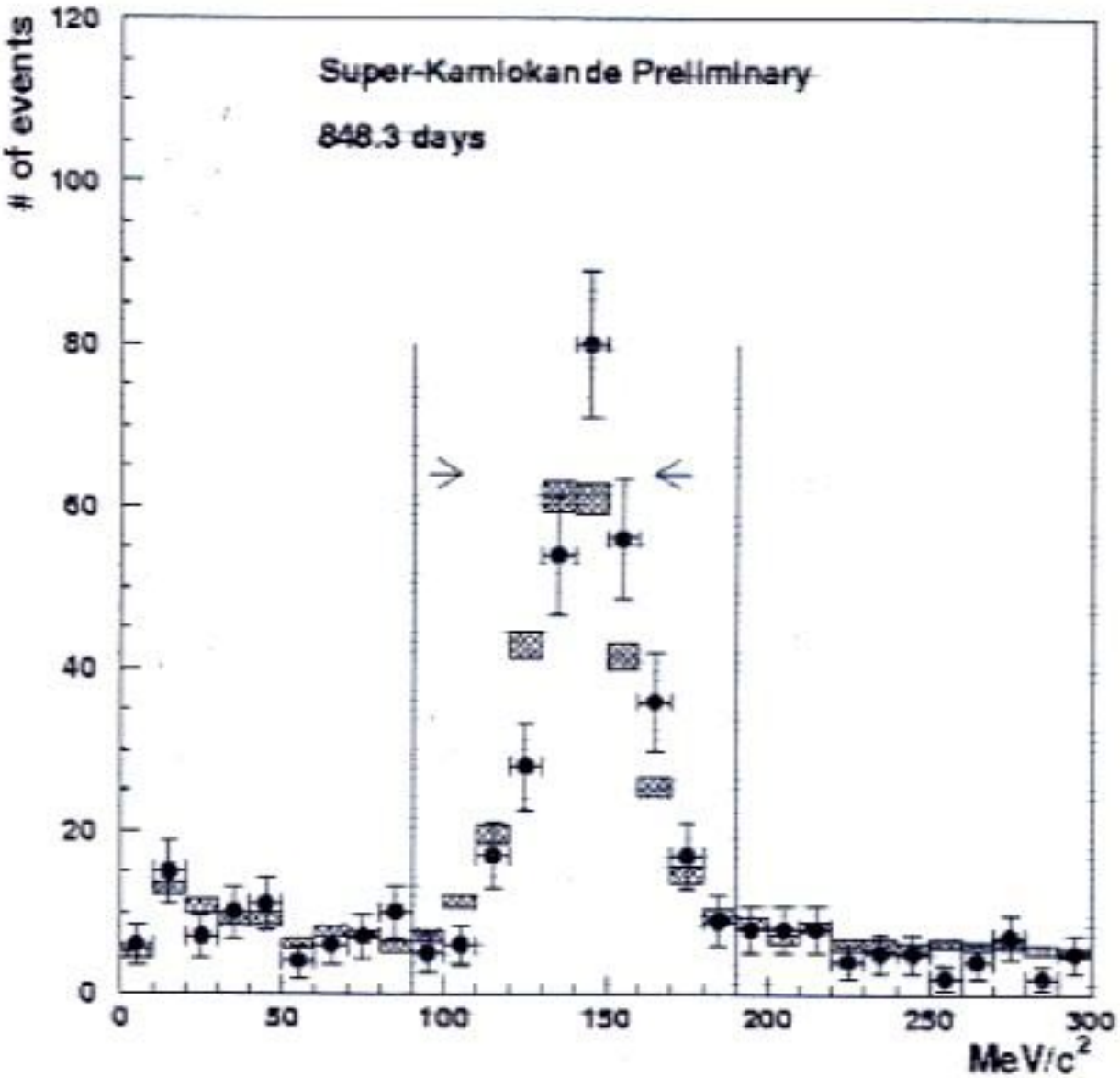
  expect reduced numbers of π^0 events
- Ratio of π^0 / e-like events:

  $(\pi^0/\text{e-like})_{DATA} / (\pi^0/\text{e-like})_{MC} = 260.8 / 225.5$

  $= 1.11 \pm 0.06 \pm 0.02 \pm 0.25$

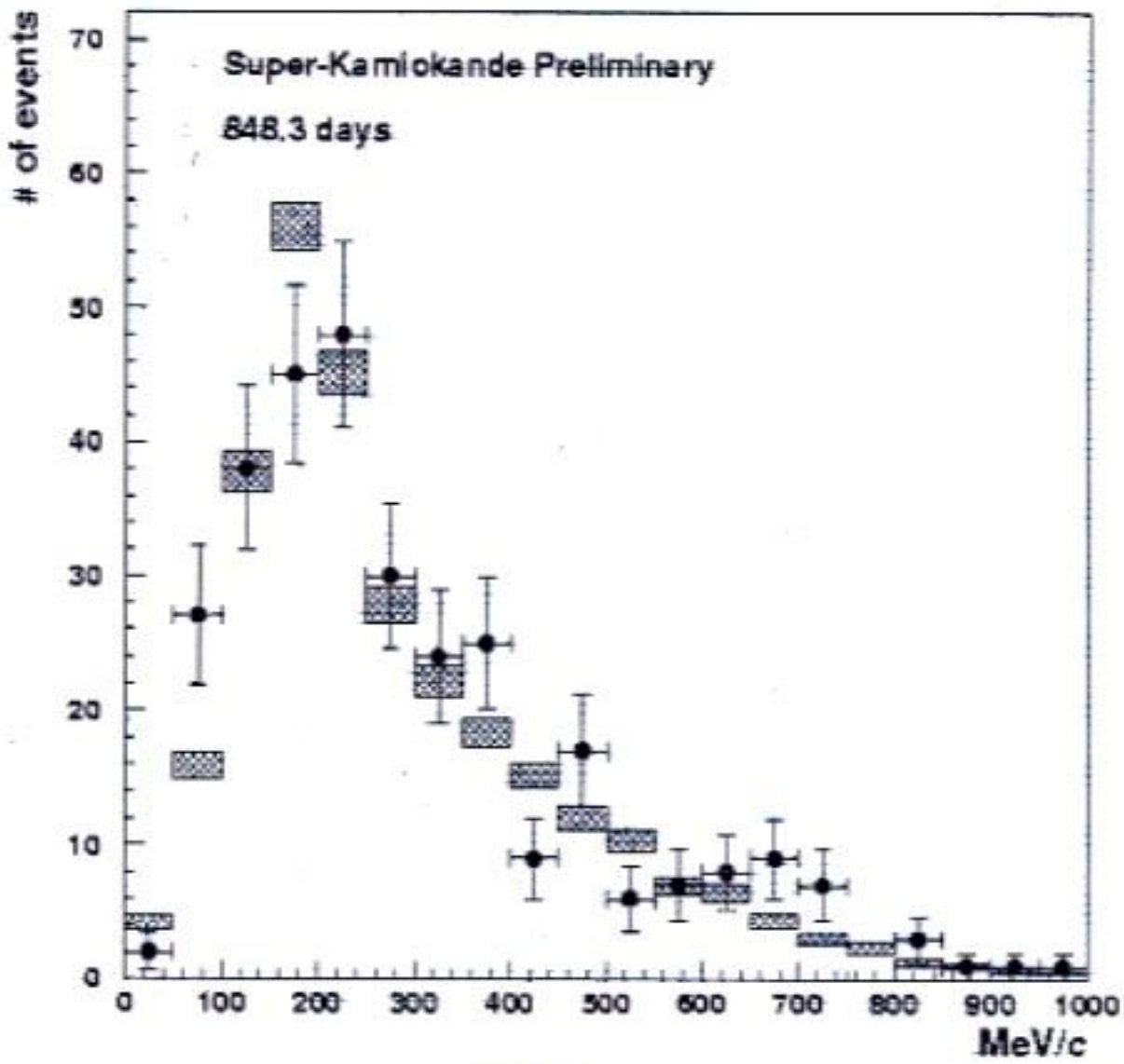
  (data stat) (MC stat) (syst. + theory)
- Not conclusive, but not favored

Reconstructed π^0 Mass



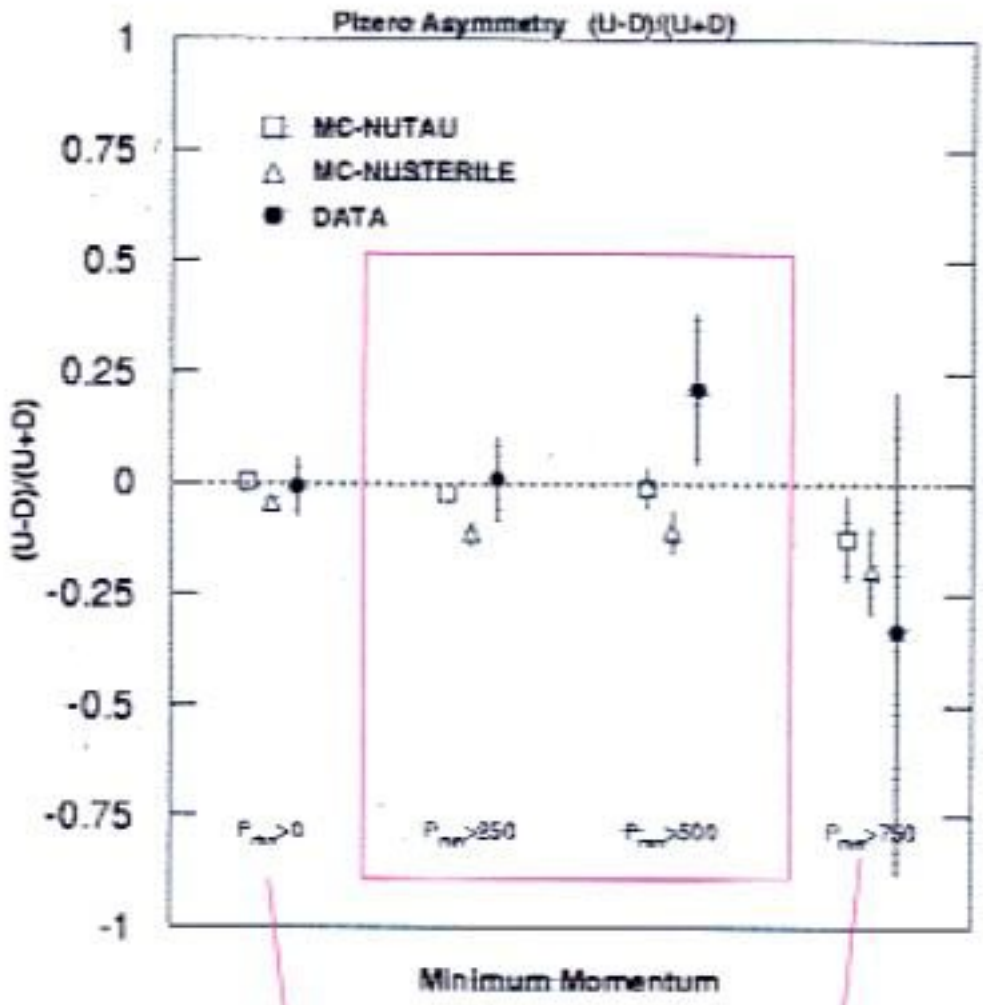
$M_{\gamma\gamma}$

Reconstructed π^0 Momentum



p_{π^0}

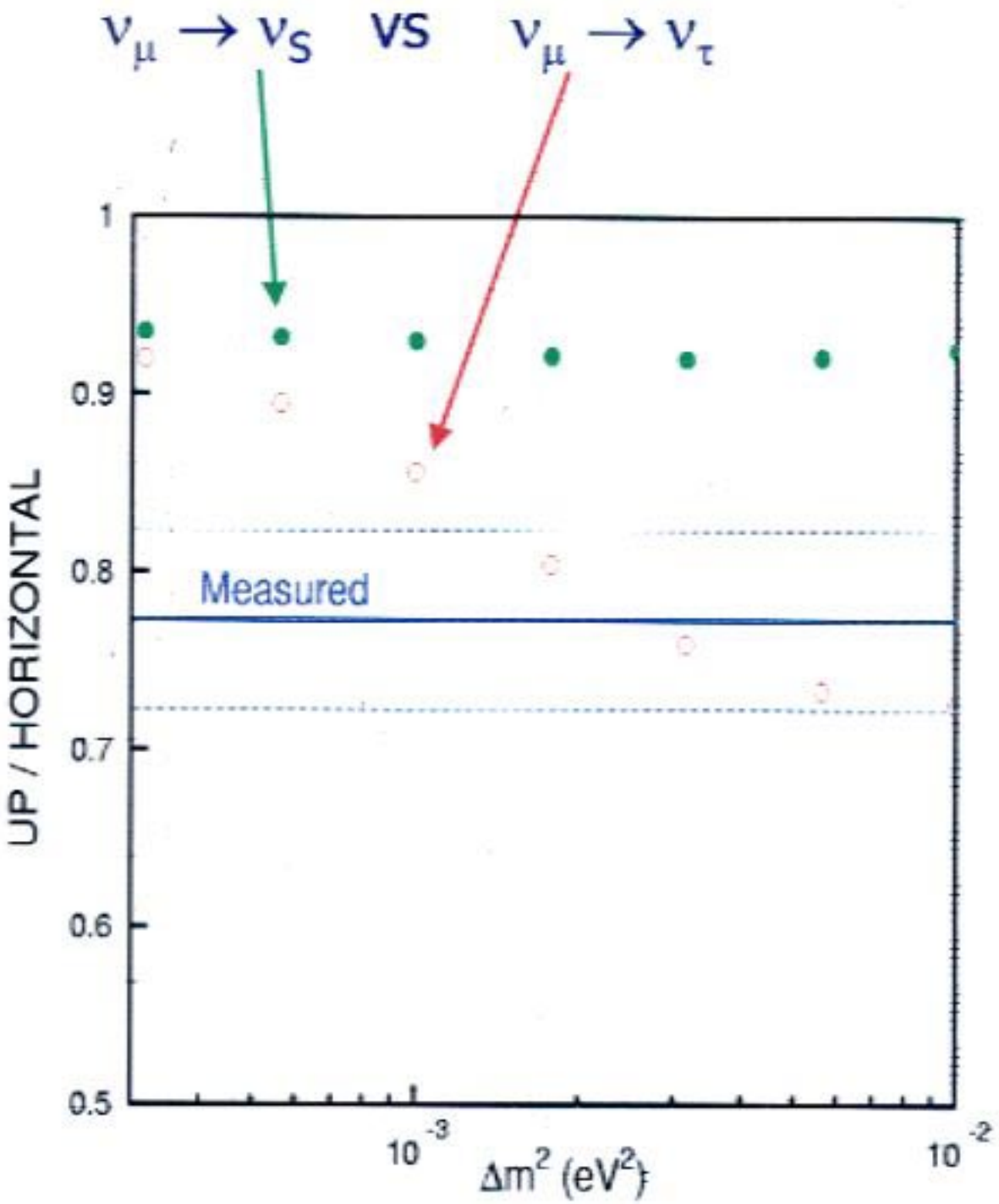
π^0 Up/Down Asymmetry



Poor statistics bin

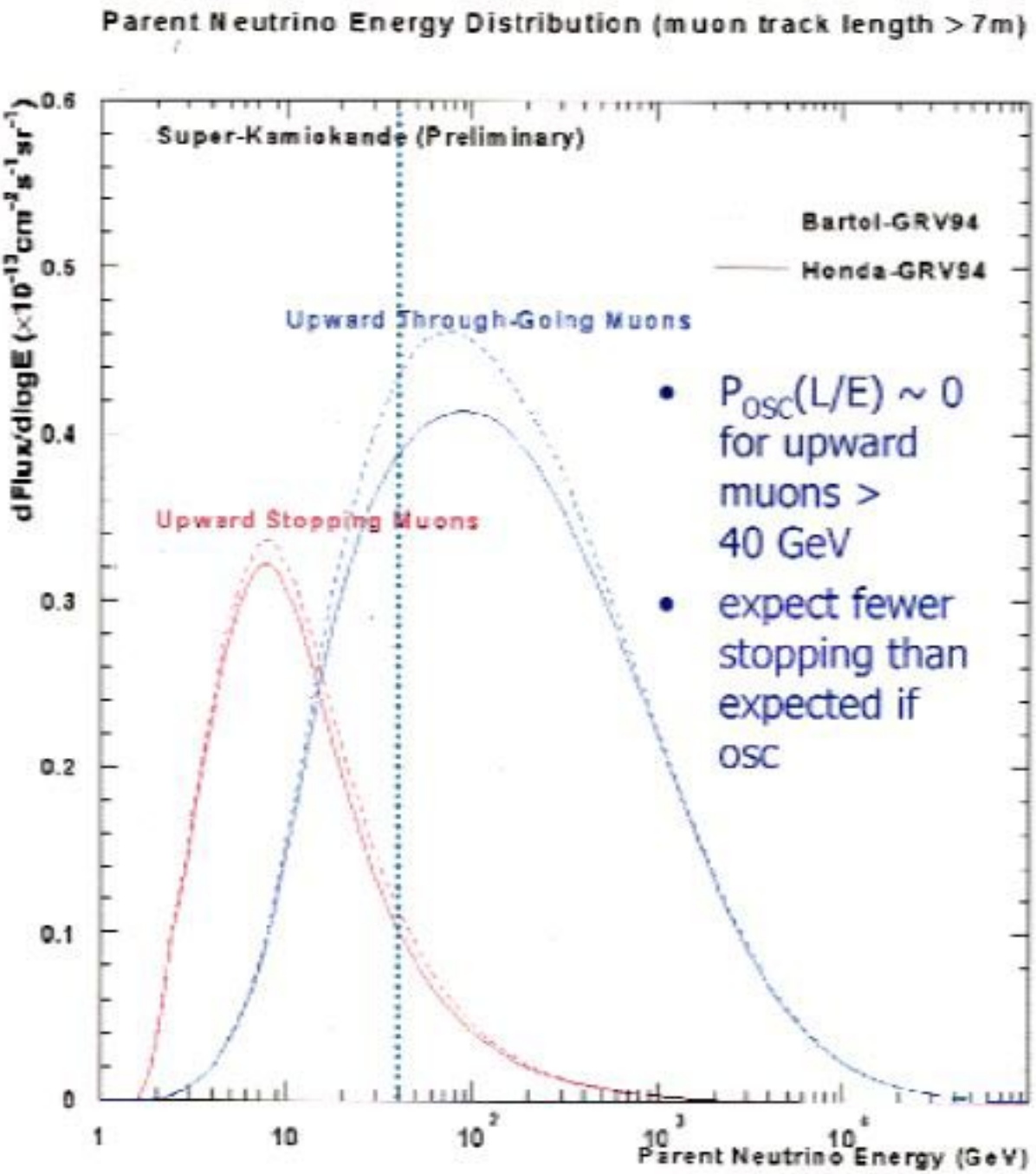
Poor angular resolution bin

μ up/horizontal ratio



Upward Muon Parent ν Spectra

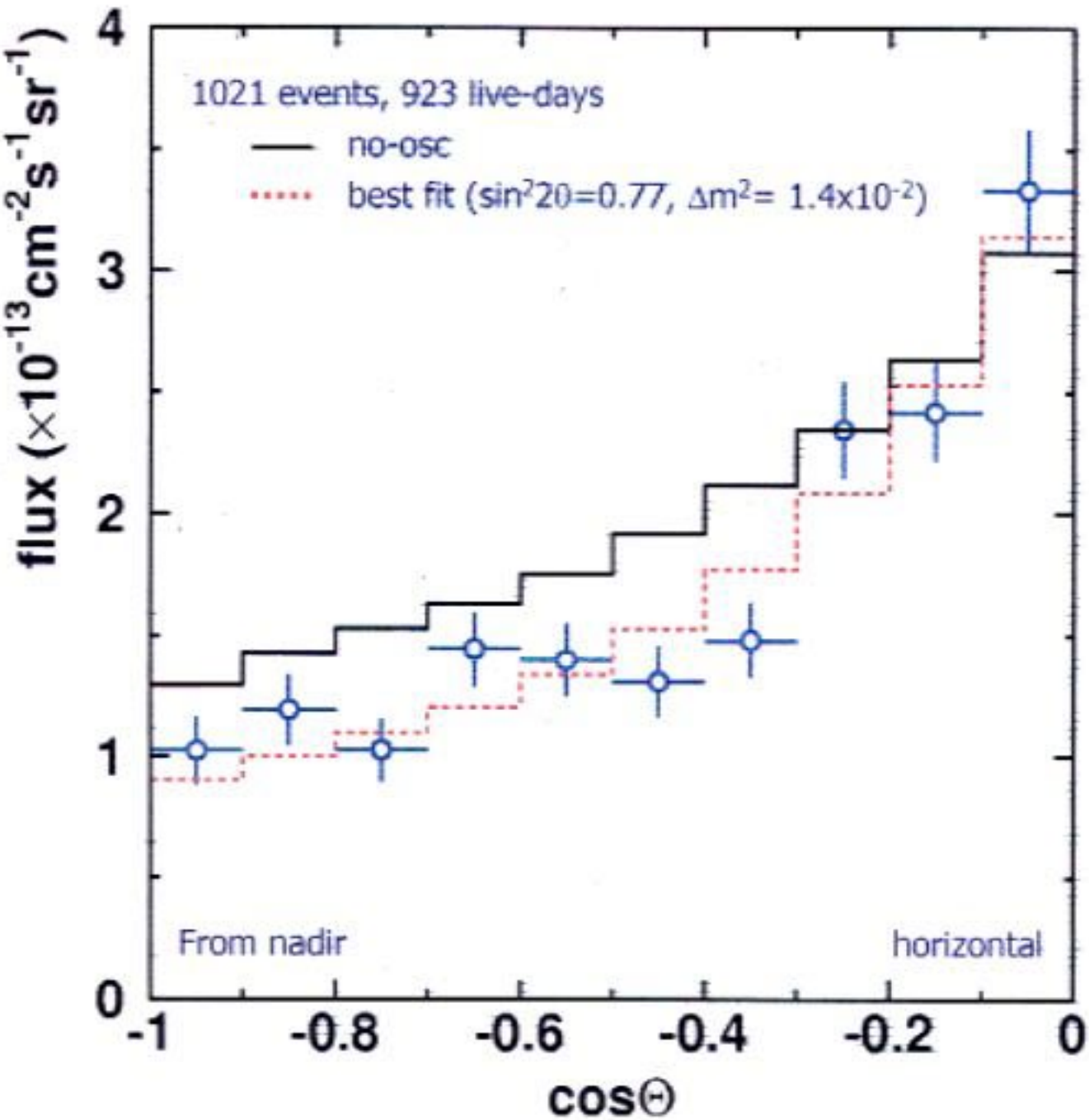
Daughters of energetic upward ν_μ



- $P_{osc}(L/E) \sim 0$ for upward muons > 40 GeV
- expect fewer stopping than expected if osc

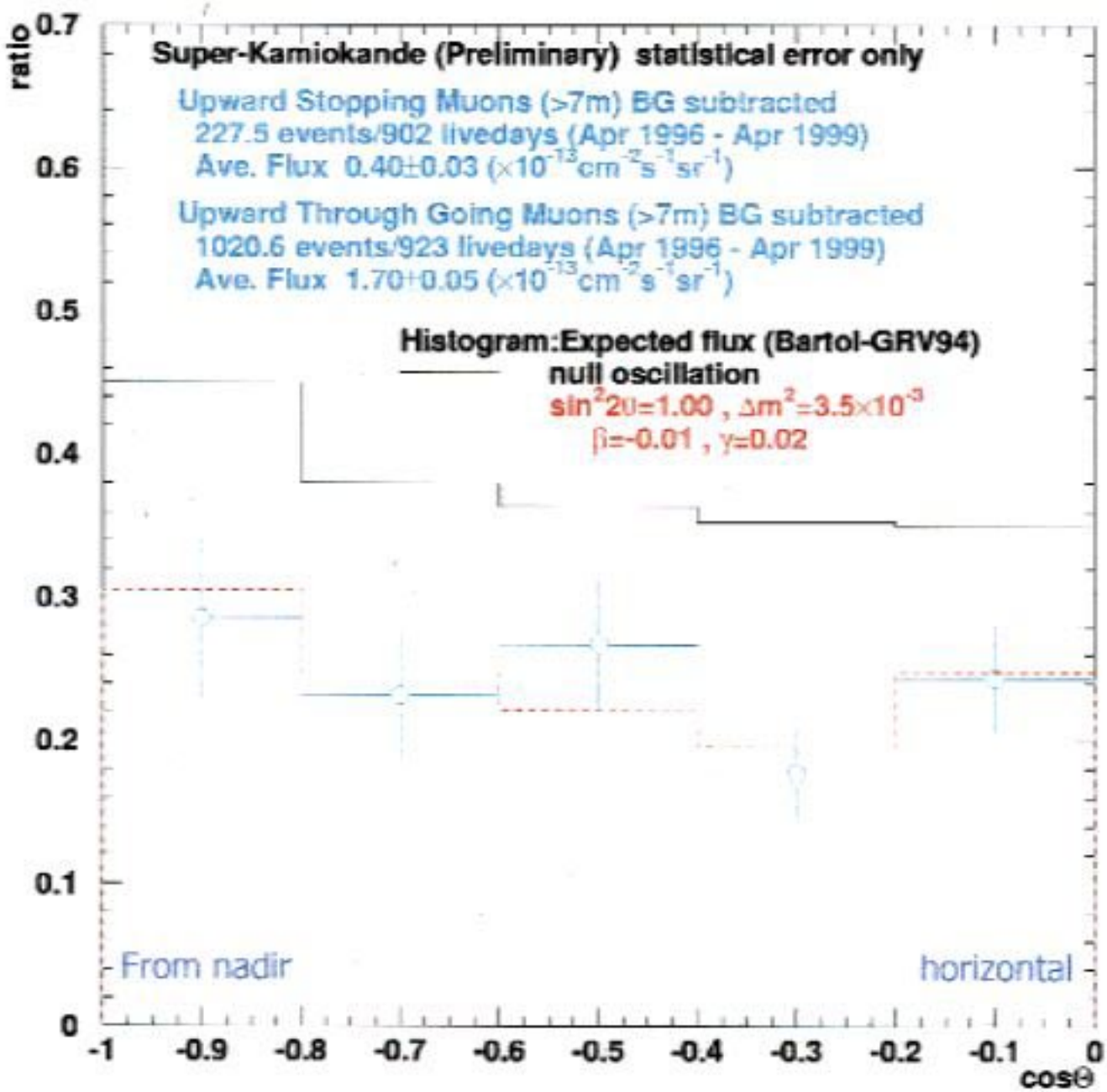
Upward-going muons

zenith angle distribution for upward through-going muons:

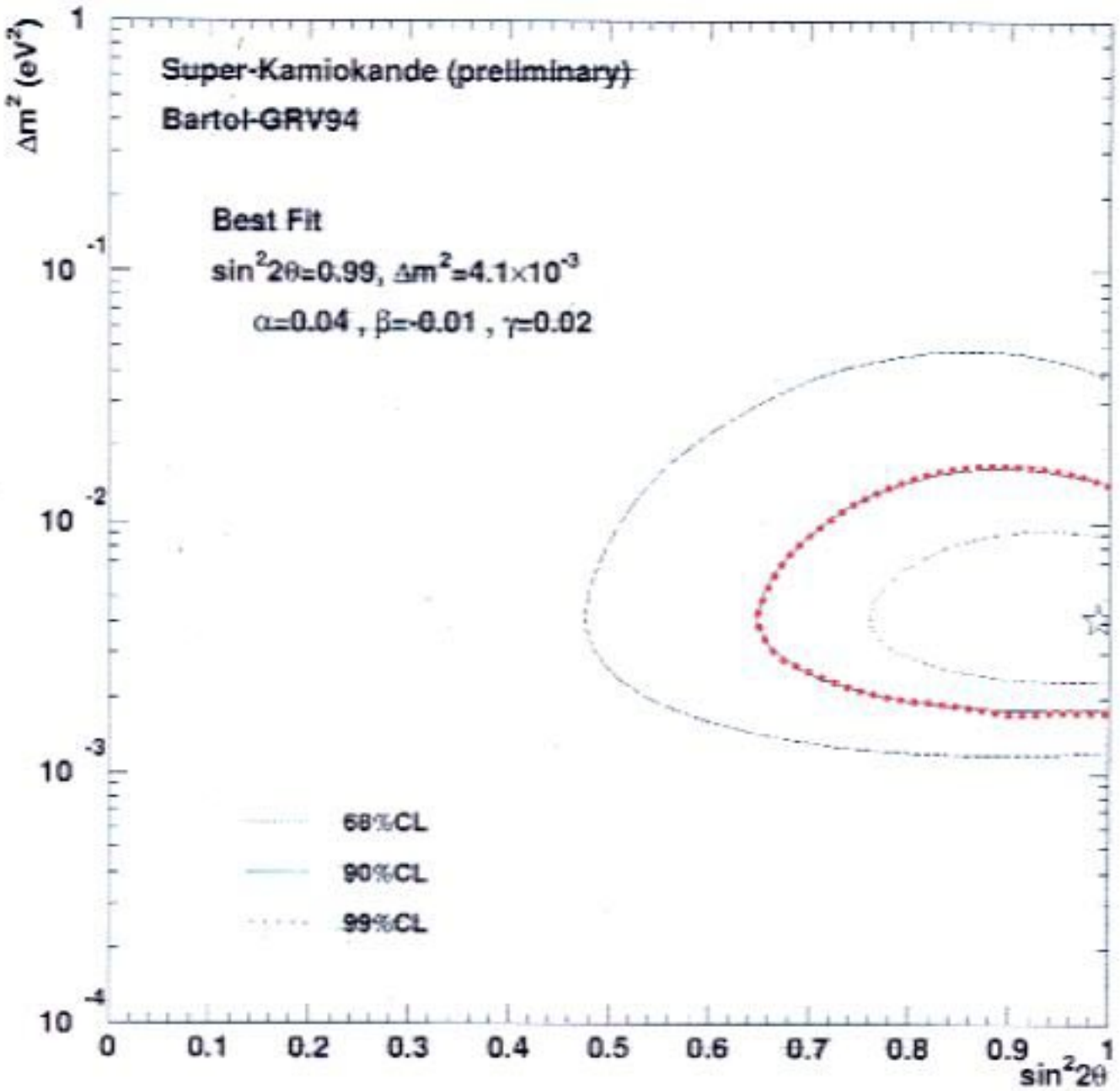


Upward-going muons

...zenith angle distribution for ratio of upward stopping to through-going muons:

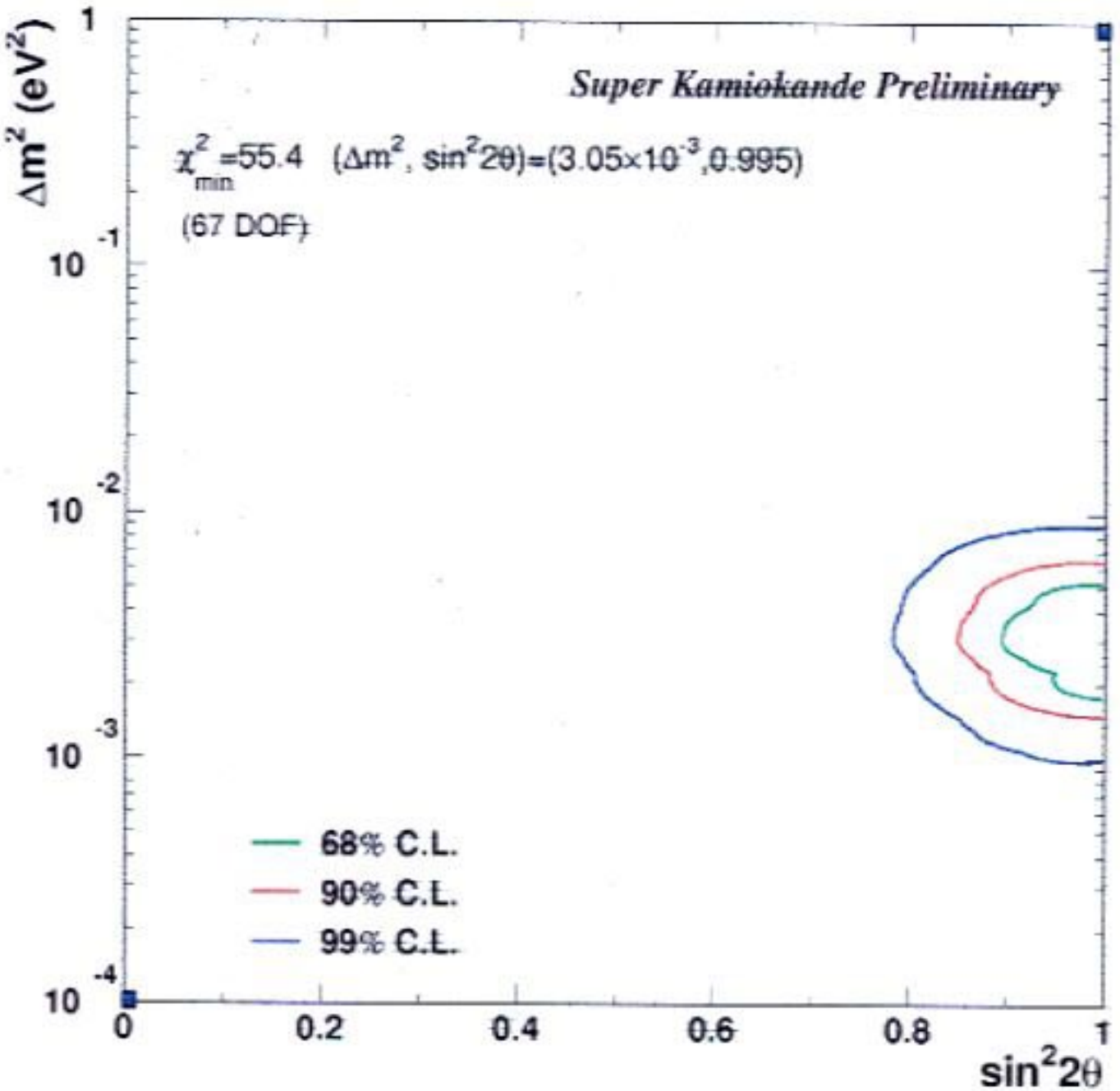


Allowed region for upward-muon stop/thru ratio



Allowed regions

Fully-contained + partially contained events

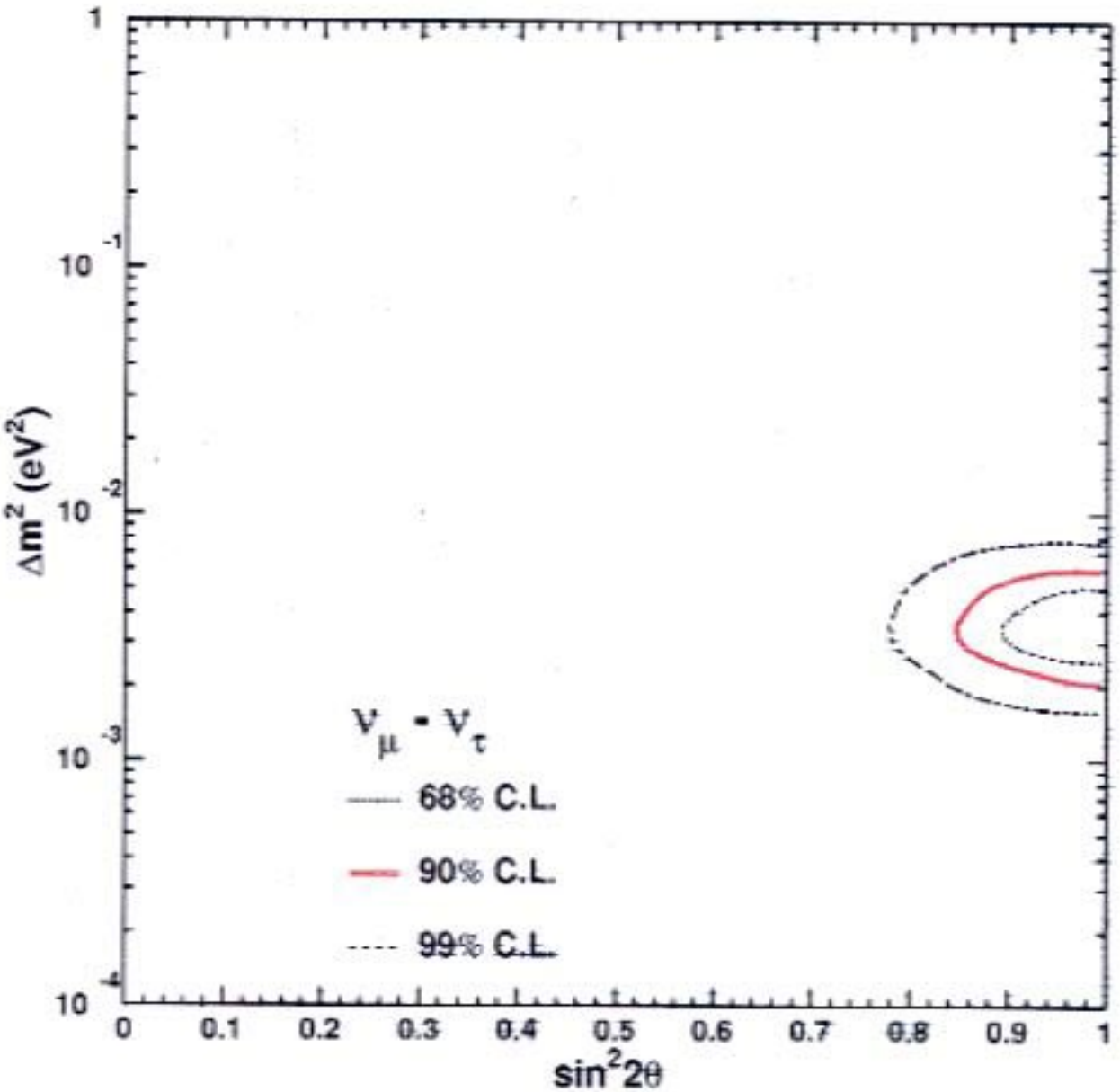


Upward muon stopping/through ratio

Allowed region for contained events + upward μ

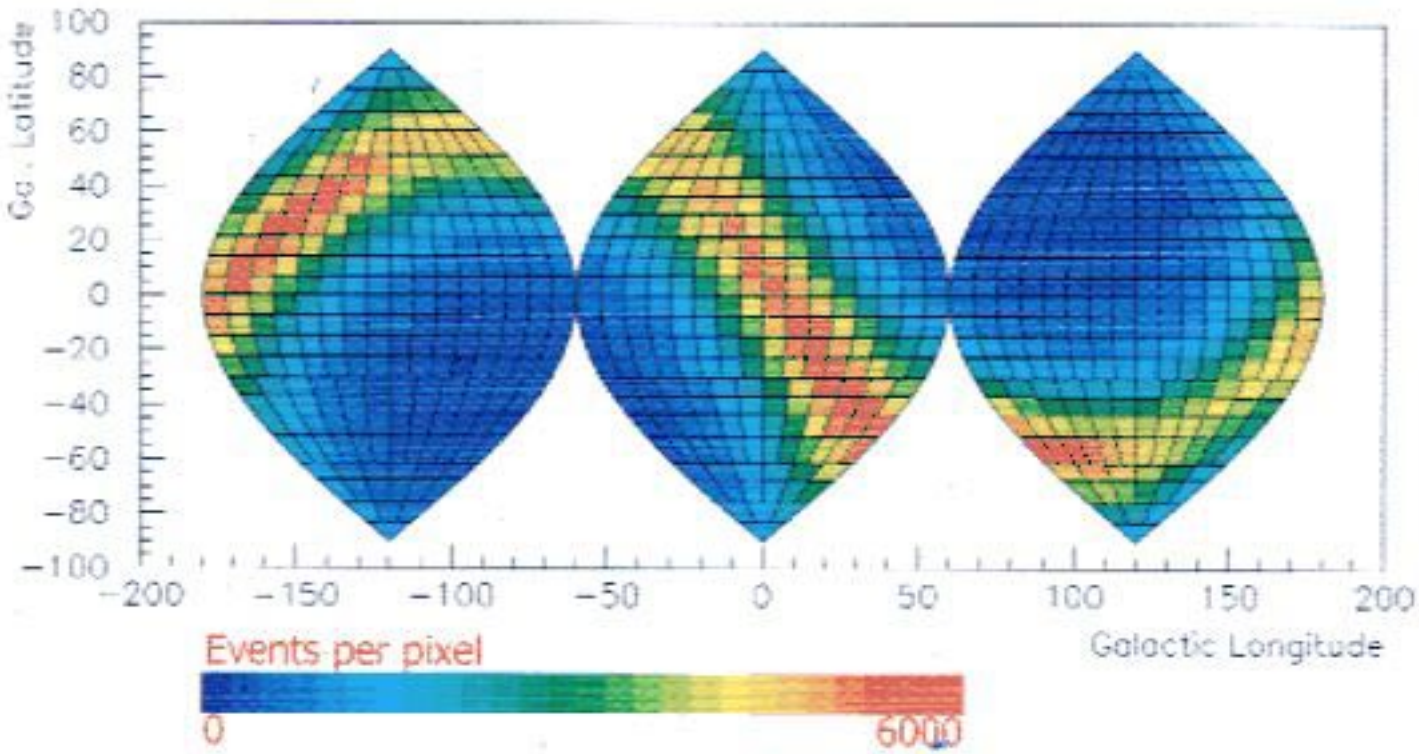
All Super-K Atmospheric νs

Fully-Contained + Partially Contained + Through-going Up-μ + Stopping Up-μ

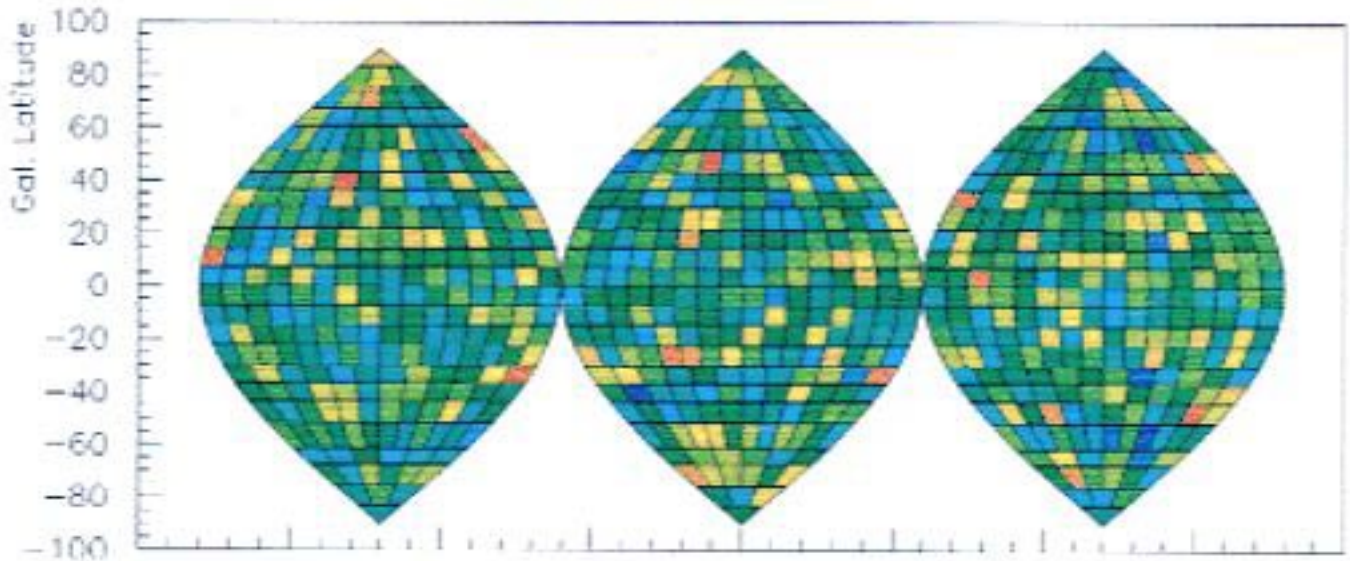


Solar neutrino skymap

Super-K observes the ecliptic in neutrinos...



Background after signal subtraction:



Solar ν Results

PRELIMINARY

·DATA SET

- Data taking time: MAY 31, 1996 ~ APR. 3, 1999
- Total live time: 825 days
- Energy threshold: 6.5 MeV
- Fiducial volume: 22.5kton
- SSM: BP98 total flux + Bahcall96 ^{8}B spectrum

·FLUX

All
824.7d $2.45\ ^{+0.04}_{-0.04}$ (stat.) $^{+0.07}_{-0.07}$ (syst.) [$\times 10^6/cm^2/s$]

($11235\ ^{+180}_{-166}$ (stat.) $^{+315}_{-303}$ (syst.) signals)

$$\frac{\text{Data}}{\text{SSM}_{BP98}} = 0.475\ ^{+0.008}_{-0.007}(\text{stat.})\ ^{+0.013}_{-0.013}(\text{syst.})$$

Day
403.2d $2.37\ ^{+0.05}_{-0.05}$ (stat.) $^{+0.07}_{-0.06}$ (syst.) [$\times 10^6/cm^2/s$]

($5317\ ^{+123}_{-116}$ (stat.) $^{+149}_{-144}$ (syst.) signals)

$$\frac{\text{Data}}{\text{SSM}_{BP98}} = 0.461\ ^{+0.011}_{-0.010}(\text{stat.})\ ^{+0.013}_{-0.012}(\text{syst.})$$

Night
421.5d $2.51\ ^{+0.06}_{-0.05}$ (stat.) $^{+0.07}_{-0.07}$ (syst.) [$\times 10^6/cm^2/s$]

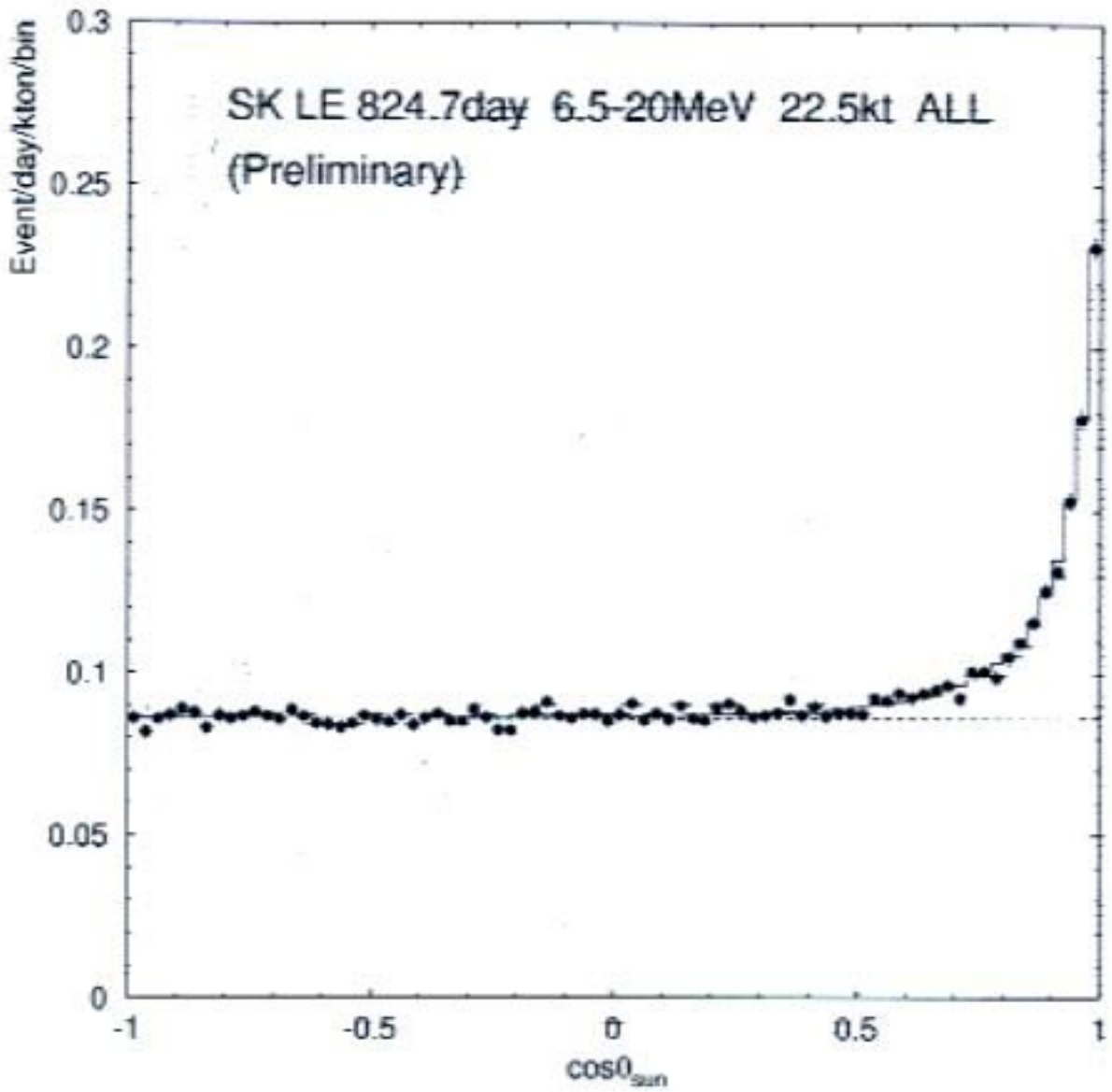
($5905\ ^{+134}_{-120}$ (stat.) $^{+165}_{-159}$ (syst.) signals)

$$\frac{\text{Data}}{\text{SSM}_{BP98}} = 0.488\ ^{+0.011}_{-0.010}(\text{stat.})\ ^{+0.014}_{-0.013}(\text{syst.})$$

·DAY/NIGHT

$$\frac{D-N}{(D+N)/2} = -0.065 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

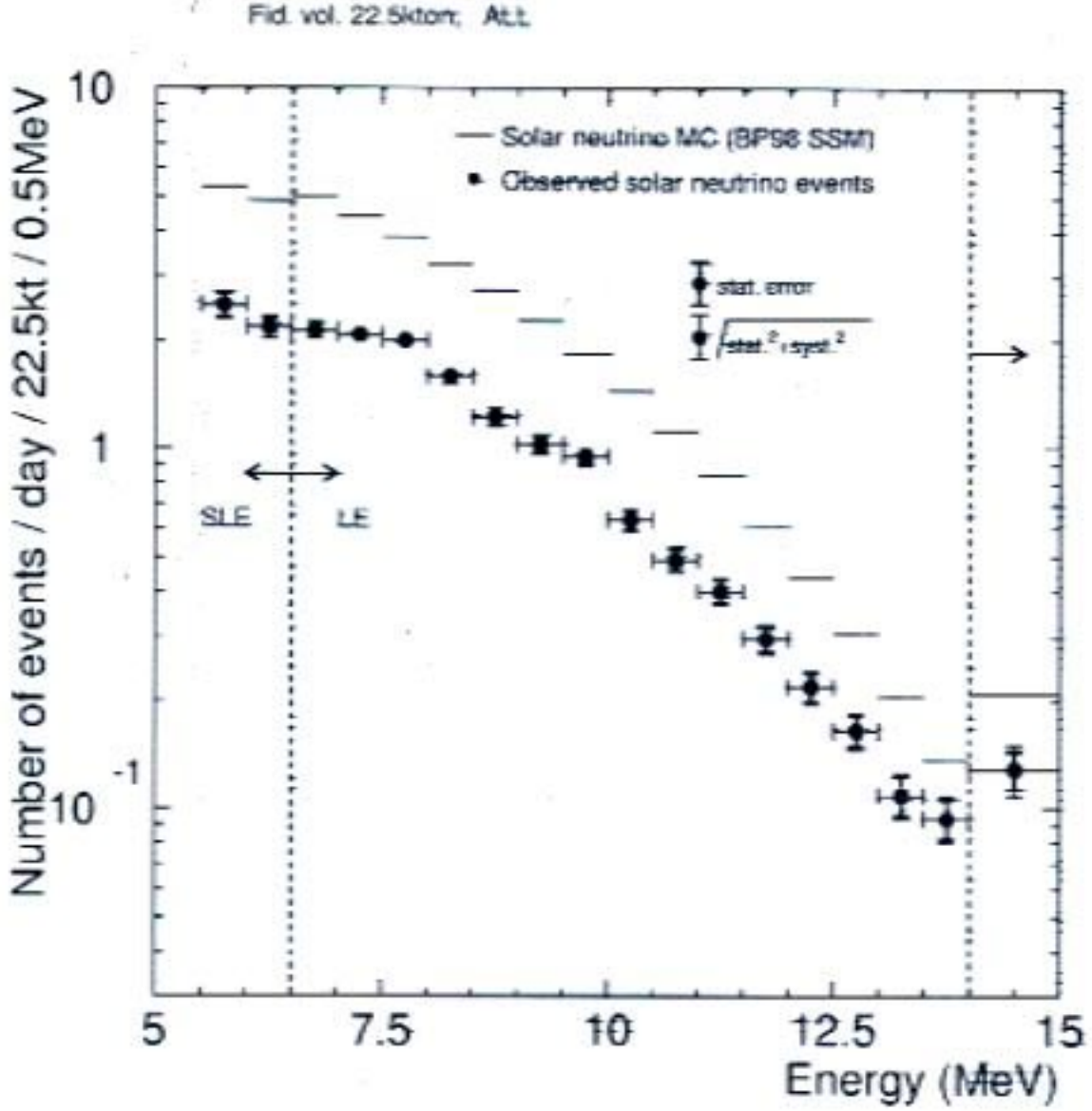
Solar ν angular distribution



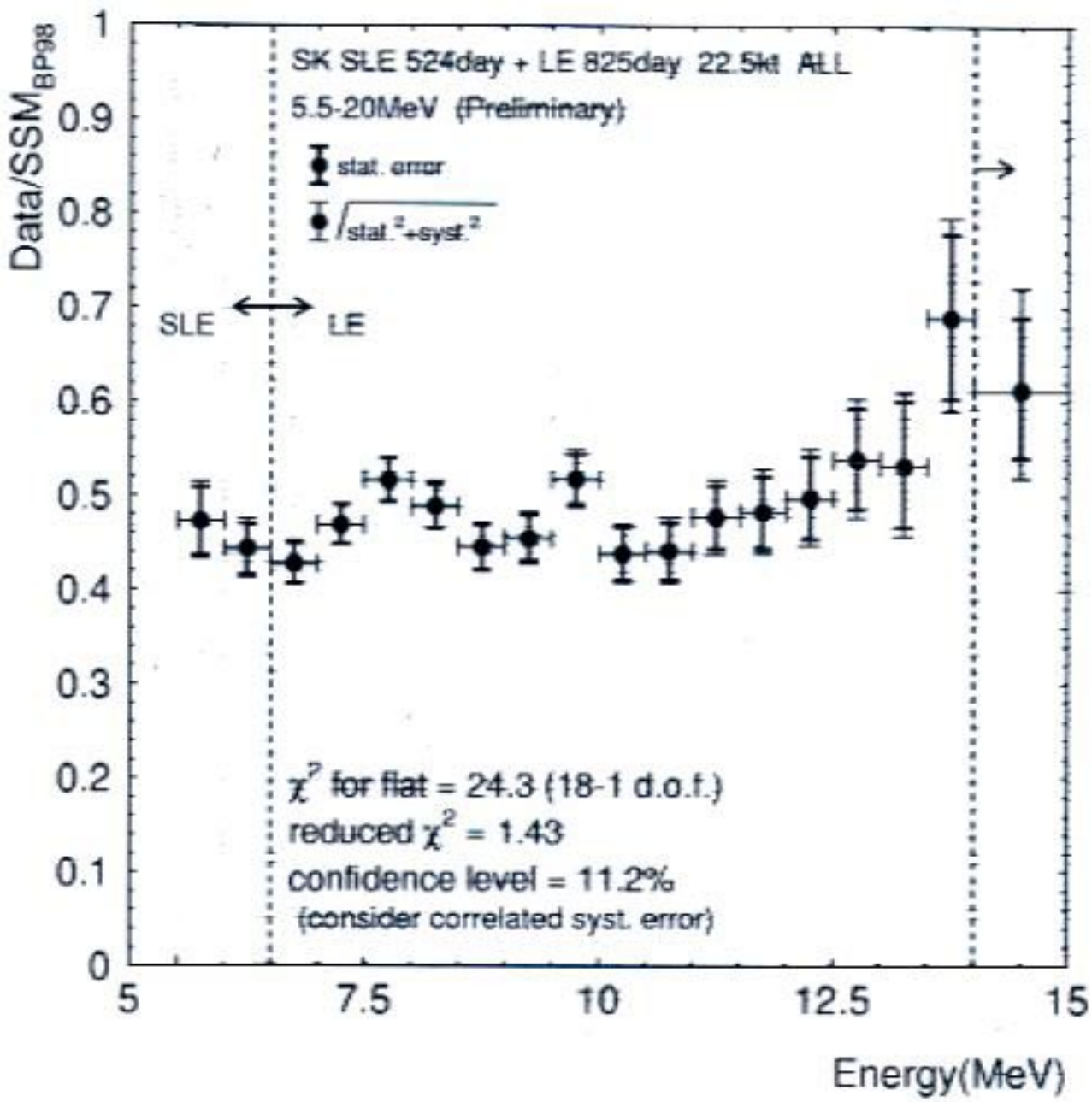
Solar ν energy spectrum

(Preliminary)

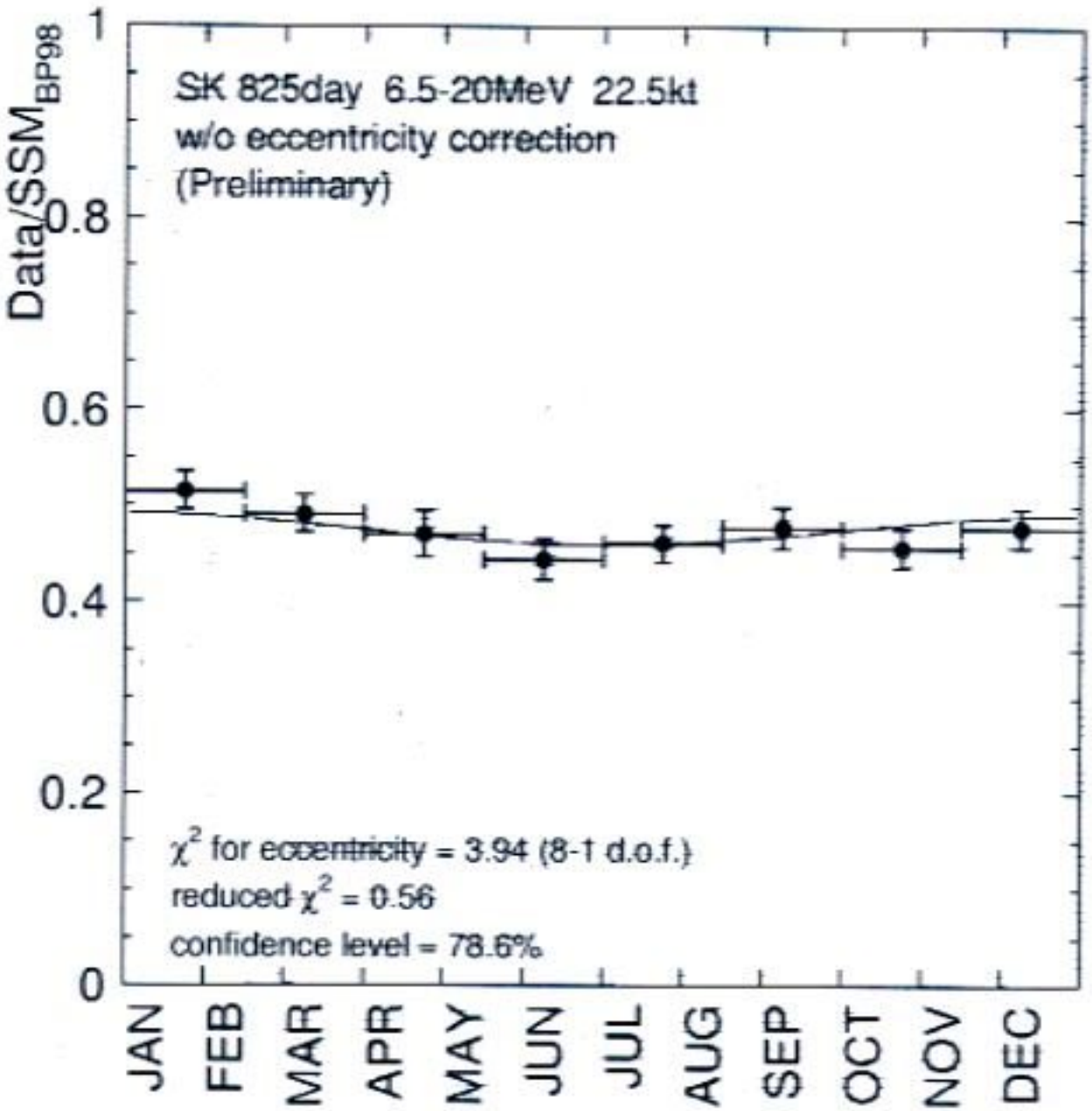
Super-Kamiokande SLE 524day + LE 825day



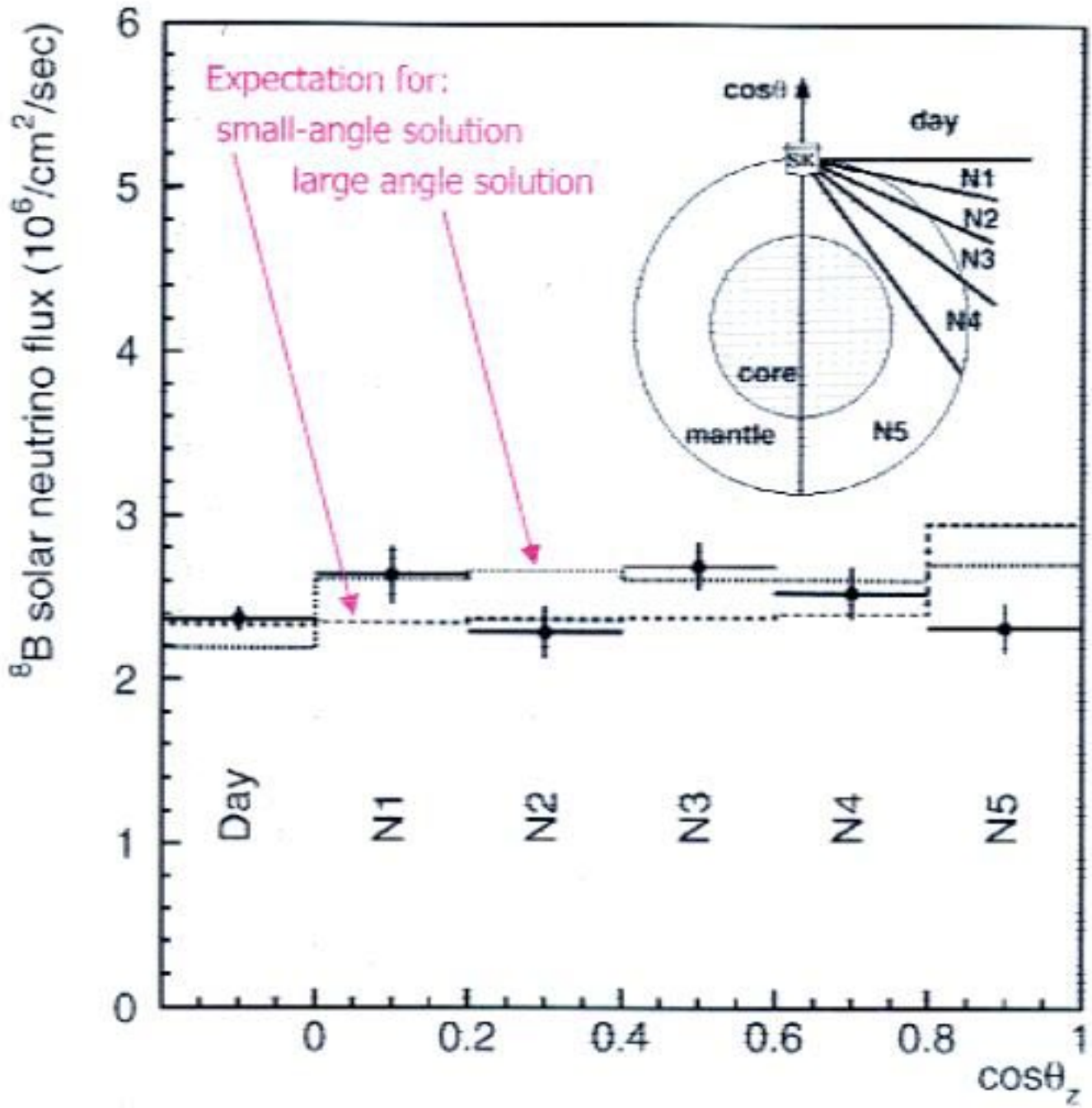
Solar ν spectrum: data/SSM



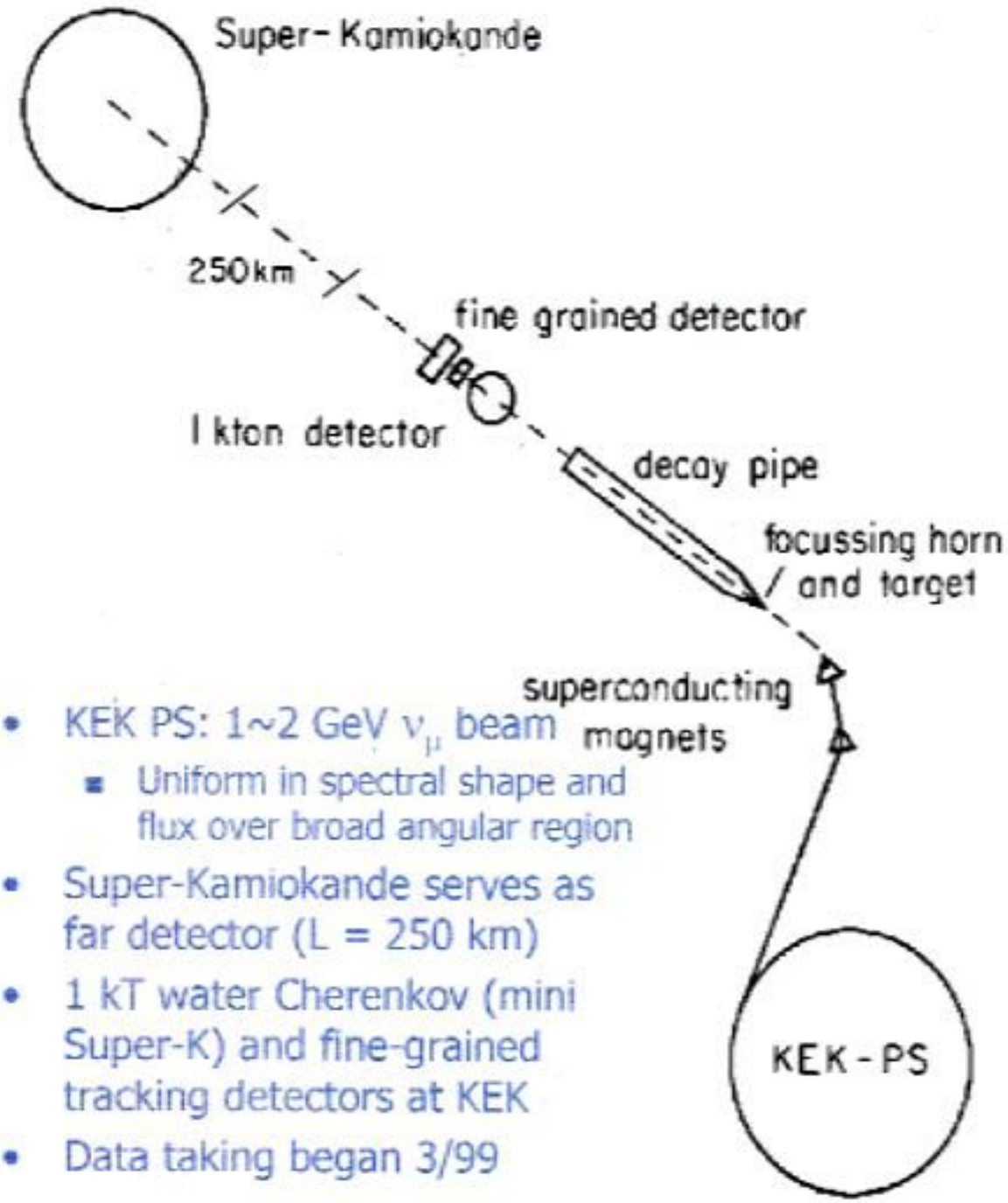
Solar ν: seasonal variation



Day-Night Effect



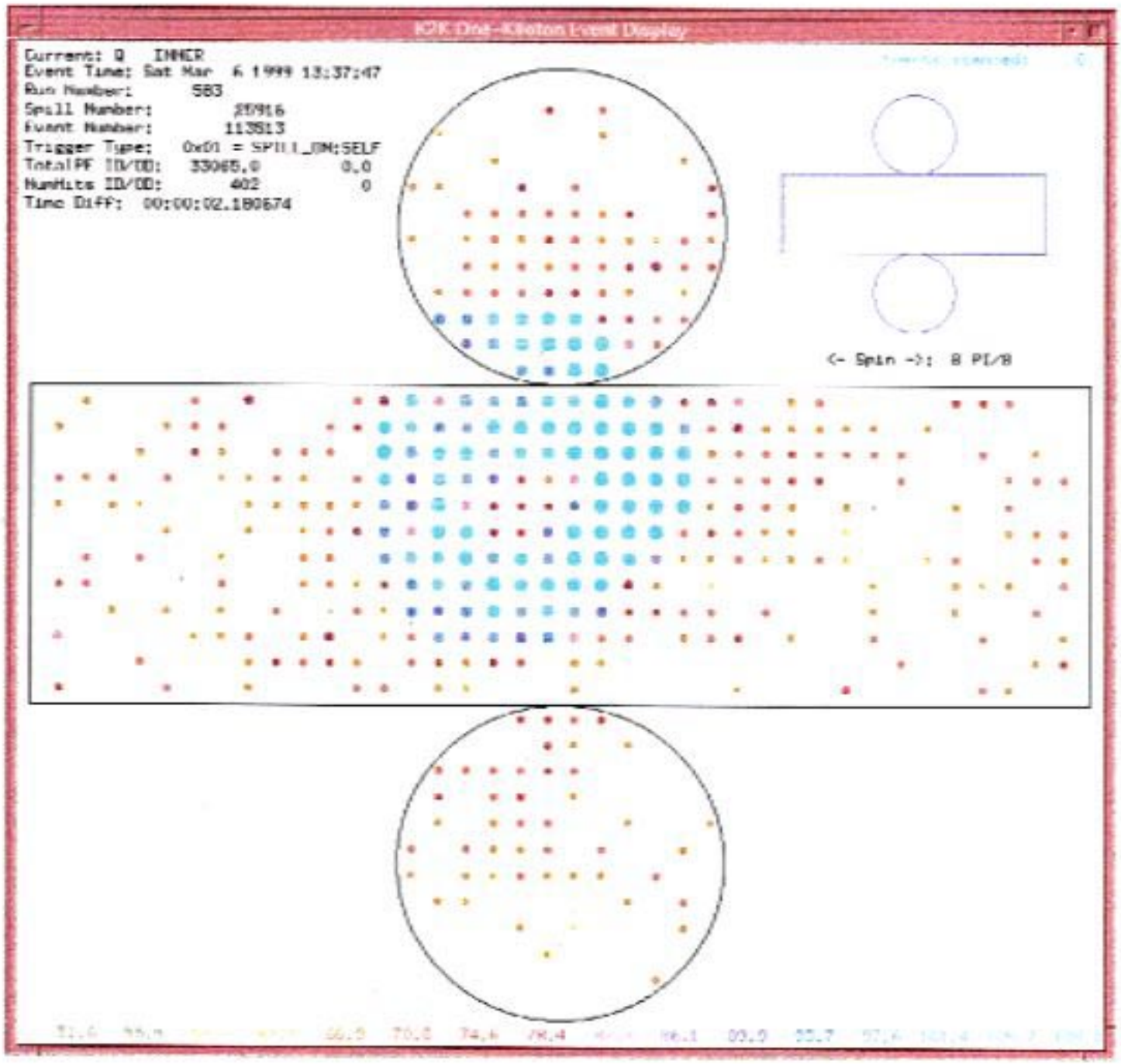
K2K: KEK to Super-K Long Baseline Experiment



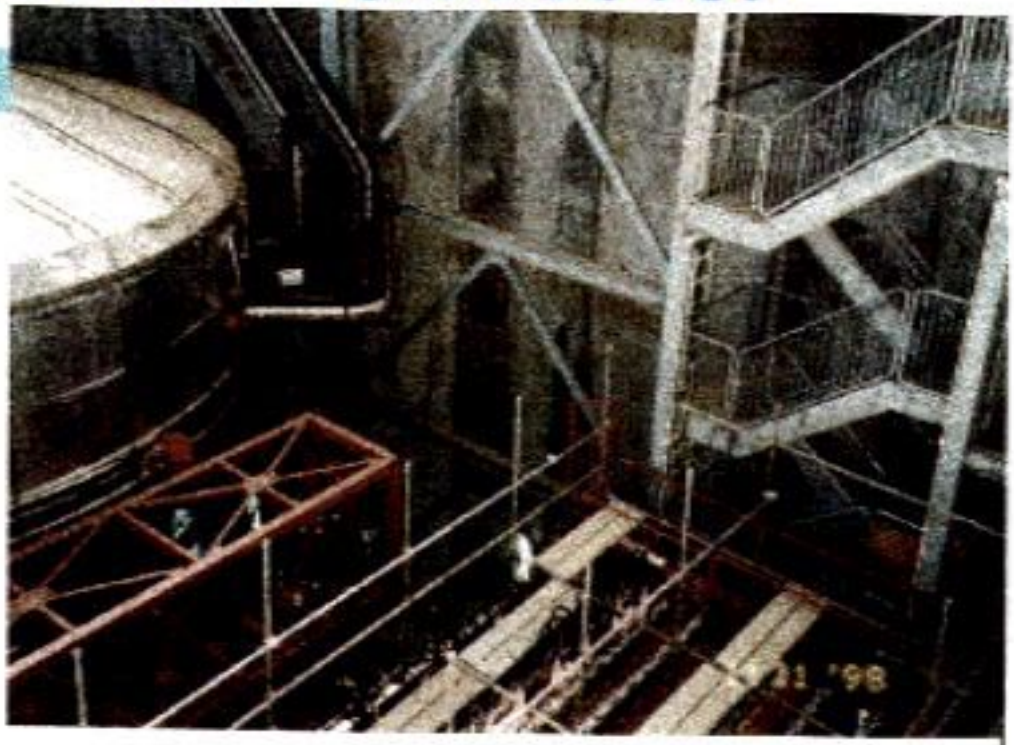
- KEK PS: 1~2 GeV ν_μ beam
  - Uniform in spectral shape and flux over broad angular region
- Super-Kamiokande serves as far detector (L = 250 km)
- 1 kT water Cherenkov (mini Super-K) and fine-grained tracking detectors at KEK
- Data taking began 3/99

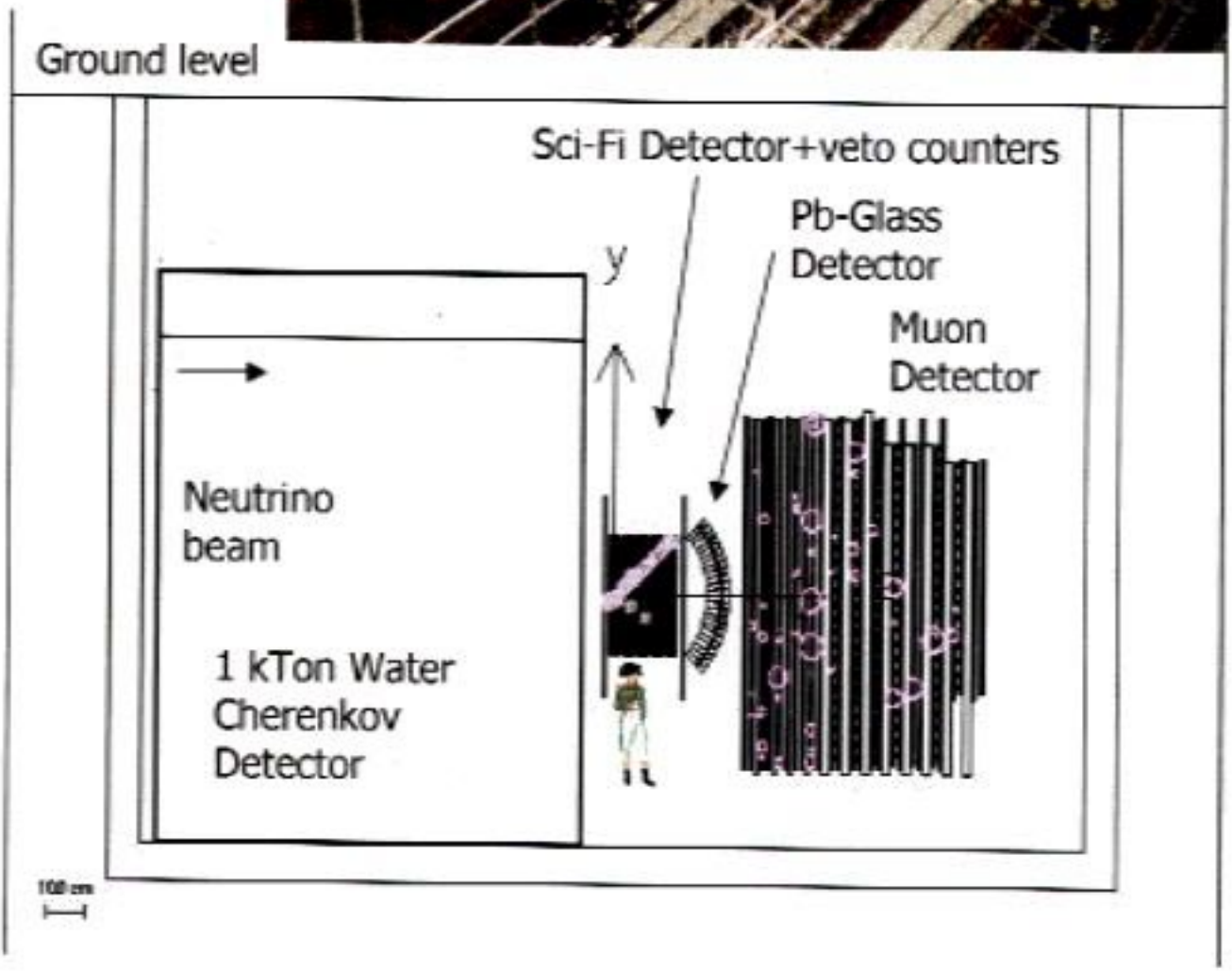
For latest news, see our website: http://neutrino.kek.jp/

Neutrino event in 1 kT detector

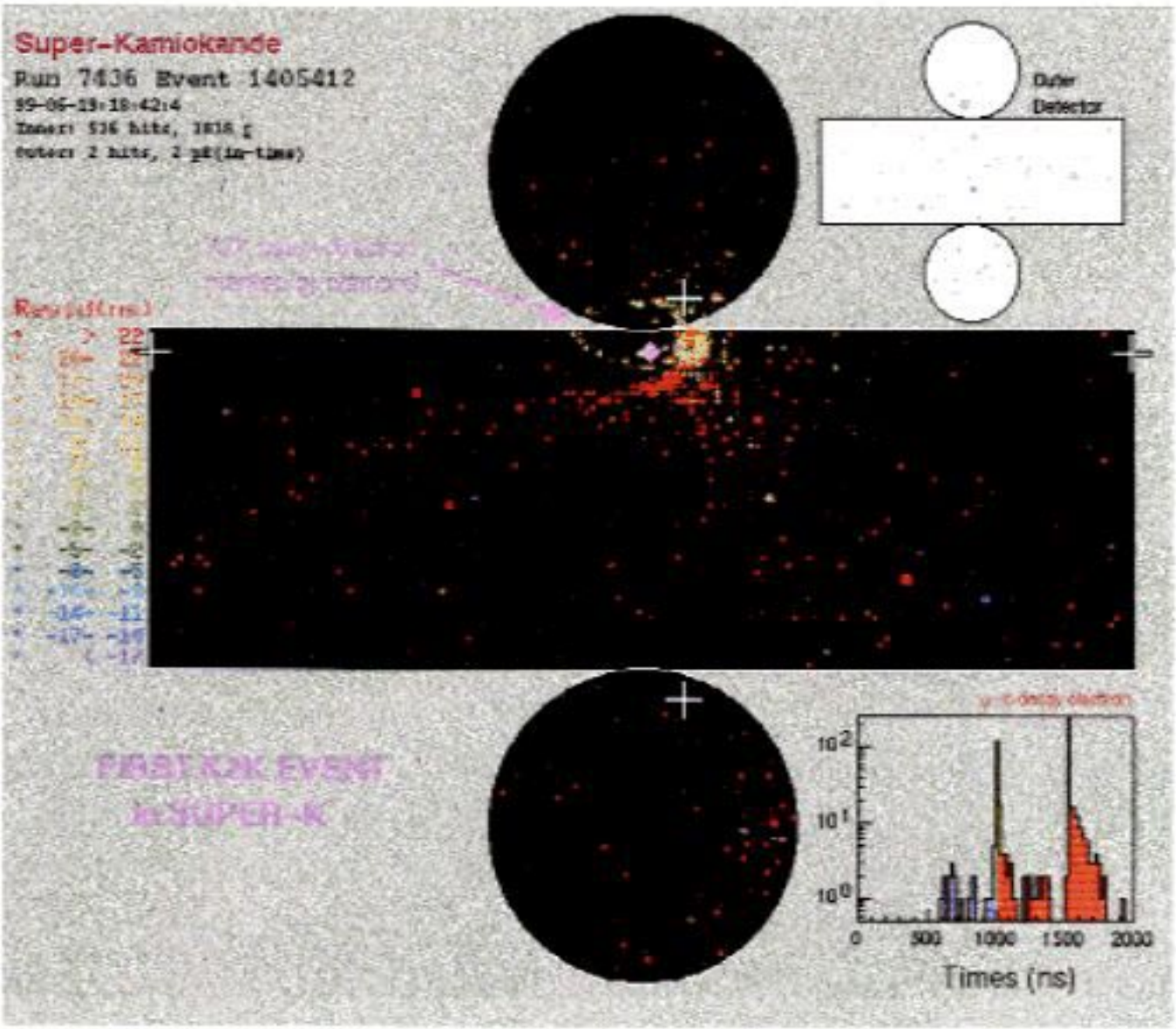


K2K Near Detector

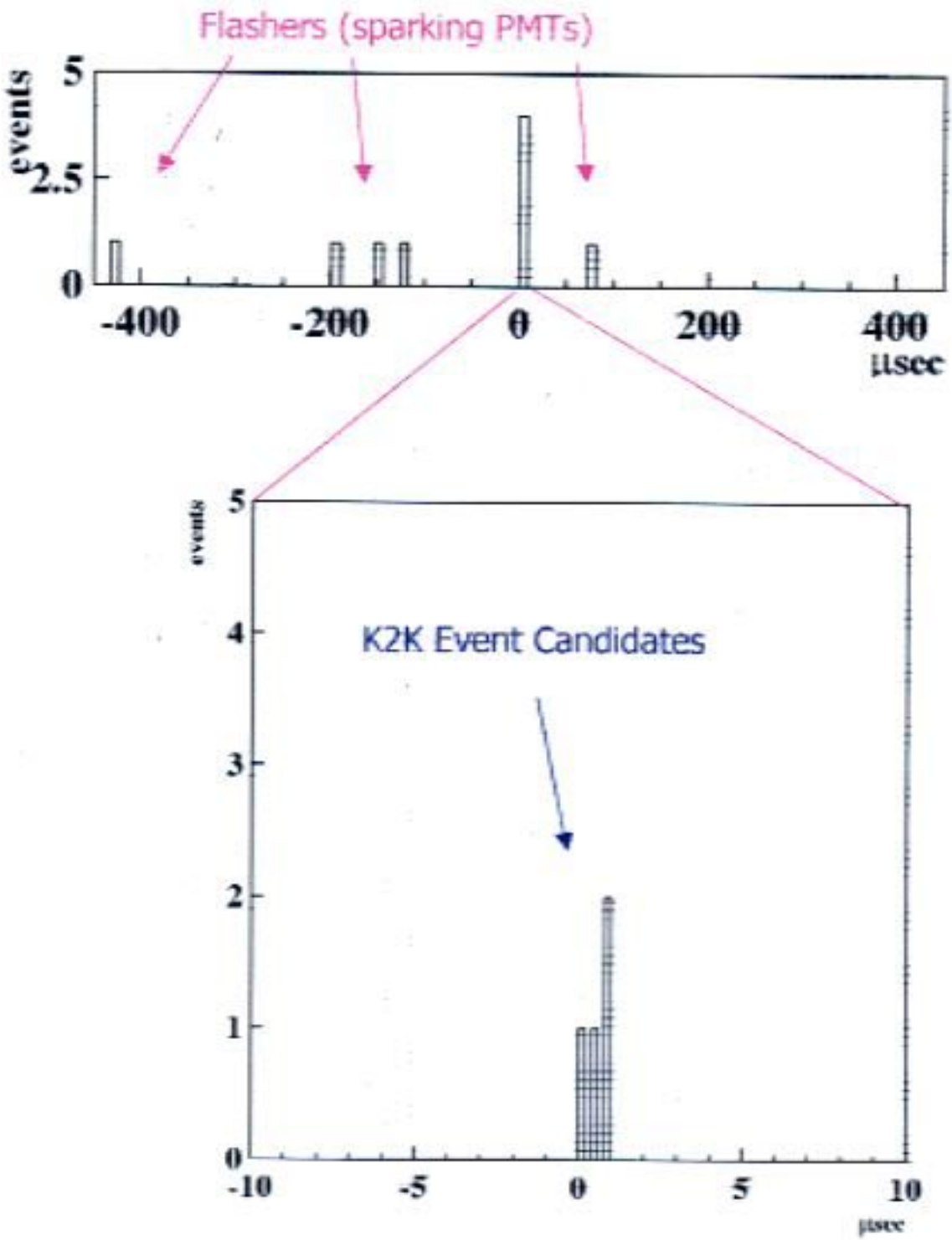




First K2K contained event at Super-K



Δt for SK events



The Future

- SuperK collecting data with livetime/realtime ~ 96%
- Logging about 13 solar ν,
  30 atmospheric ν,
  1 upgoing muon per day
- K2K began data taking 3/99; next run 10/99
- Watch this space