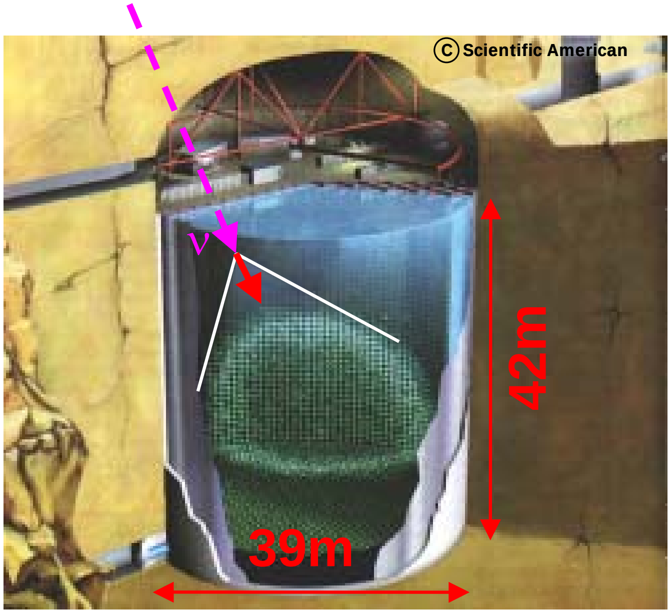
Super-Kamiokande
(Present and Future)



Y.Suzuki
Kamioka Observatory
ICRR, Univ. of Tokyo
2004-02-23 @ Seesaw

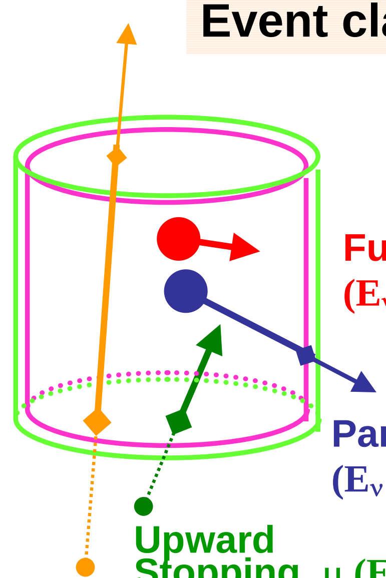
- Atmospheric Neutrinos
- Solar Neutrinos

- **50,000 tons (22,500 ton fid.) Water Cherenkov Detector**
- **1,000 m underground**
- **Inner-Detector (ID) : 11,146 20 inch PMTs (SK-I) ~5200 (SK-II)**
- **Outer-Detector (OD) : 1,885 8 inch PMTs**

What we know now
(Results from SK-I Atm-ν)

- **Quick Summary**
  - Two flavor analysis
    - Oscillation Parameters
  - Three flavor analysis
    - Effect of Δm_{12}
  - Sterile
  - Tau appearance
- **L/E analysis** new
  - First Oscillatory Evidence

Event classification

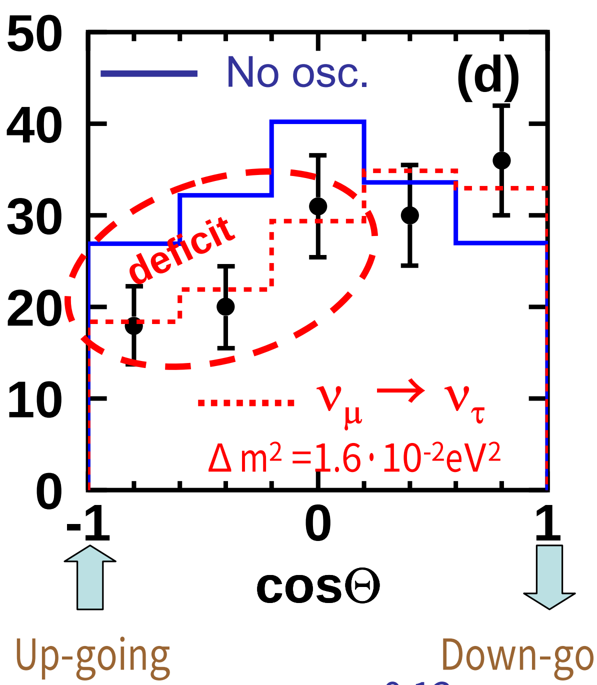


Kamiokande & Super-K

- **Discovery of Atmospheric Neutrino Oscillation by Super-Kamiokande in 1998**

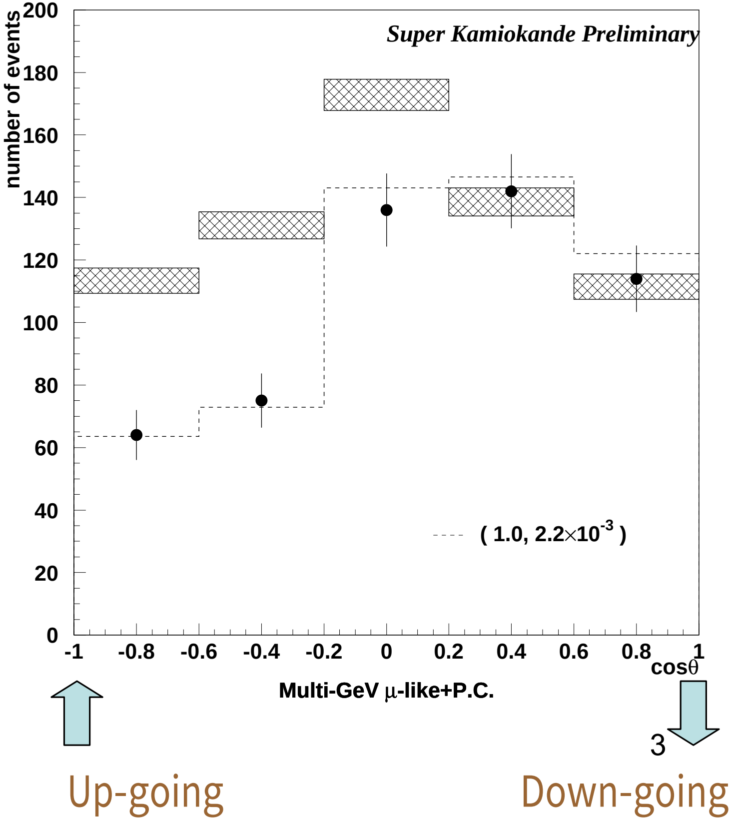
(Kamiokande,1994)

multi-GeV μ -like events



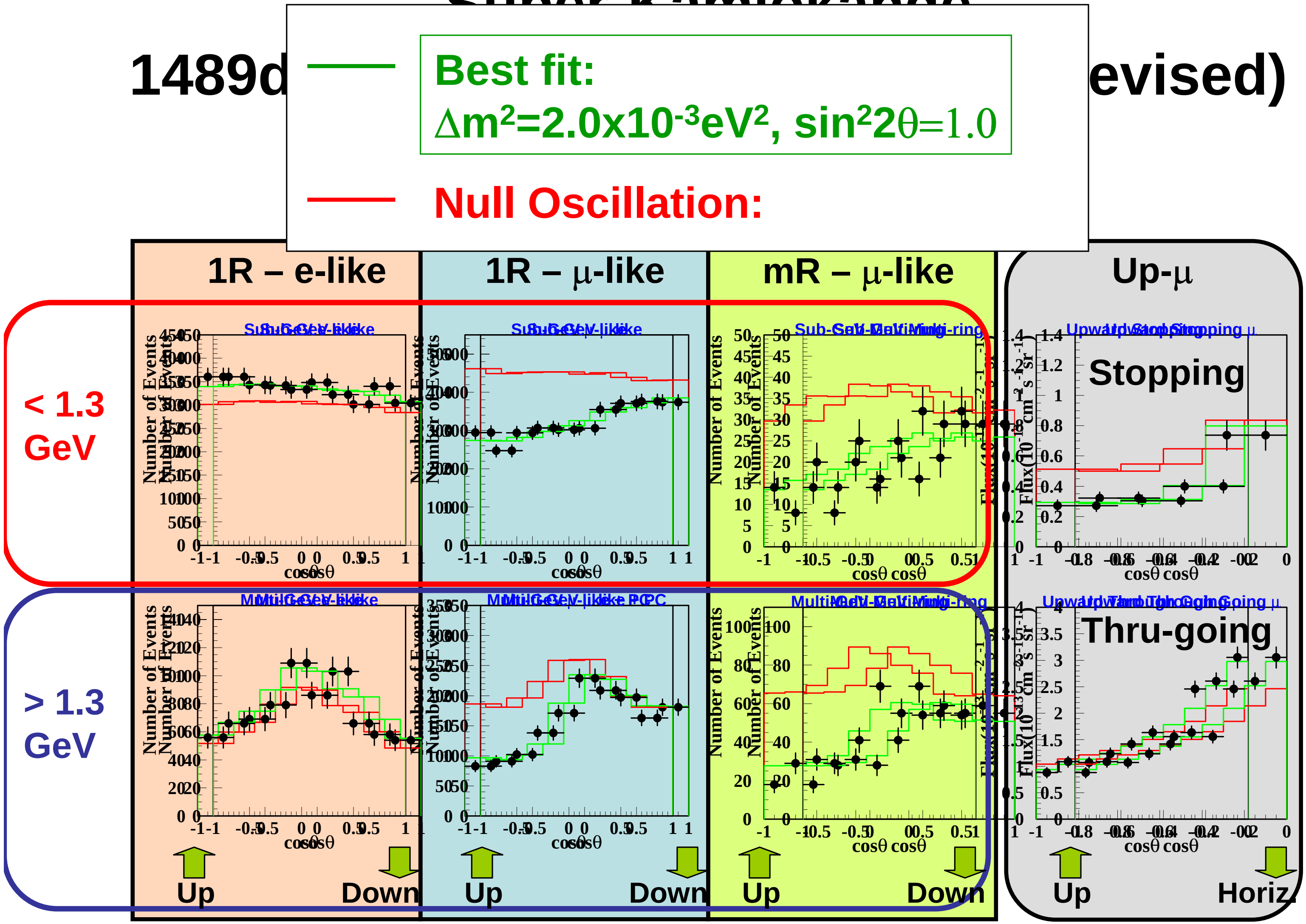
Up/Down=0.58 $^{+0.13}_{-0.11}$ (2.9 σ)

Super-Kamiokande, 1998



Super Kamiokande

1489d … evised)



Combined allowed regions (revised)

Best fit (in previous figures)

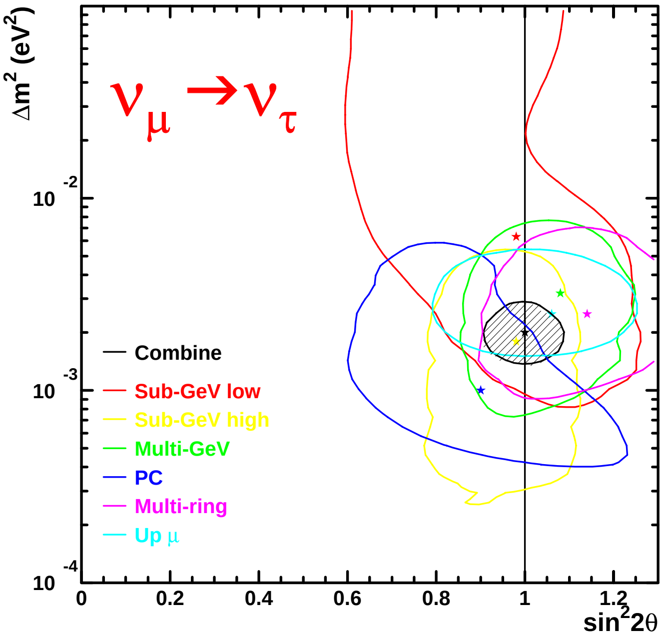
χ^2_{min}=170.8/170 d.o.f

(Δm^2=2.0x10^{-3}eV^2, $\sin^2 2\theta$=1.0)

Null Oscillation

χ^2_{min}=445.2/172 d.o.f

Oscillation significance
$\Delta\chi^2$=274

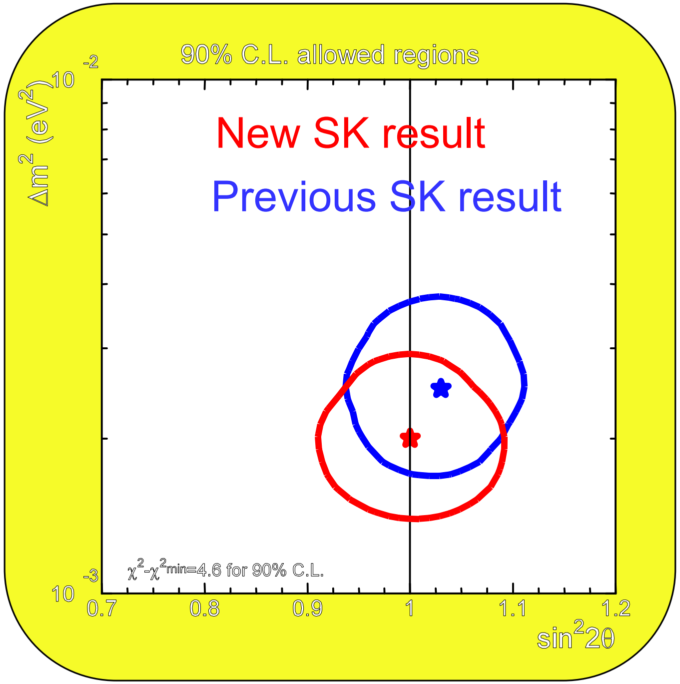


Δm^2 = (1.3~3.0)x10^{-3}eV^2
$\sin^2 2\theta$ > 0.90
@ 90%CL

Consistency among subsets of data:

Each allowed region overlaps

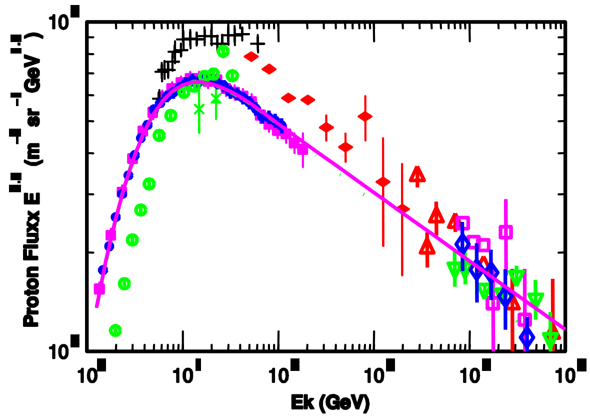
Notes for the improvement



Each change contributes to the shift in the allowed Δm^2 region.

- Detector simulation
- Data Analysis

- MC improvement
  - 3D flux calculation
  - Primary flux



  - Neutrino Interaction
    - $M_A^{QE} = 1.0 \rightarrow 1.1$
    - $M_A^{single\ \pi} = 1.0 \rightarrow 1.1$

and so on

Better agreement with K2K near detector data

3 flavor analysis

Assumption in SK analysis

$m_{\nu 3}$

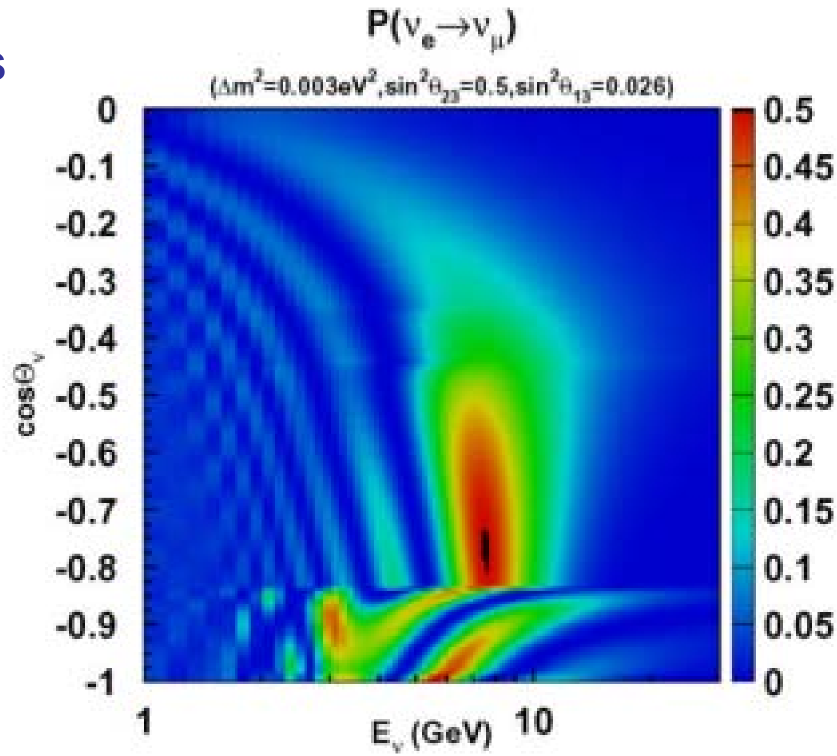
$m_{\nu 2}$

$m_{\nu 1}$

$\Delta m_{12}=0$

$\Delta m_{13}= \Delta m_{23}$

$\Delta m_{13}^2, \theta_{23}, \theta_{13}$



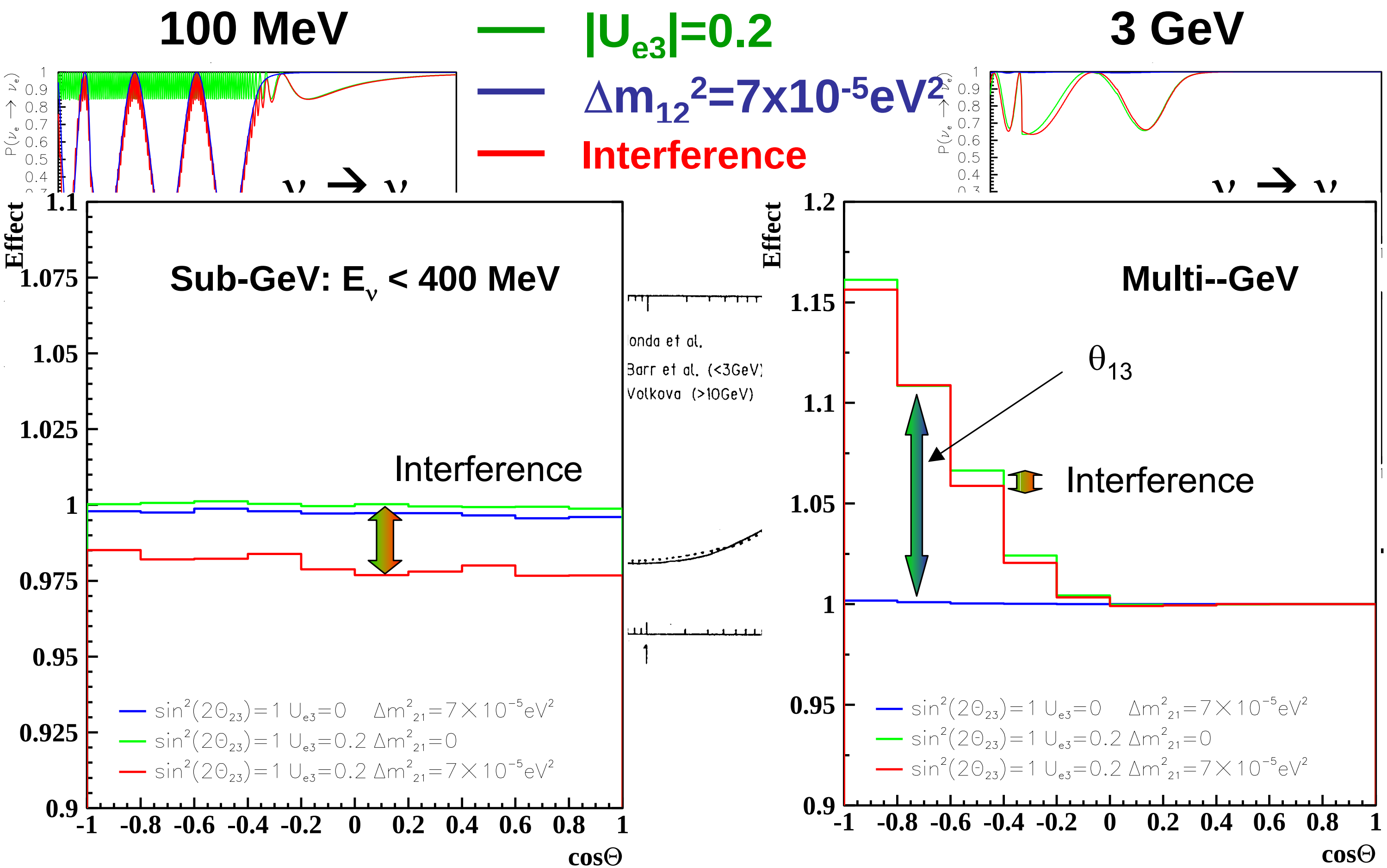
Matter effect through those parameters

Note for the effect from Δm_{sol}^2 on the atmospheric oscillation

- **Electron appearance in `Low Energy`**
- **But *is* negligible**
  - **Cancellation ($\nu_\mu : \nu_e$ = 2 : 1 & ~full mixing of θ_{23})**

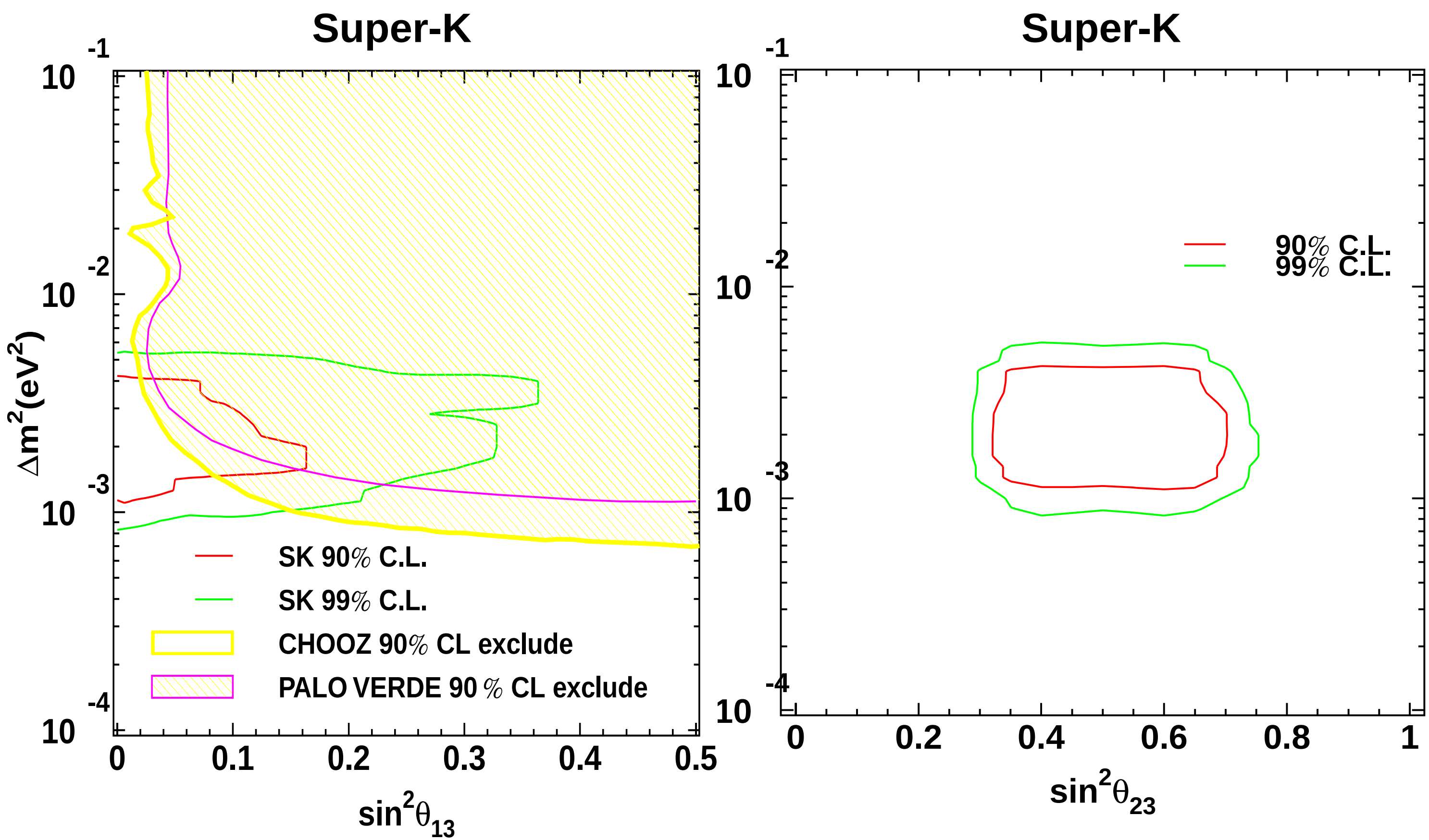
- **Now we know Δm_{12}^2 is relatively large**
- **Re-examination**
  - **Matter effect**
  - **Interference from the transitions through θ_{12} & θ_{13}**

Effect of Δm_{sol}^2 on the atmospheric oscillation



SK assumption, Δm_{12}=0 is marginally OK.

Allowed region for active 3-flavor oscillations



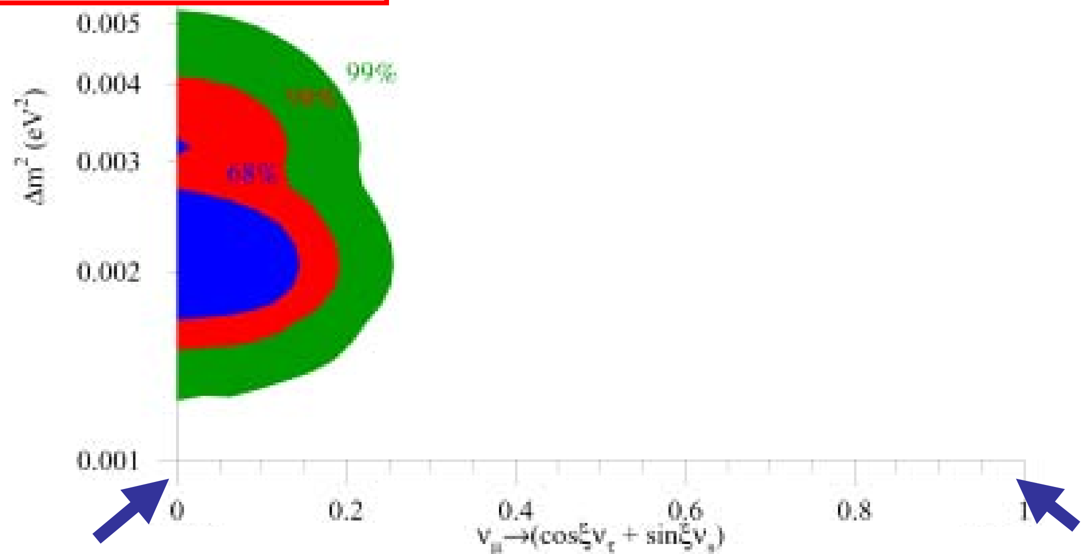
$\sin^2\theta_{13} < 0.16$ @$\Delta m^2 = 2\times10^{-3} eV^2$

Getting closer to the CHOOZ's limit on θ_{13}

Oscillation to sterile neutrinos?

- Use NC deficit or Matter effect to discriminate
- Use all the SK data
  (including NC, up-through-going-muons and High-E PC)
  ➔
- 100% transition to the sterile state have been rejected
  (>99%C.L.)

$\nu_\mu \rightarrow \cos\xi\nu_\tau + \sin\xi\nu_s$

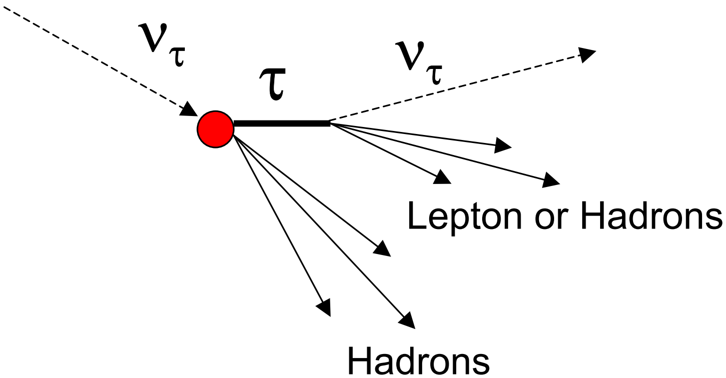


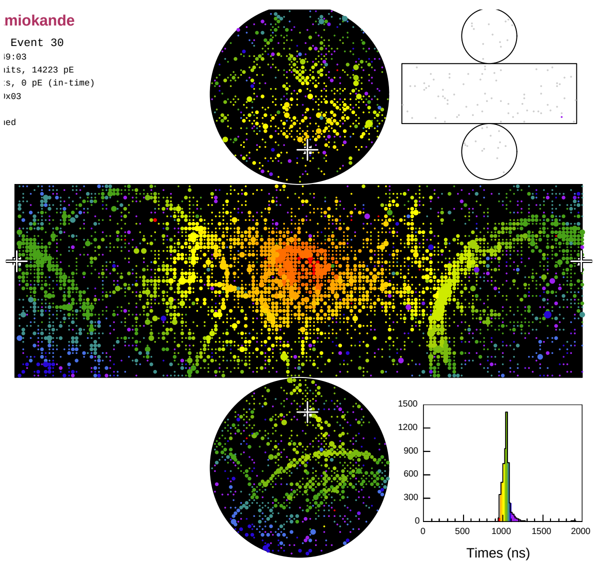
pure $\nu_\mu \rightarrow \nu_\tau$

$\sin^2\xi$

pure $\nu_\mu \rightarrow \nu_s$

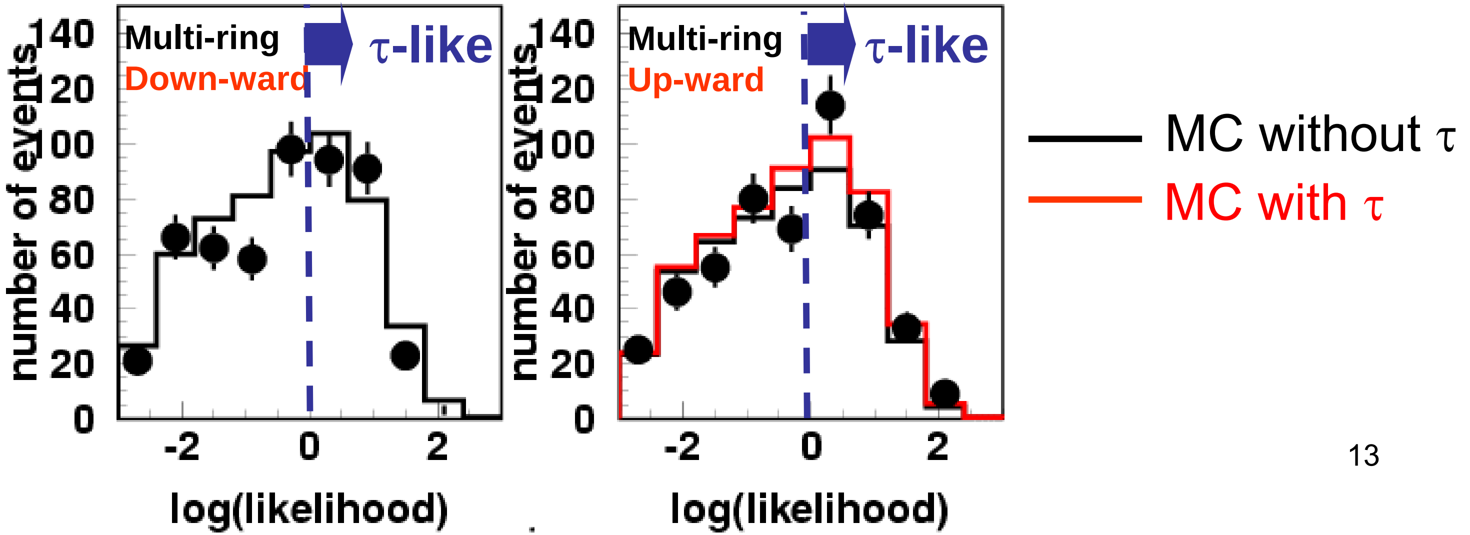
Search for ν_τ production in atm-ν



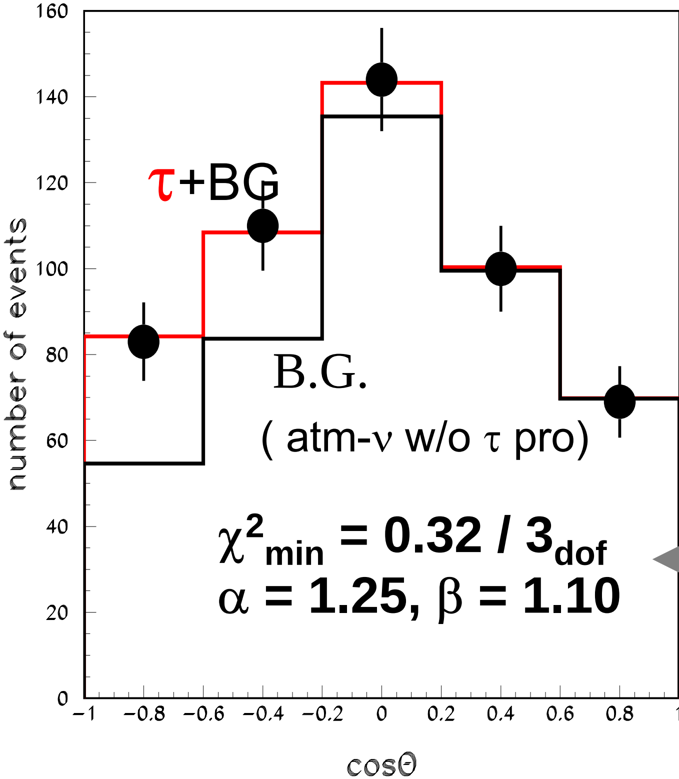


- τ events cannot be identified by event-by-event basis
  - Many Hadrons
  - Low rate
    - 1 CC ν_τ FC ev /kton/yr
  - BG ~ 130 ev /kton/yr
- Need statistical analysis

- Adopted three different analyses:
  1) Energy flow
  2) Neural Network
  3) Likelihood Method
     - **Selection Criteria**
       - **multi-GeV, multi-ring**
       - **most energetic ring is e-like**
     - **Calculate Likelihood and cut events to enhance τ**



zenith angle dist. of τ-like events



$$\chi^2 = \sum_{\cos\Theta}^{5} \left(\frac{N_{data} - \left(\alpha N_{MC}^{\tau} + \beta N_{MC}^{BG}\right)}{\sigma} \right)^2$$

$N_\tau = 48 \pm^{19}_{20}$ events

$N^{FC}_{\tau} = N_{\tau} / eff(\tau)$

$= 105 \pm^{42}_{45} \pm^{12}_{17}$ events

Expected: 86 for 1489 days

consistent with $\nu_\mu \leftrightarrow \nu_\tau$

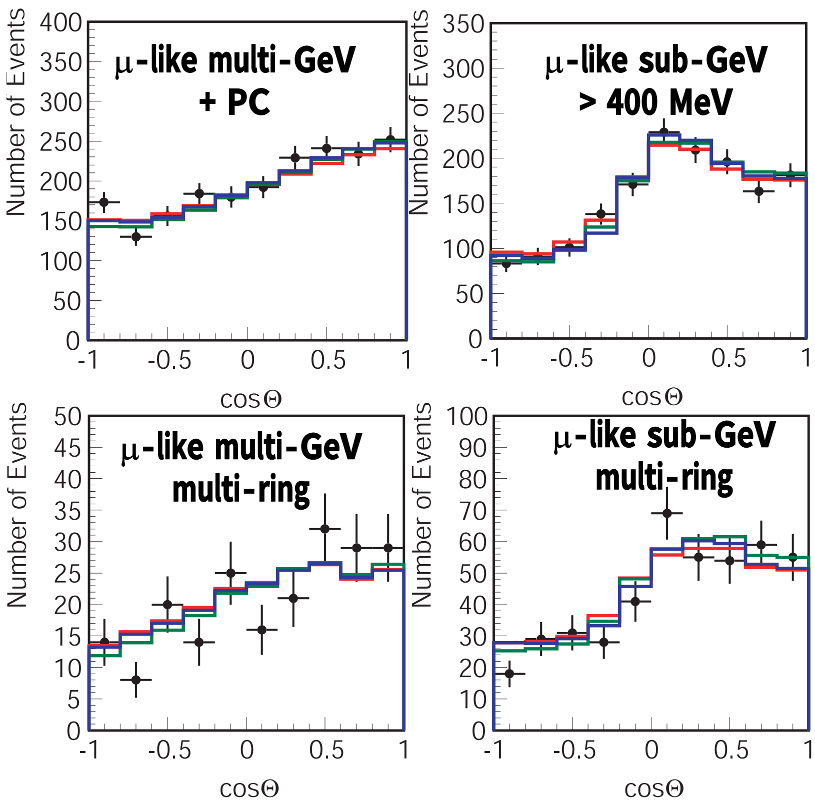
Other analyses give similar results:

Neural Network = $92 \pm^{35}_{35} \pm^{21}_{16}$ events

Energy Flow = $79 \pm^{44}_{40}$ events

L/E Analysis

new



Zenith angle distributions

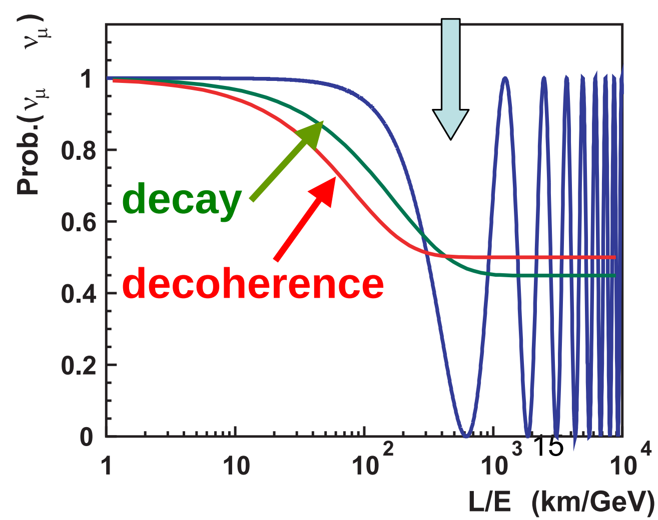
Oscillation

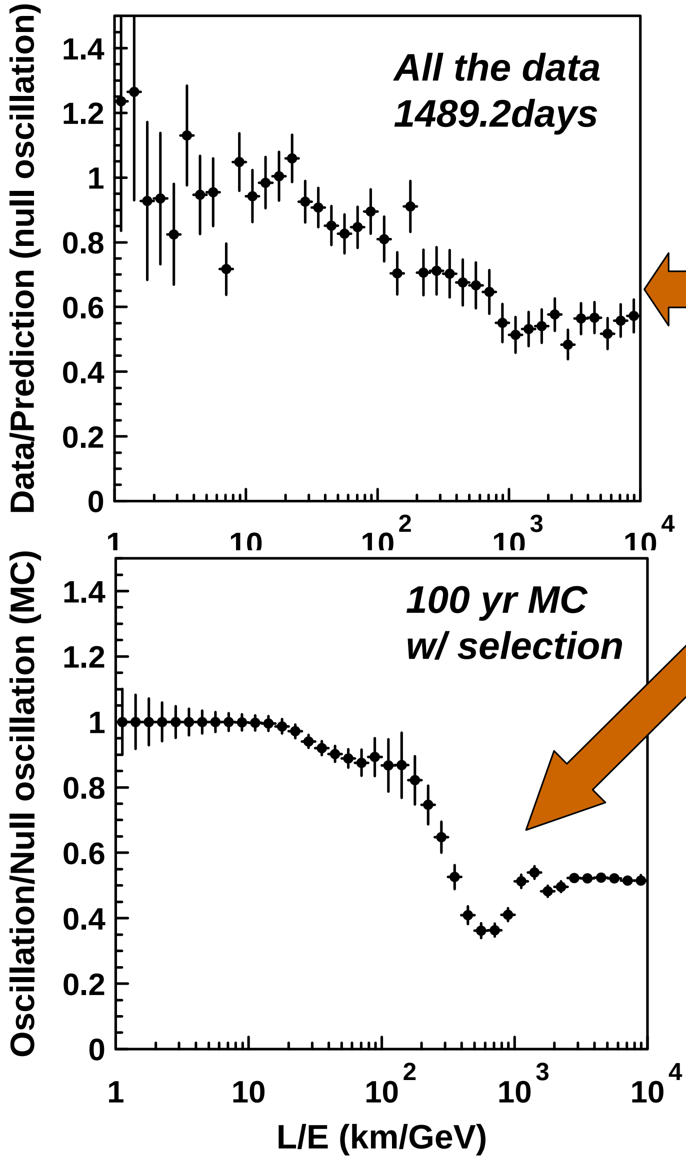
Decay

Decoherence

- Other models can also fit the measured zenith angle distributions.
- Distinguish Hypotheses in L/E

Dip for oscillation





Strategy

- Difficult to observe the dip
- Select events only with good L/E resolution
- The dip may be observed

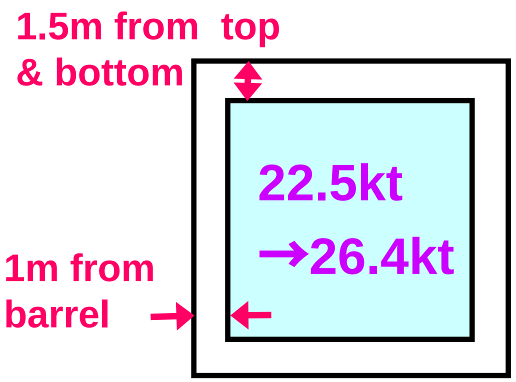
→Direct oscillatory evidence
→Strong constraint on the parameters; especially Δm^2

Event samples in L/E analysis

FC single-ring, multi-ring μ-like

Expand fiducial volume

→ **More statistics for high energy muons**

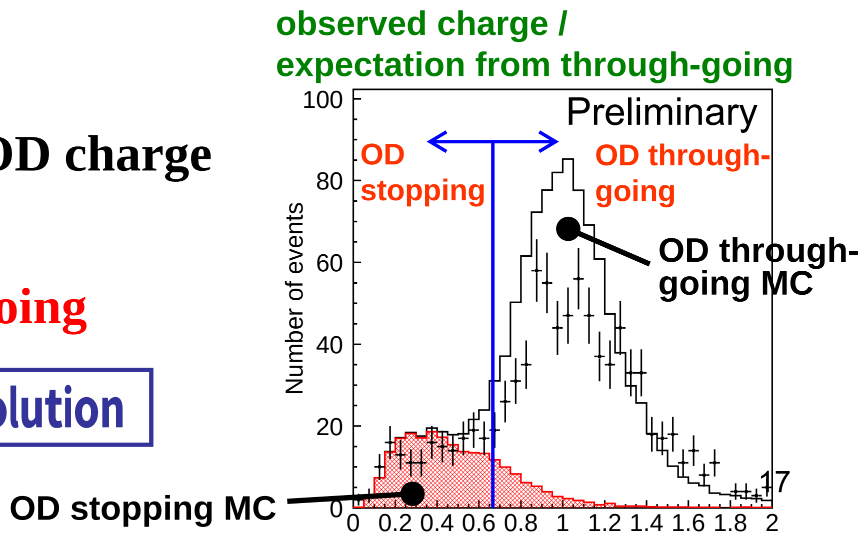


PC

Categorize PC events by OD charge

- I. OD stopping
- II. OD through going

→ **Different L/E resolution**



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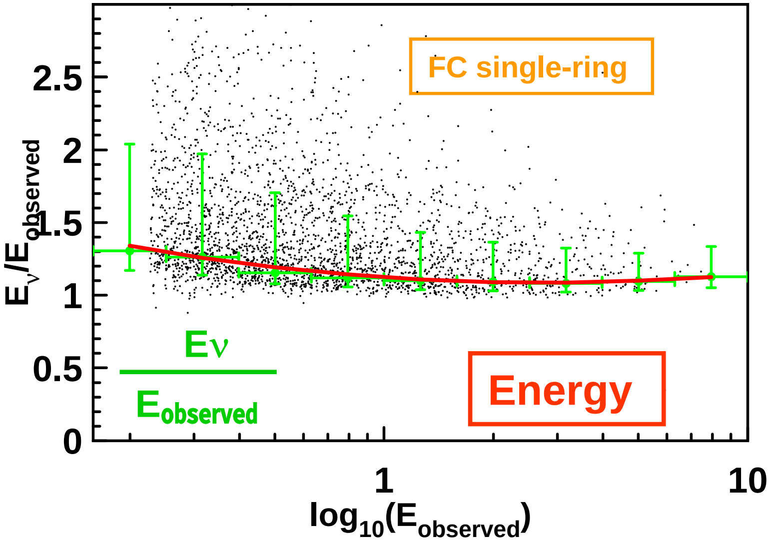
Event summary

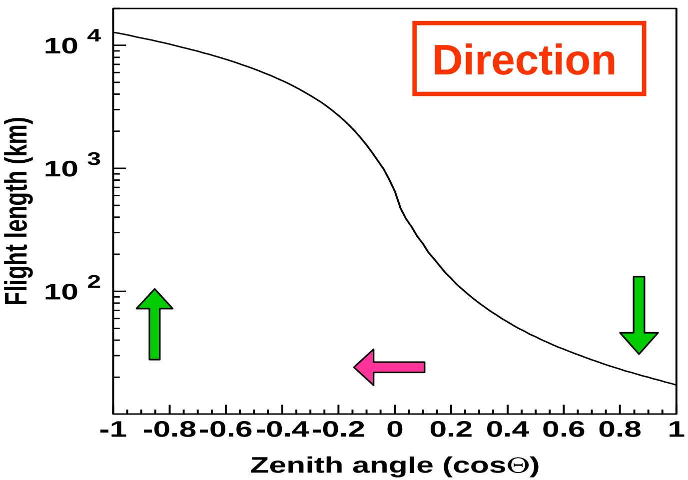
	Data	MC	CC ν_μ
FC			
single-ring	1619	2105.6	(98.3%)
multi-ring	502	813.0	(94.2%)
PC			
stopping	114	137.0	(95.4%)
through-going	491	670.1	(99.2%)
Total	2726	3725.7	

Reconstruction of E and L



$E_\nu \leftarrow E_{observed}$

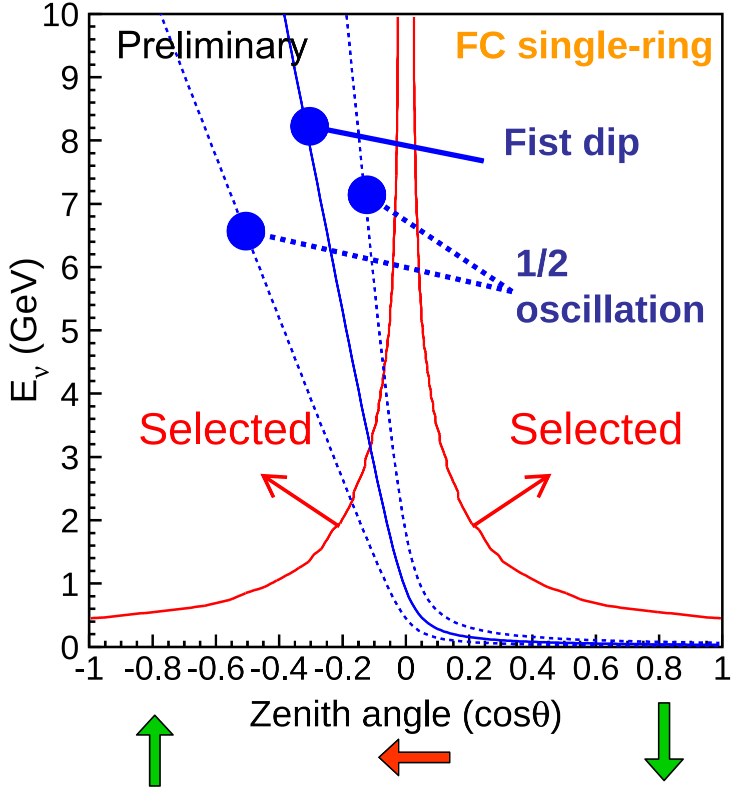
Reconstructed from observed energy using relations based on MC simulation



Flight length (L) ← Zenith angle

Estimated from the zenith angle of the particle direction

L/E resolution cut



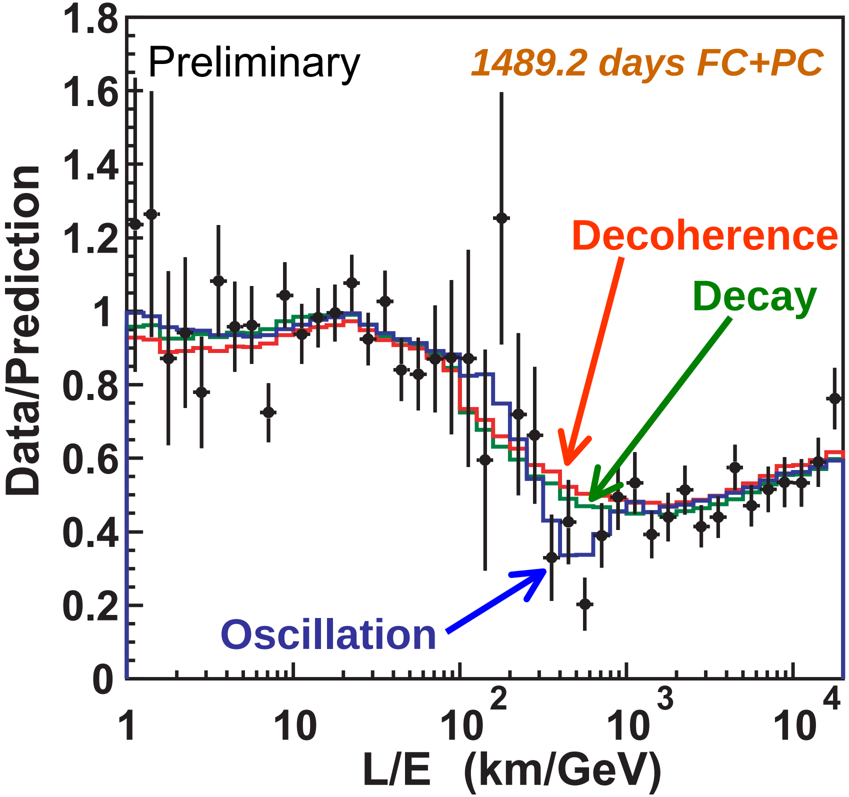
Select events with $\Delta(L/E) < 70\%$

Reasons for the rejected events

horizontally going events:
→ due to large dL/dcosθ

low energy events:
→ due to large scattering angle

Result of L/E analysis



- The first dip has been observed.
- This provide a strong evidence of neutrino oscillation.
- The first dip observed cannot be explained by other hypotheses

3.4 σ to decay
3.8 σ to decoherence

Oscillation	χ^2_{min}=37.8/40 d.o.f
Decay	χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$ =11.4
Decoherence	χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$ =14.6

Definition of χ^2

$$L\,(N_{\exp}, N_{obs}) = \prod_{n=1}^{43} \frac{\exp(-N_{\exp}^{n})(N_{\exp}^{n})^{N_{obs}^{n}}}{N_{obs}^{n}!} \times \prod_{i=1}^{25} \exp\left(\frac{-\varepsilon_i^2}{2\sigma_{\mathrm{i}}^2}\right)$$

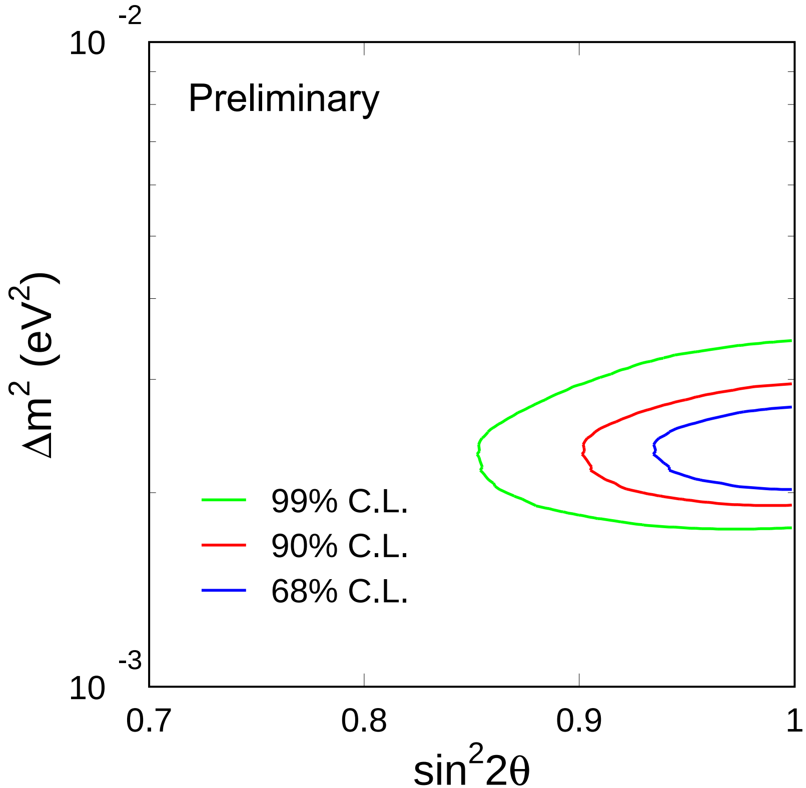
Poisson with systematic errors

$$\chi^2 \equiv -2\ln\left(\frac{L\,(N_{\exp}, N_{obs})}{L\,(N_{obs}, N_{obs})}\right) = \sum_{n=1}^{43}\left[2(N_{\exp}^{n} - N_{obs}^{n}) + 2N_{obs}^{n}\ln\left(\frac{N_{obs}^{n}}{N_{\exp}^{n}}\right)\right] + \sum_{i=1}^{25}\left(\frac{\varepsilon_i}{\sigma_i}\right)^2$$

N_{obs} : observed number of events
N_{exp} : expectation from MC
ε_i : systematic error term
σ_i: sigma of systematic error

Various systematic effects in detector, flux calculation and neutrino interaction are taken into account

Constraint on the neutrino oscillation parameters from L/E analysis



Best Fit:

$\Delta m^2 = 2.4 \times 10^{-3}, \sin^2 2\theta = 1.00$

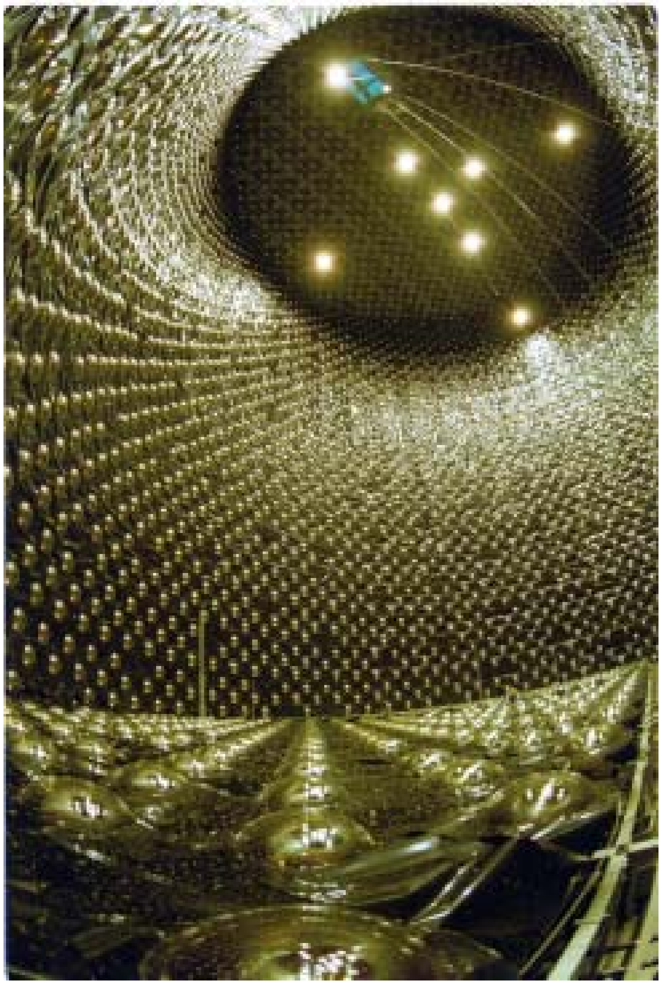
$\chi^2_{min} = 37.8/40$ d.o.f.

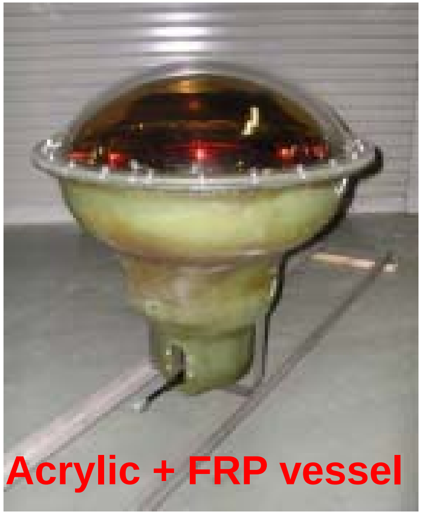
($\sin^2 2\theta = 1.02$, $\chi^2_{min} = 37.7/40$ d.o.f)

Allowed region (@90%C.L.)
$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2
$0.90 < \sin^2 2\theta$

Consistent with the standard zenith angle analysis

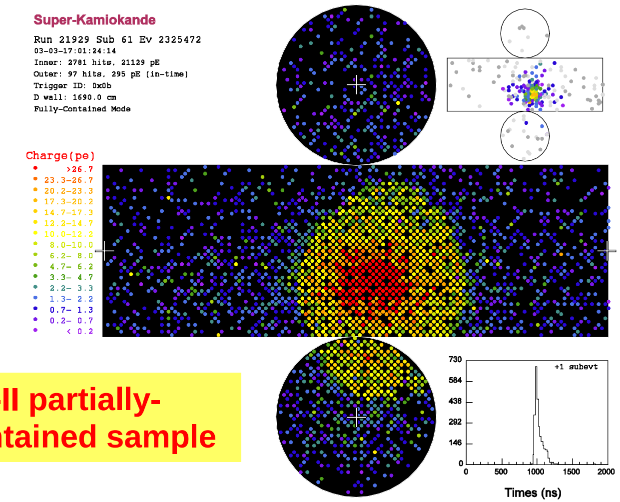
Reconstruction of Super-K II



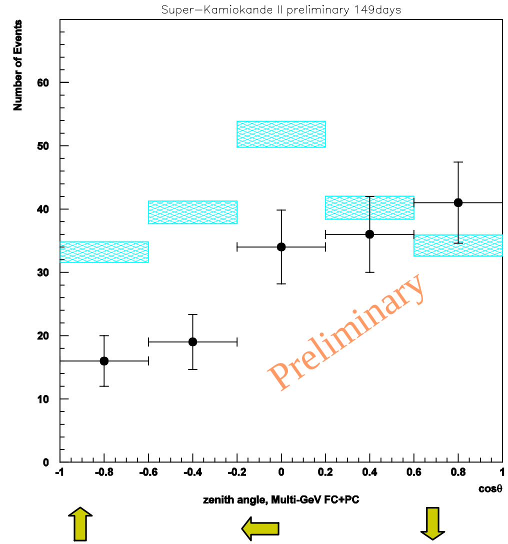


- **Reconstructed in October 2002**
  - 47% of the PMTs (~5200)
  - Full OD 8 inch PMTs (1885)
  - PMTs in plastic shells to prevent future chain implosions

SK-II is taking data, started in December, 2002



SK-II partially-contained sample



Multi-GeV FC μ-like +PC

Number of events & Event rate

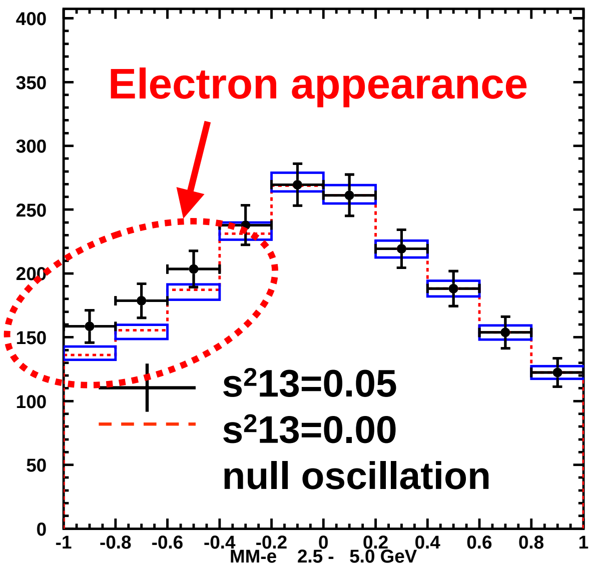
(Preliminary)

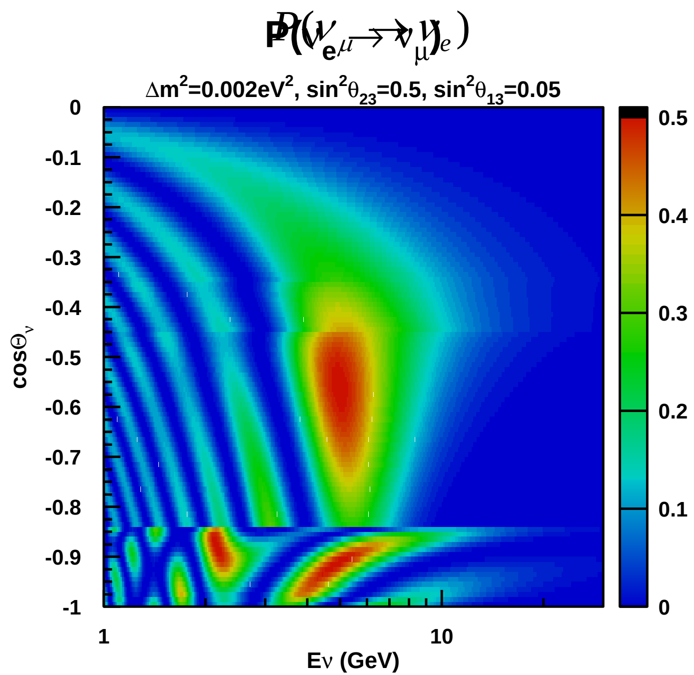
	SK-II 149.3 days	SK-I 1489 days
Fully-contained	1245 (8.33±0.24)	12180 (8.18±0.07)
Partially-contained	80 (0.54±0.06)	911 (0.62±0.02)

θ_{13} measurements in atmospheric neutrinos in Future

Sk 20yr (450ktonyr)

1+multi-ring, e-like, 2.5 - 5 GeV

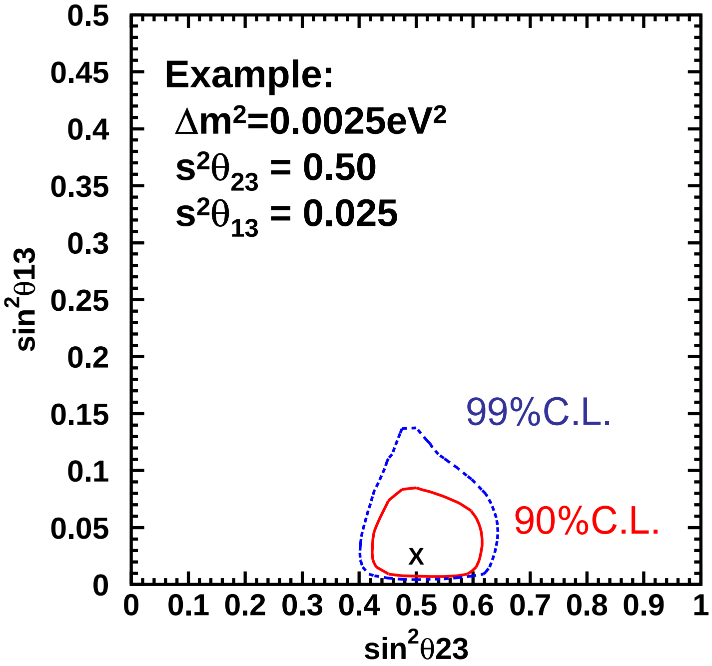


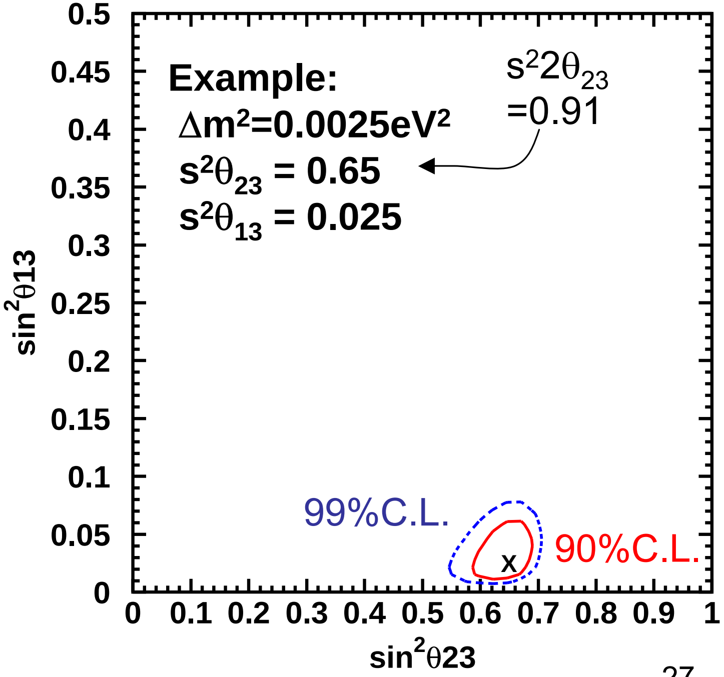


Matter Effect

SK 20 yrs

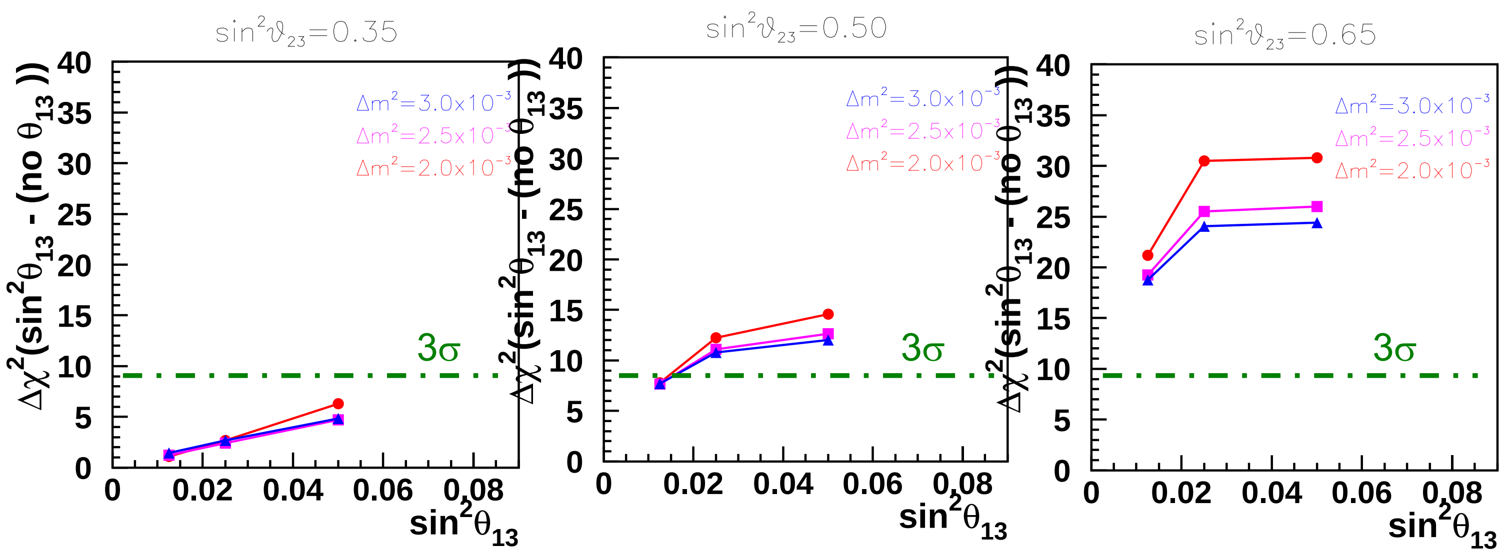
$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right) +$$





Sensitivity for non-zero θ_{13}

SK 20 years (450 ktonyr)



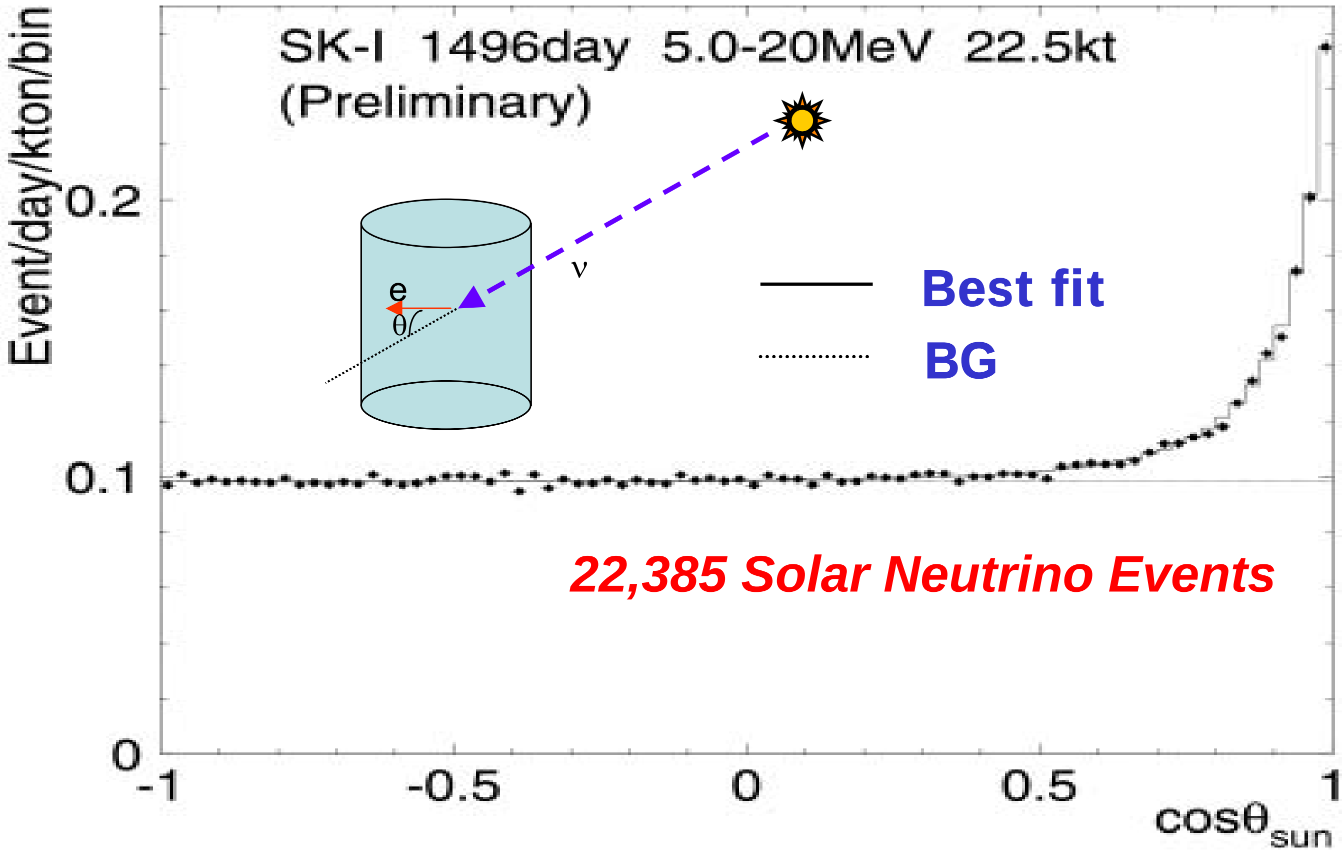
($\Delta\chi^2 \propto \sim$ exposure)

Solar neutrinos

- Original Aim of Super-K Solar Neutrino
  → detect flux independent evidence
    - Day/night flux difference, spectrum distortion, seasonal variation
- But the evidence was obtained by the comparison of SK (ES) & SNO (CC) flux in 2001.
- And we still have not seen such direct evidence yet.

Solar Neutrino Signal in SK

May 31, 1996 – July 13, 2001



SK-I 1496 day final data

- 22,385 solar neutrino events

^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^{6} /cm^{2}/sec]

48,200 solar neutrino

$$\frac{\text{Data}}{\text{SSM(BP2000)}} = 0.465 \pm 0.0$$

BP2004 (~15% diff.)
5.82(1±0.23) x 10^{-6} / cm^{2} / s
Bp2000:
5.05(1 $^{+0.20}_{-0.16}$) x 10^{-6} / cm^{2} / s

- 16,700 *e*-type solar neutrinos (from SNO)
- About 5,700 μ/τ-type solar neutrinos

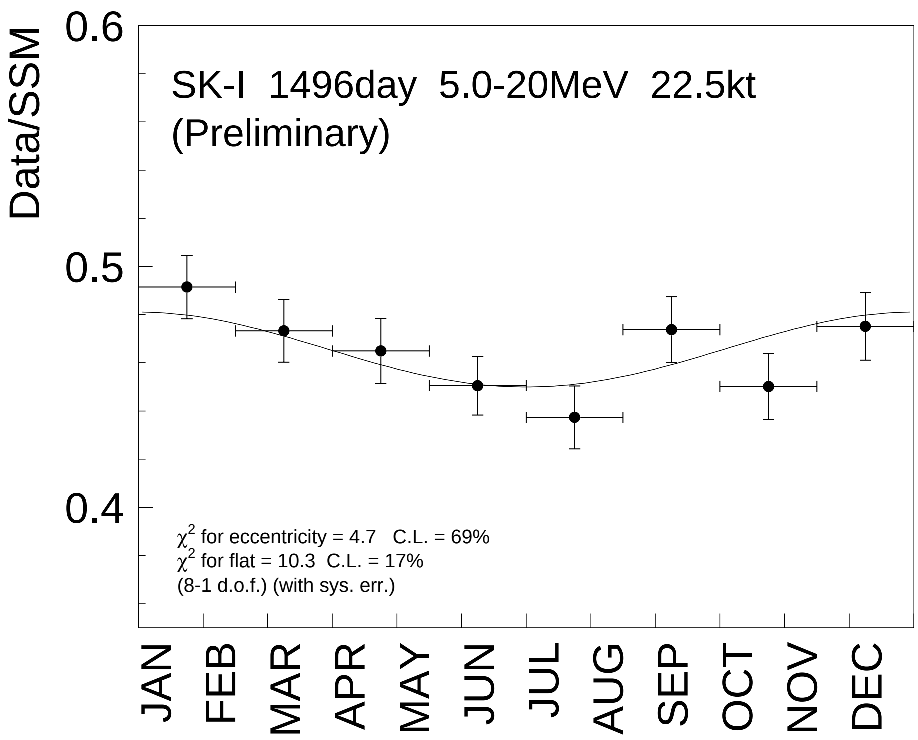
Evidence for the Flavor Conversion

Day-Night Flux difference

$\phi(^{8}B)_{day}$ = 2.32 ± 0.03 $\pm^{0.08}_{0.07}$ $\phi(^{8}B)_{night}$ = 2.37 ± 0.03 ± 0.08

$$\frac{D-N}{(D+N)/2} = -(0.021 \pm 0.020 \pm^{0.013}_{0.012})$$

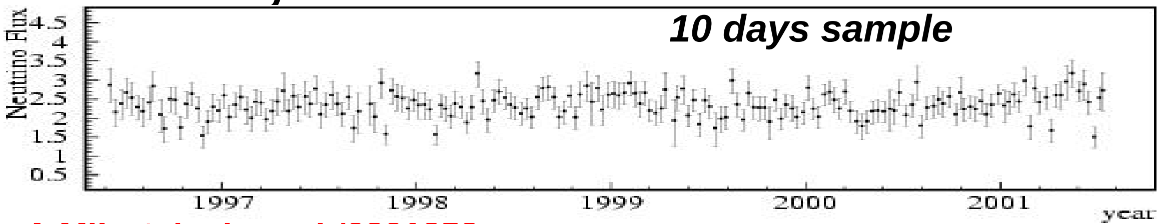
Seasonal variation



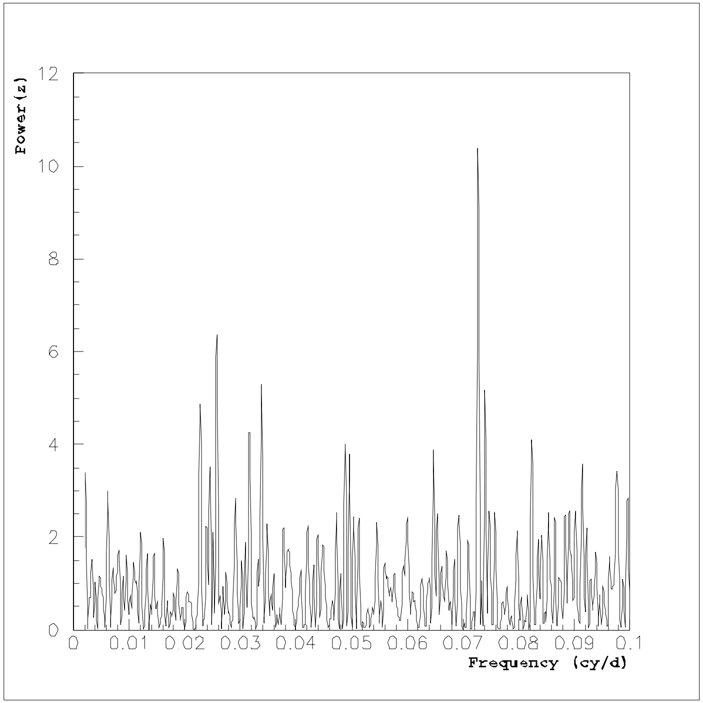
$\chi^2 = 4.7 / 7$dof (eccentricity) ; $\chi^2 = 10.7 / 7$dof (flat)

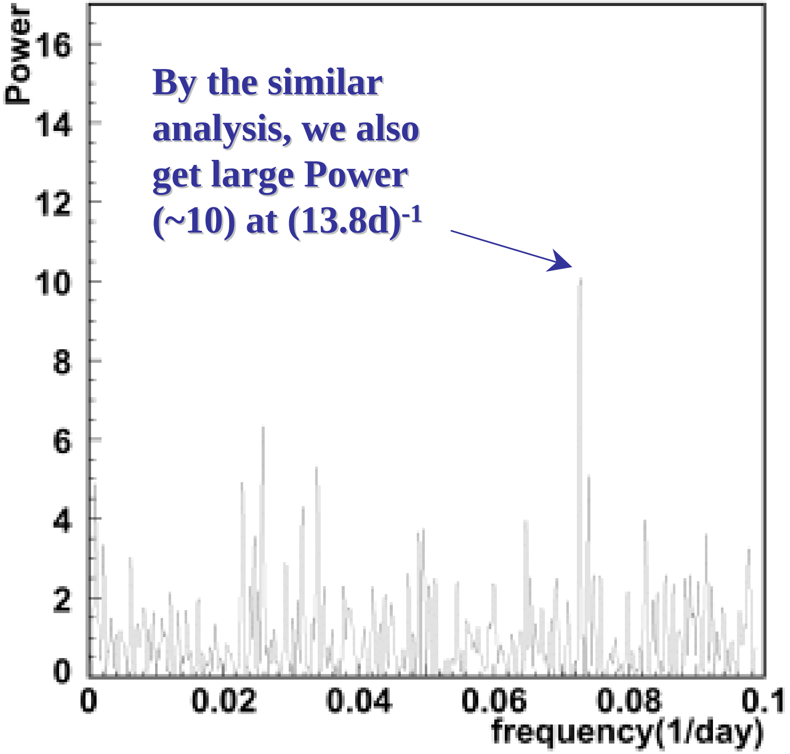
Consistent with the expectation from the earth's eccentricity

Periodicity in the SK solar neutrino data?



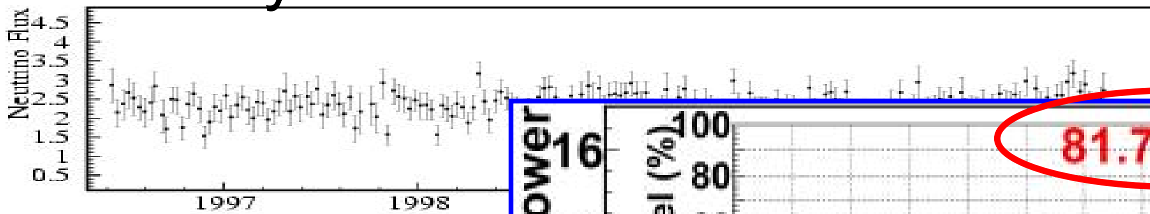
A.Milsztajn, hep-ph/0301252

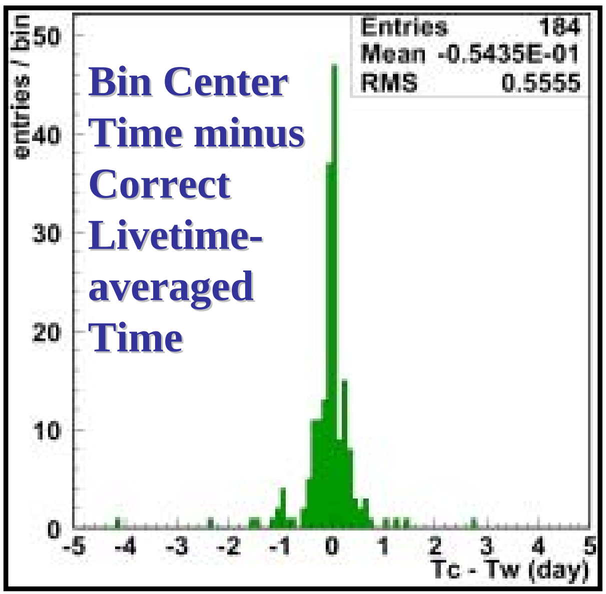


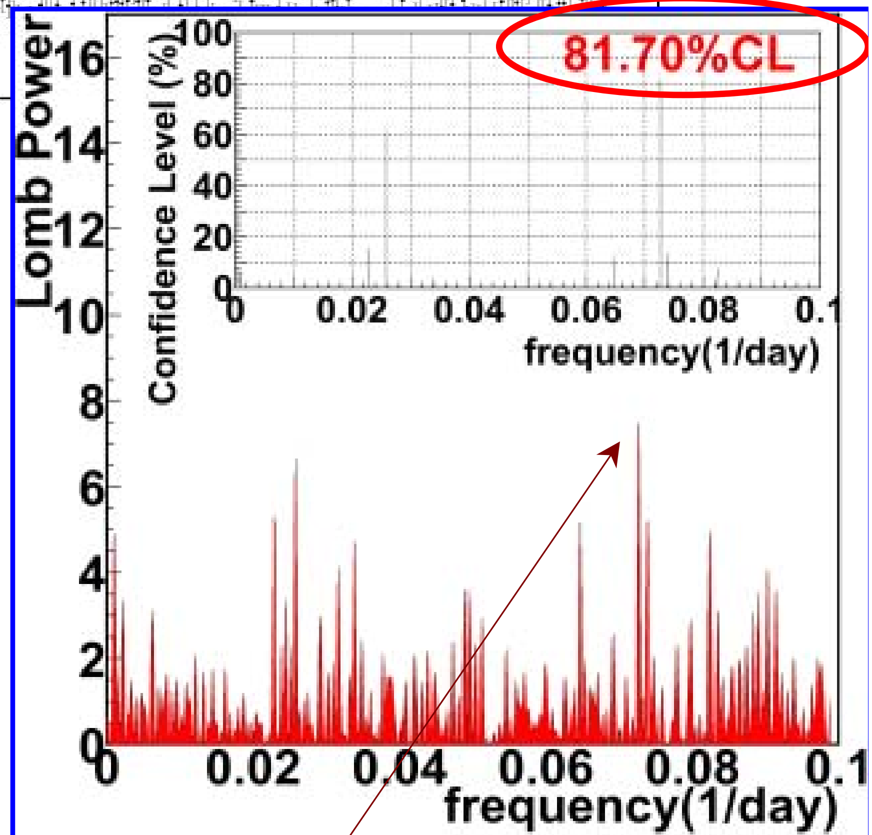


T = 13.75 days (98.9%C.L.)

Periodicity in the SK solar neutrino data?

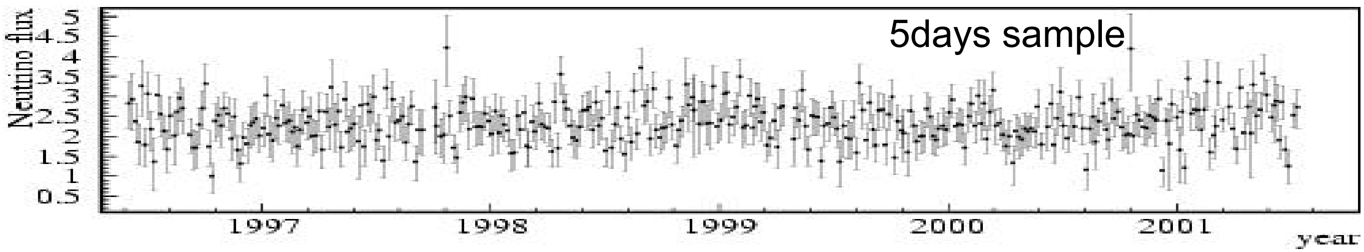




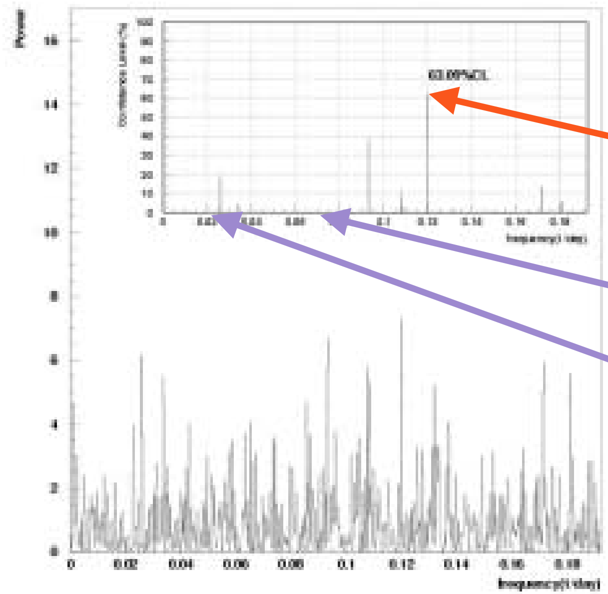


Lomb Power decreases, if Correct bin-time is used!!

5 days sample



Lomb method



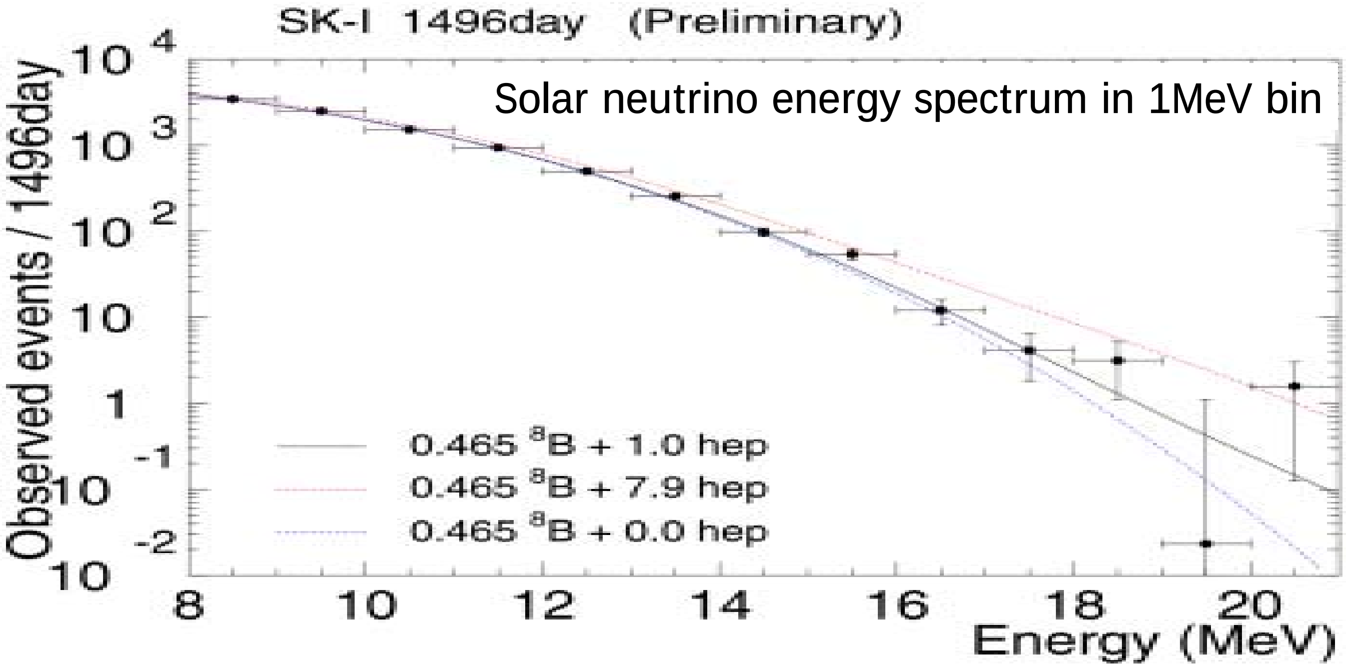
8.35 day (63.09%CL)

13.75 day

38.70 day

No Significant Periodicity

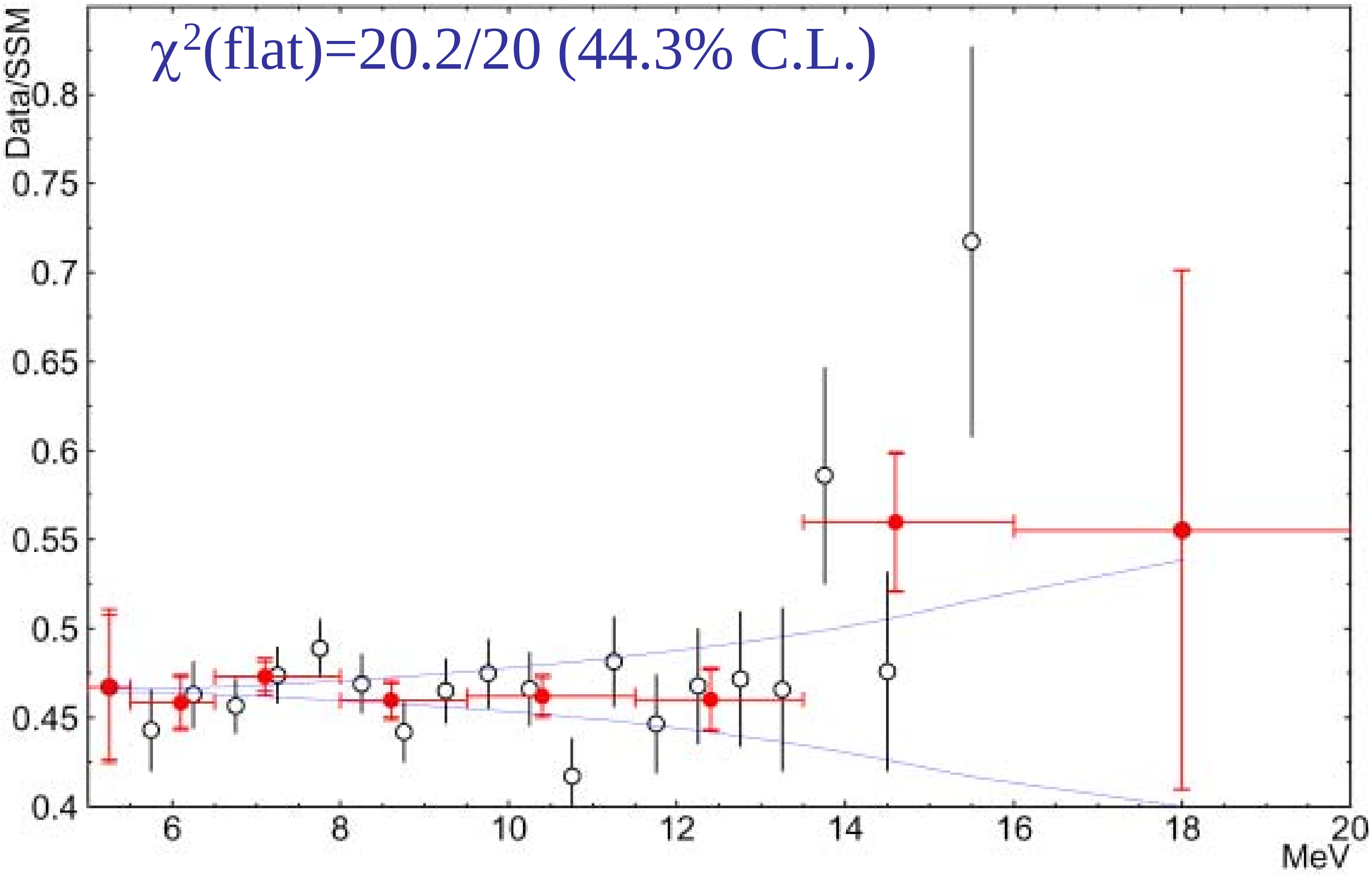
hep neutrinos



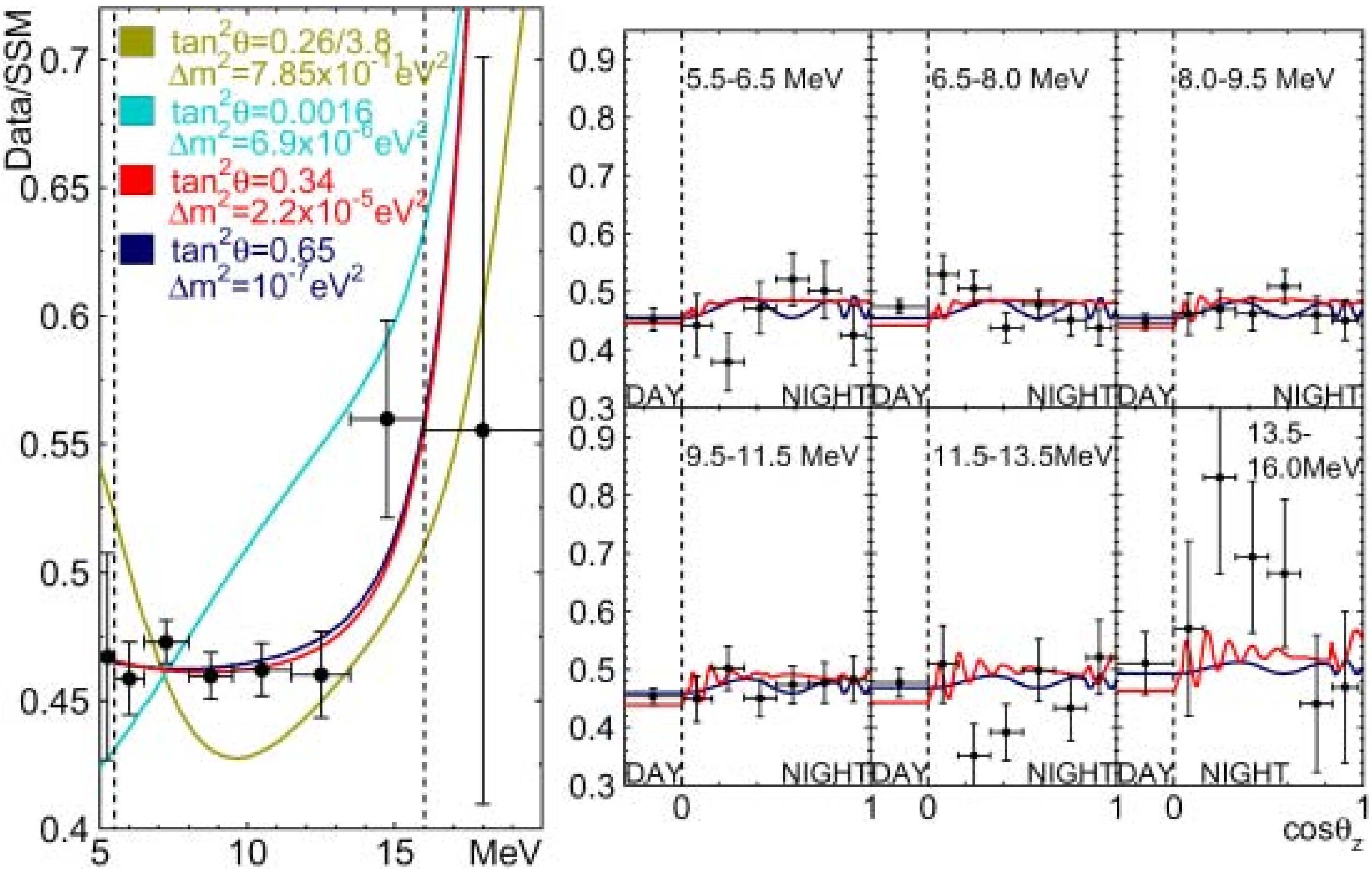
In 18~21 MeV : 4.9 ±2.7 events
Expect ~1.06 hep neutrino from SSM

***hep* flux upper limit < 73 [x10³/cm²/s] (90%C.L.)**
(< 7.9 x SSM(BP2000))

Recoil Electron Spectrum



Zenith Spectum of SK: Data & Solutions



Zenith 'seasonal' spectrum likelihood (new)

Likelihood for solar neutrino extraction

 # Backgrounds in each energy bins — **# Signal Events** — **Event Energy** — **Event "Time"**

$$\mathbf{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(B_i \cdot u_i(c_\nu) + m_i S \cdot p(c_\nu, E_\nu) \times z_i(t_\nu)\right)$$

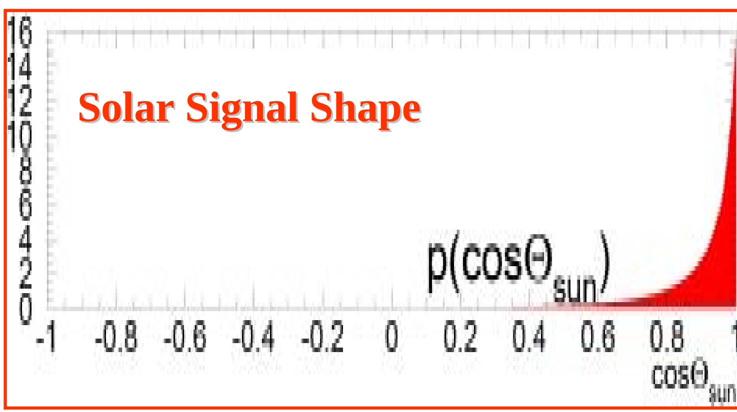
21 Energy bins

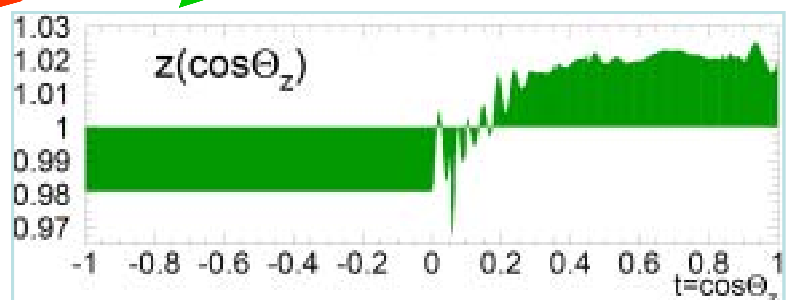
Background Shape

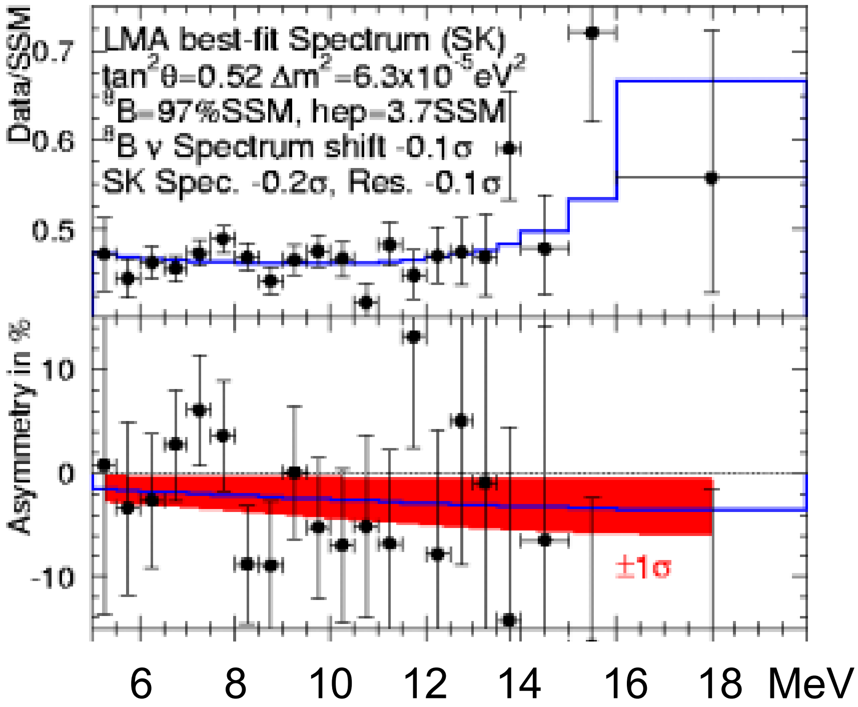
$\cos\theta_{sun}$

$$m_i = \frac{\mathrm{MC}_i}{\sum_j \mathrm{MC}_j}$$

All the time information Is added (un-binned) Including seasonal inf.



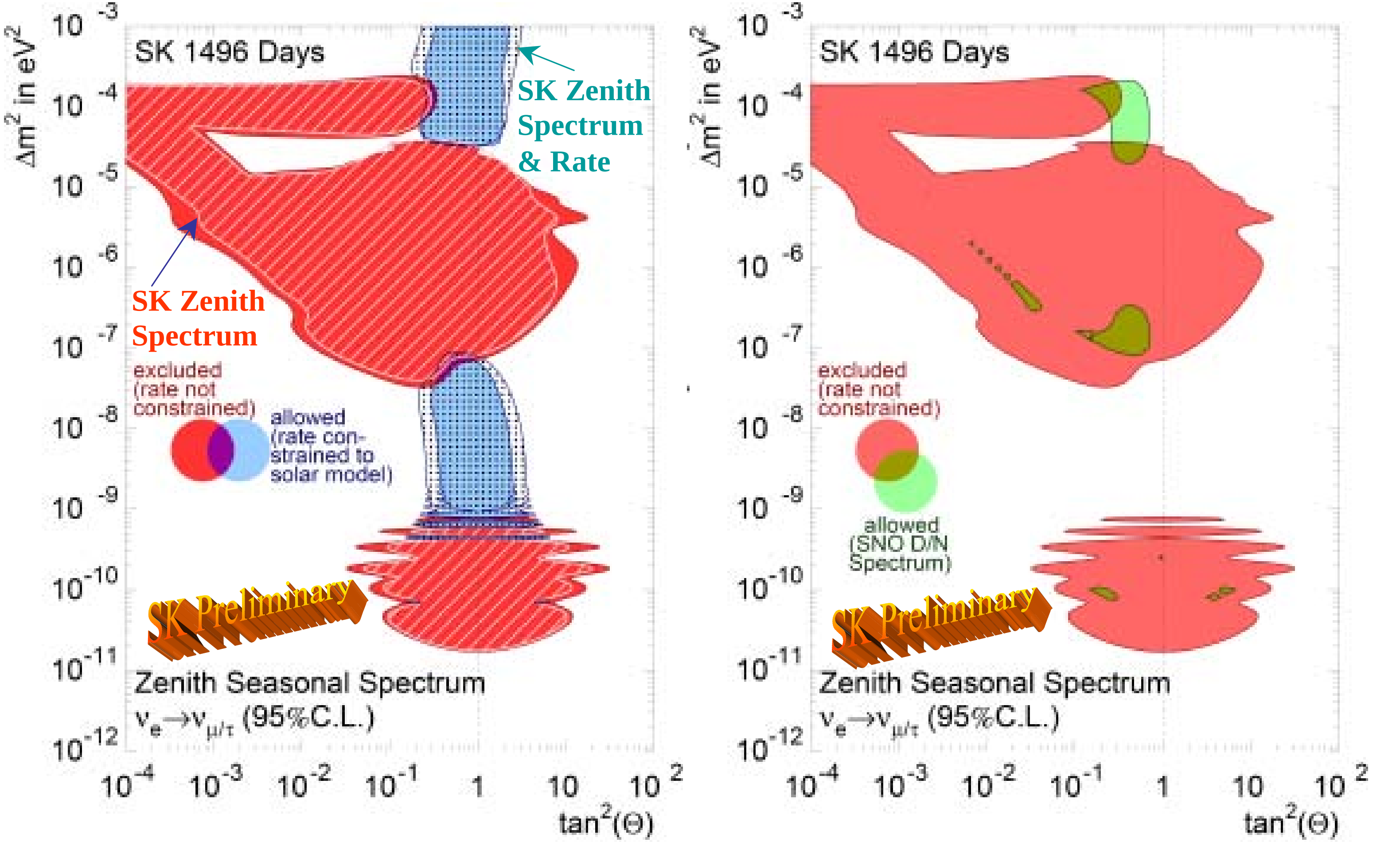




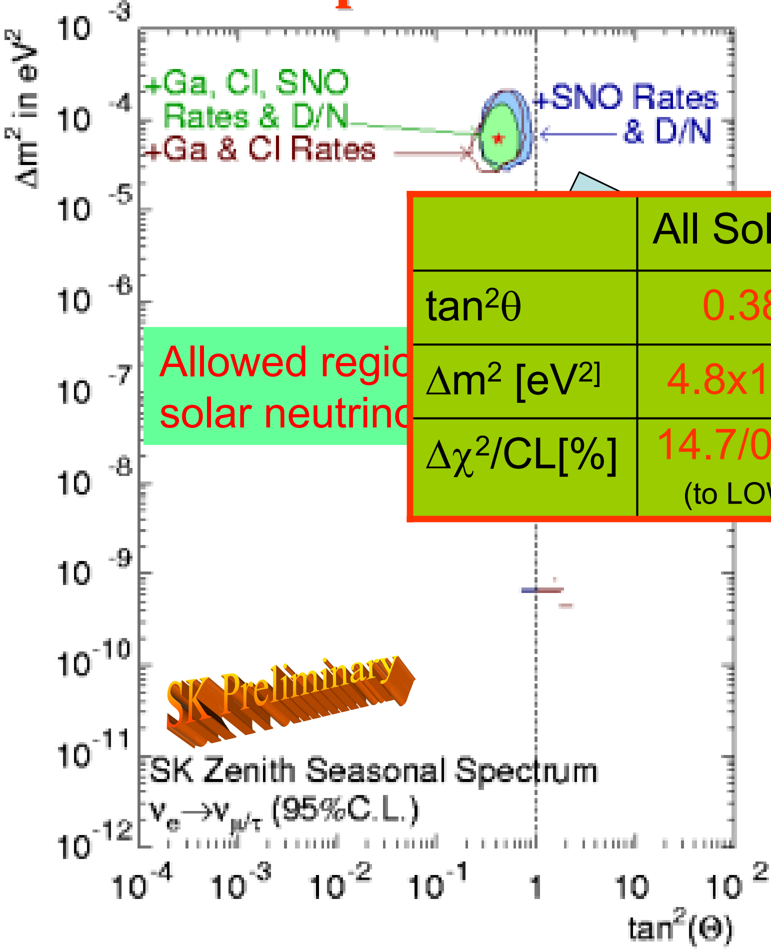
A_{ND} = -1.8 $\pm$ 1.6$^{+1.3}_{-1.2}$ %

consistent with -2.1%

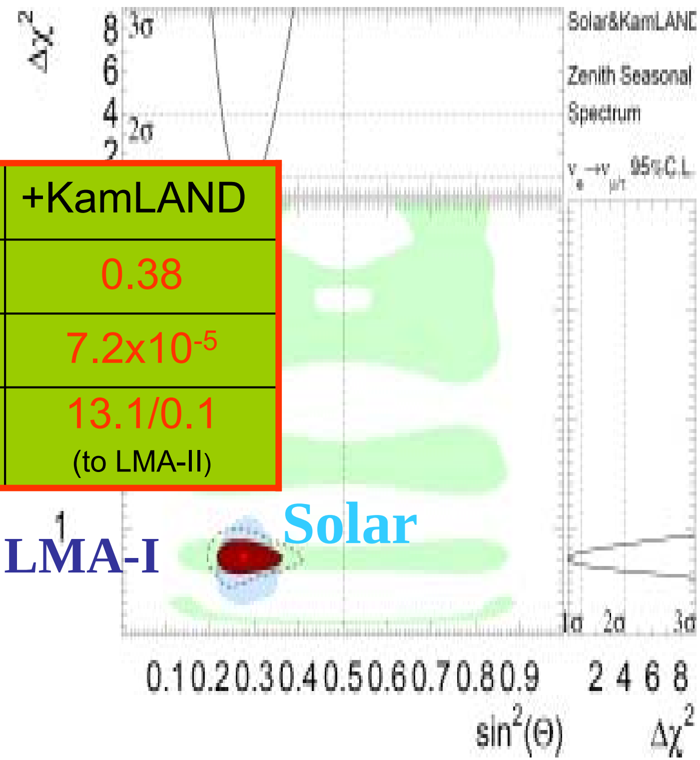
Parameter constraint from SK data



All solar neutrino experiments

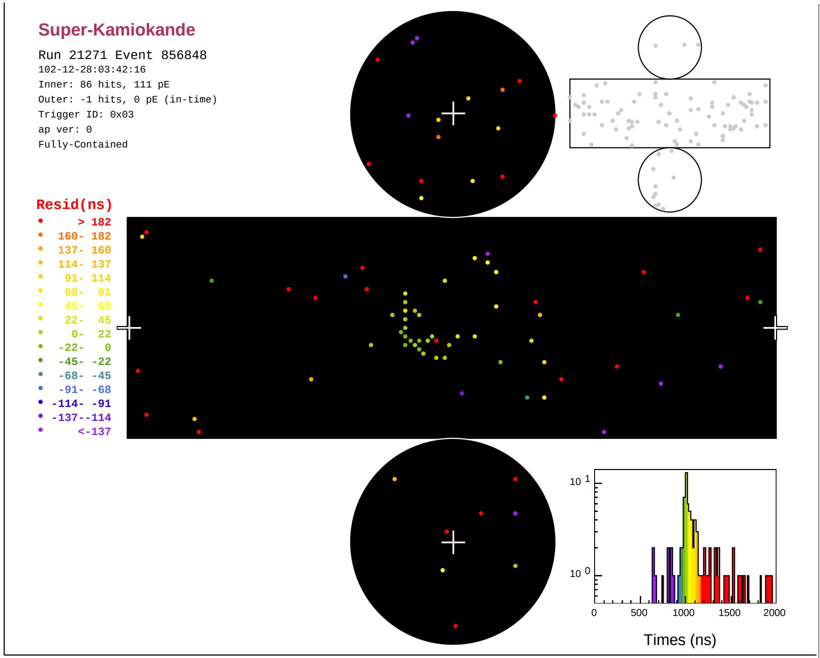


	All Solar	+KamLAND
$\tan^2\theta$	0.38	0.38
Δm^2 [eV^2]	4.8×10^{-5}	7.2×10^{-5}
$\Delta\chi^2$/CL[%]	14.7/0.06 (to LOW)	13.1/0.1 (to LMA-II)

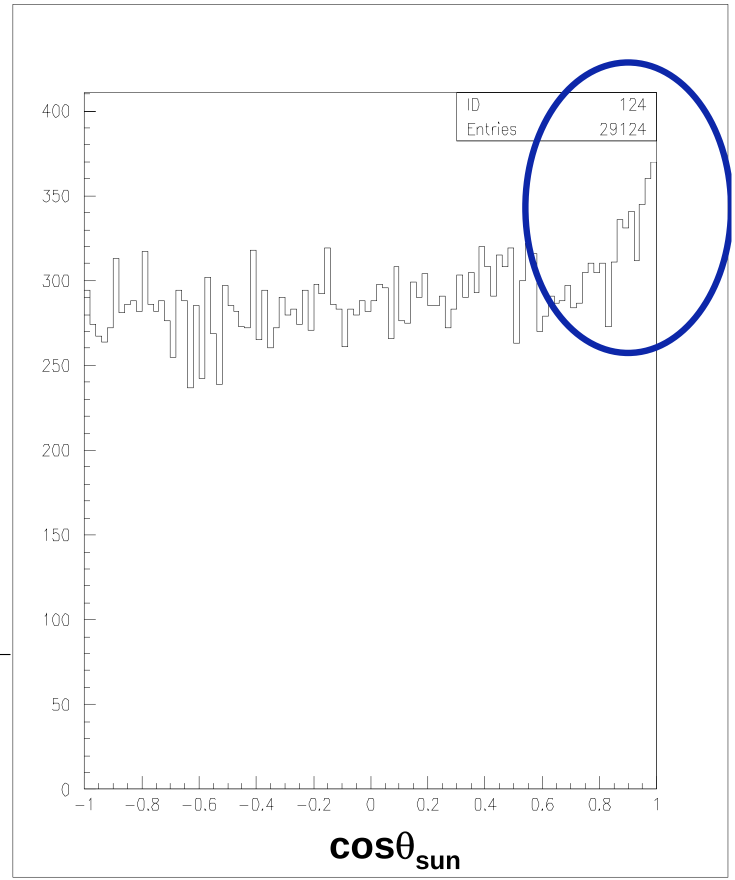


KamLAND analysis from:
hep-ph/0302230v2 (A. Ianni)

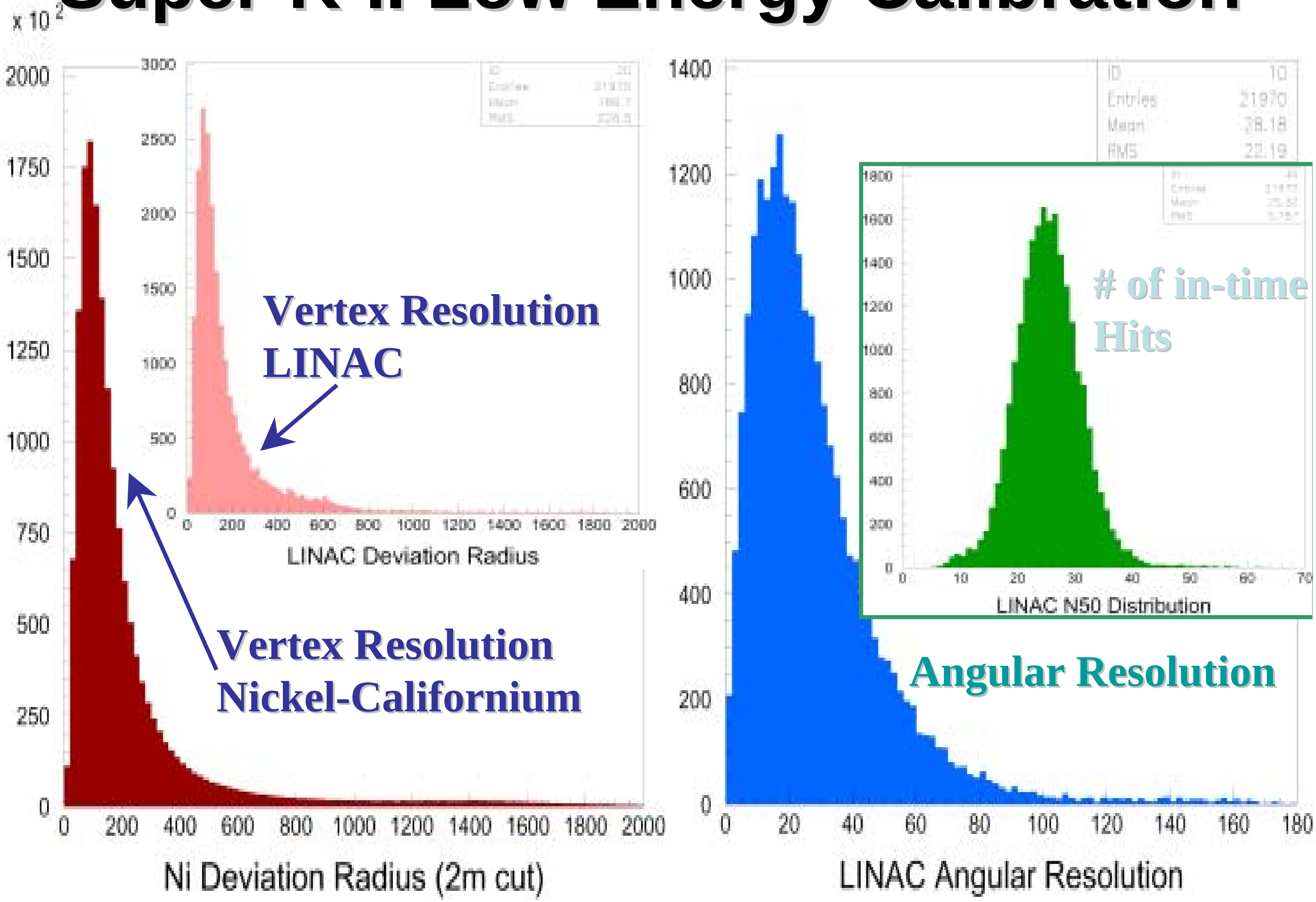
SK-II



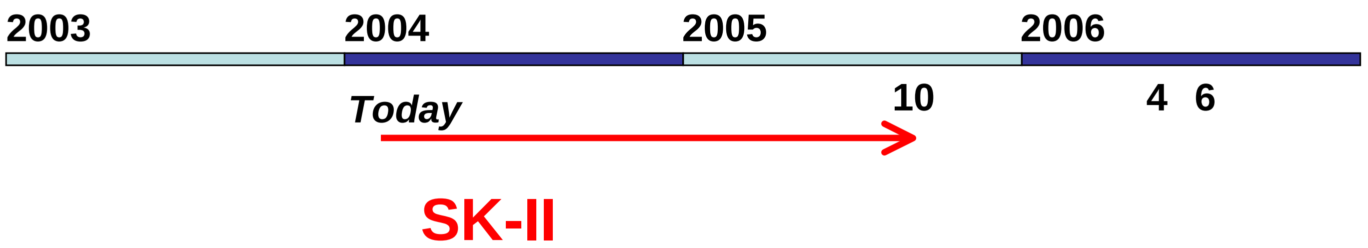
Typical low energy event



Super-K-II Low Energy Calibration

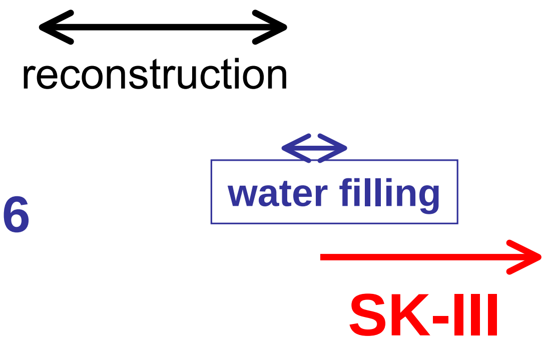


Full reconstruction schedule (approved)



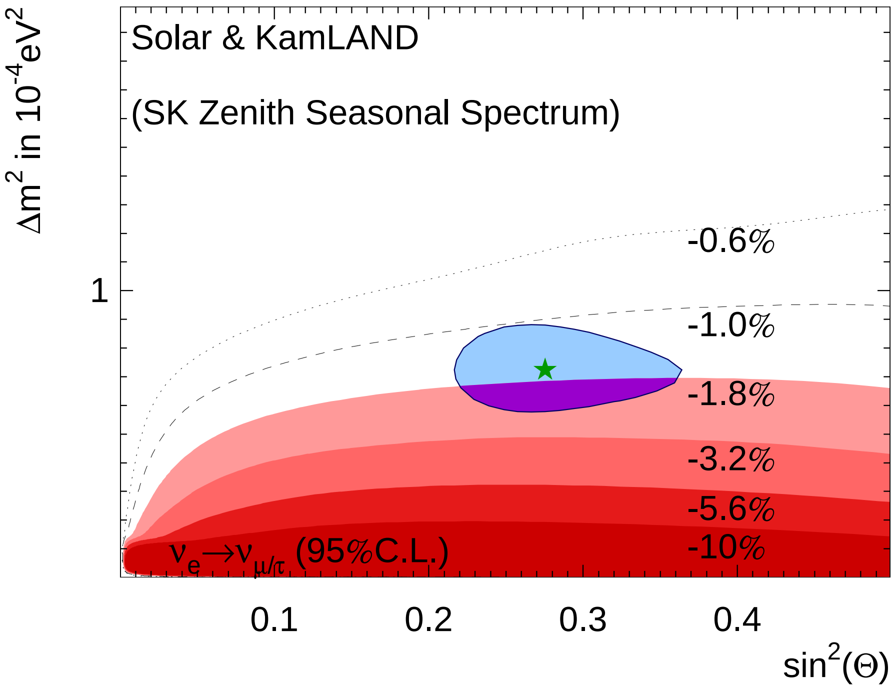
- **Reconstruction:**

  Nov,2005 to March, 2006
- **Water filling: April and May in 2006**
- **Start taking data from June 2006**

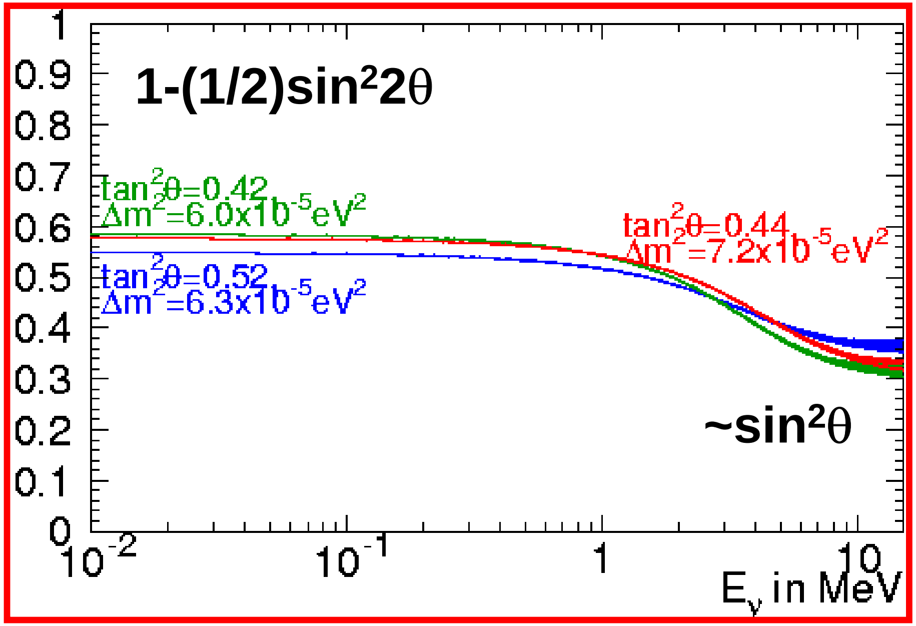


Future solar neutrino observation in Super-K

Day / Night flux differences

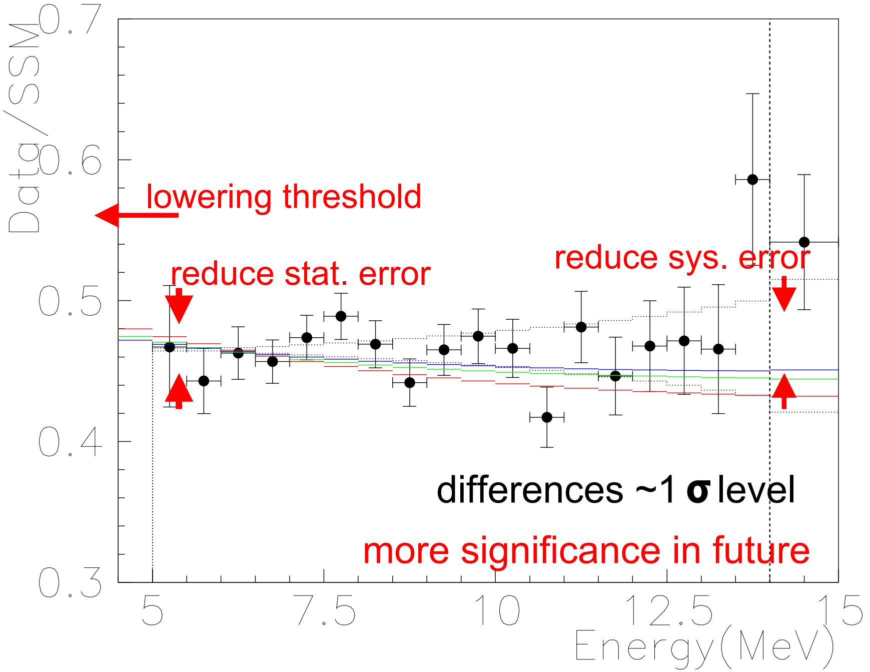


Future solar neutrino observation in Super-K

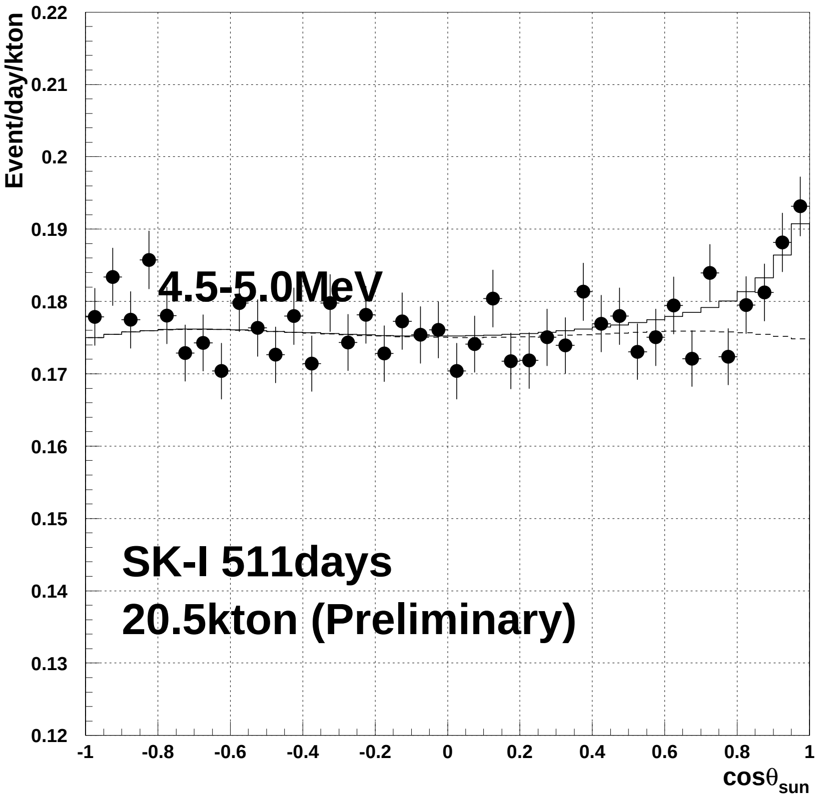


Upturn in low energy is expected for LMA

Future solar neutrino observation in Super-K



Lowering threshold



In SK-I, after install the 2nd level trigger system, the efficiency above 4.5MeV became ~100% (Sep. 2000~)

Remaining B.G. for lower energy
→gamma from the rock
→radio isotope (e.g. Rn)

Acrylic cover againt Rn From PMT (for SK-III)

Possibility to lower the threshould Below 4.0 MeV

END