Recent results of Super-Kamiokande

Y. Koshio
Kamioka observatory
ICRR, Univ.of Tokyo

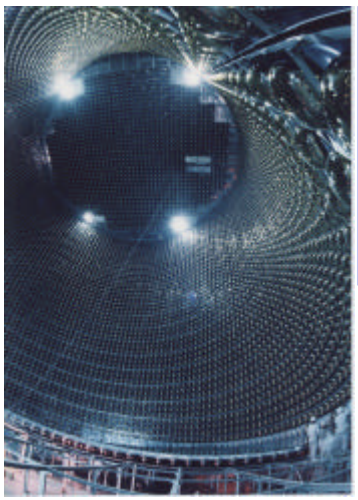
- Status of Super-Kamiokande
- Atmospheric neutrinos
- Solar neutrinos
- Summary

Status of Super-Kamiokande

We are now here

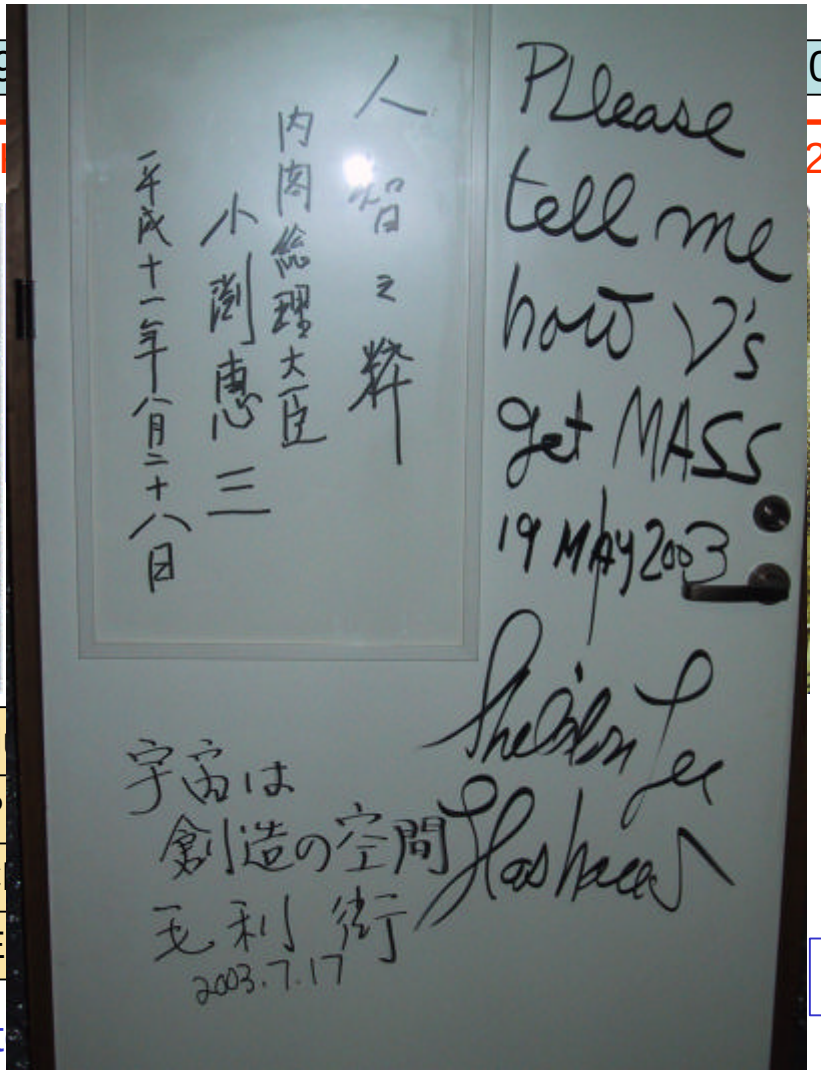
1996 | 1997 | 199 | 04 | 2005 | 2006 | 2007

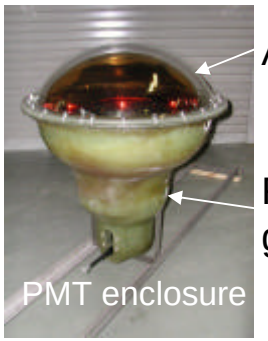
SK-2 | reconstruction and water filling | SK-3



11146	N
40%	P
~6 p.e./MeV	C
5MeV	E

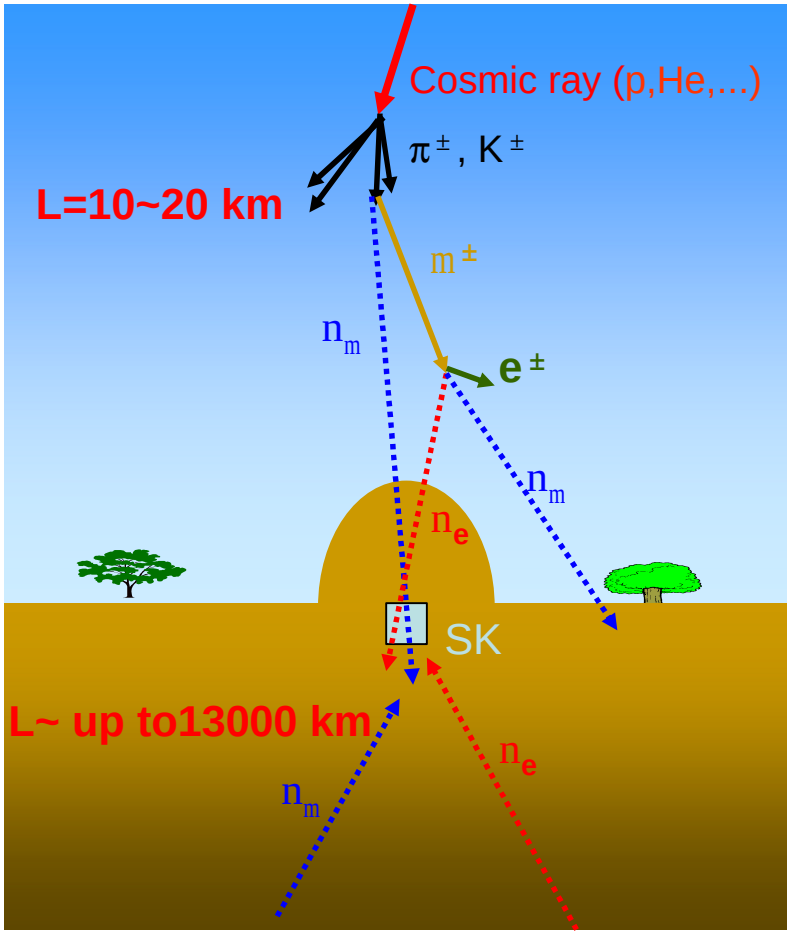
Number of inner det

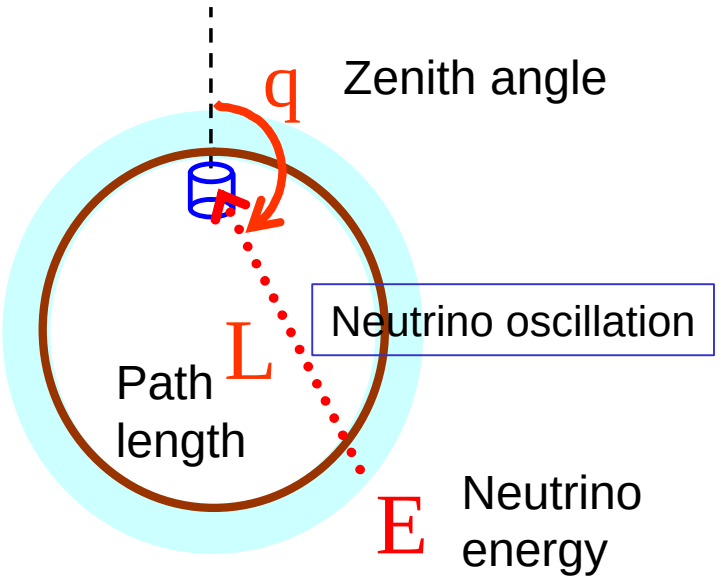




SK-3 start **June 2006**

Atmospheric Neutrinos

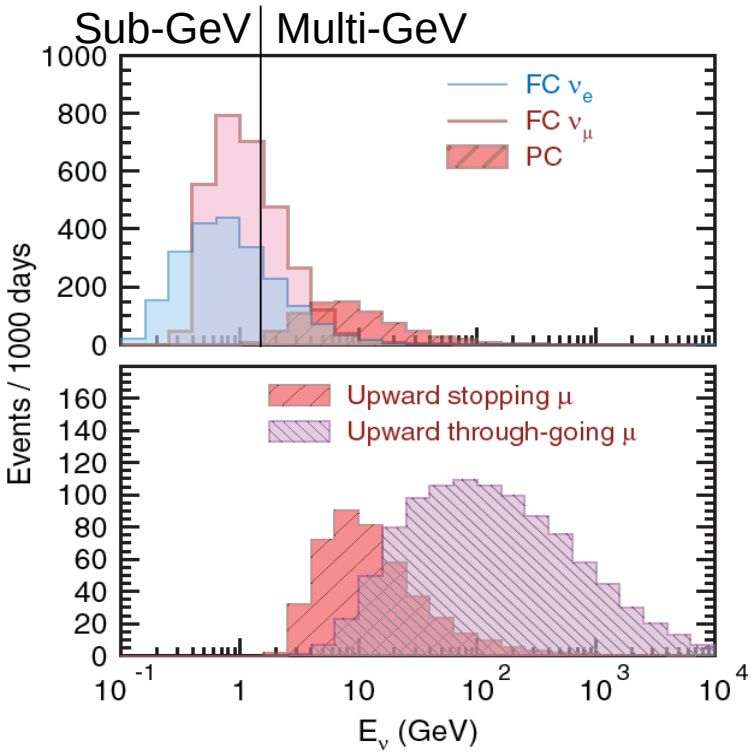




Interaction in Super-K

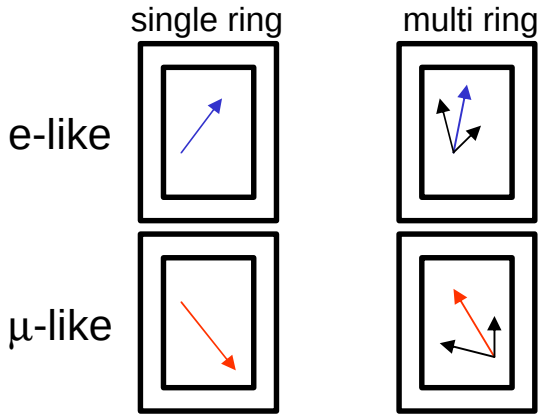
- $\nu + N \rightarrow l + N'$
- $\nu + N \rightarrow l + N' + \pi$
- $\nu + N \rightarrow l + N' + \text{multi-}\pi$
- $\nu + {}^{16}O \rightarrow l + {}^{16}O + \pi$

Energy distribution

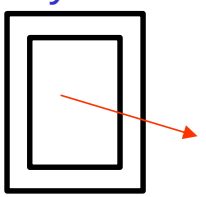


Event categorized

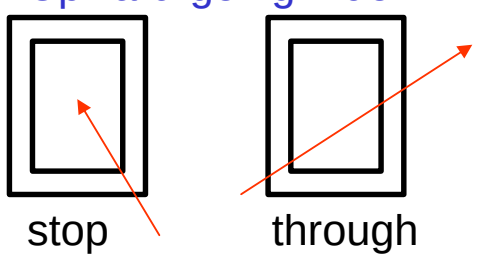
Fully-contained



Partially-contained



Upward-going muon

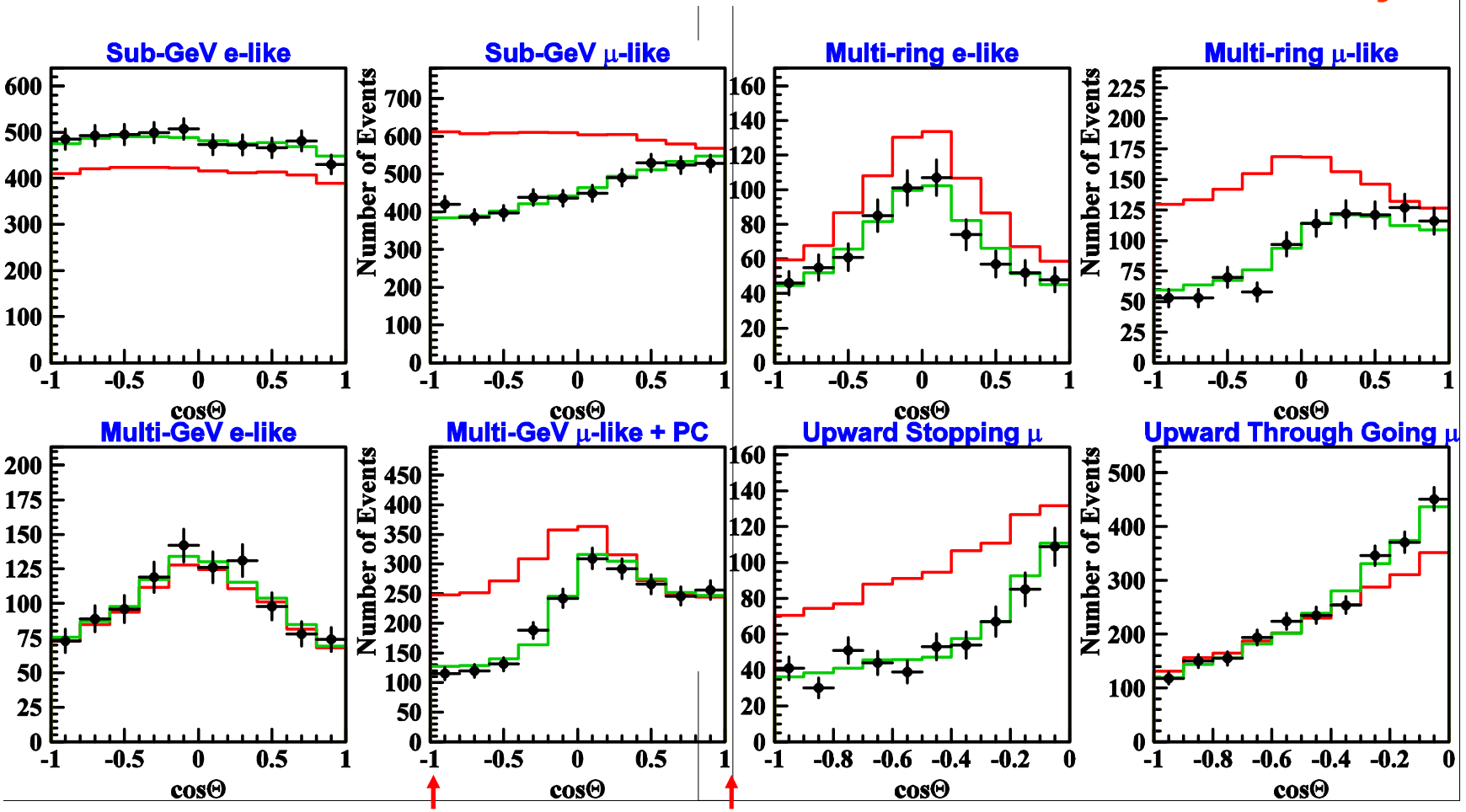


Zenith angle distribution in SK-1 and SK-2

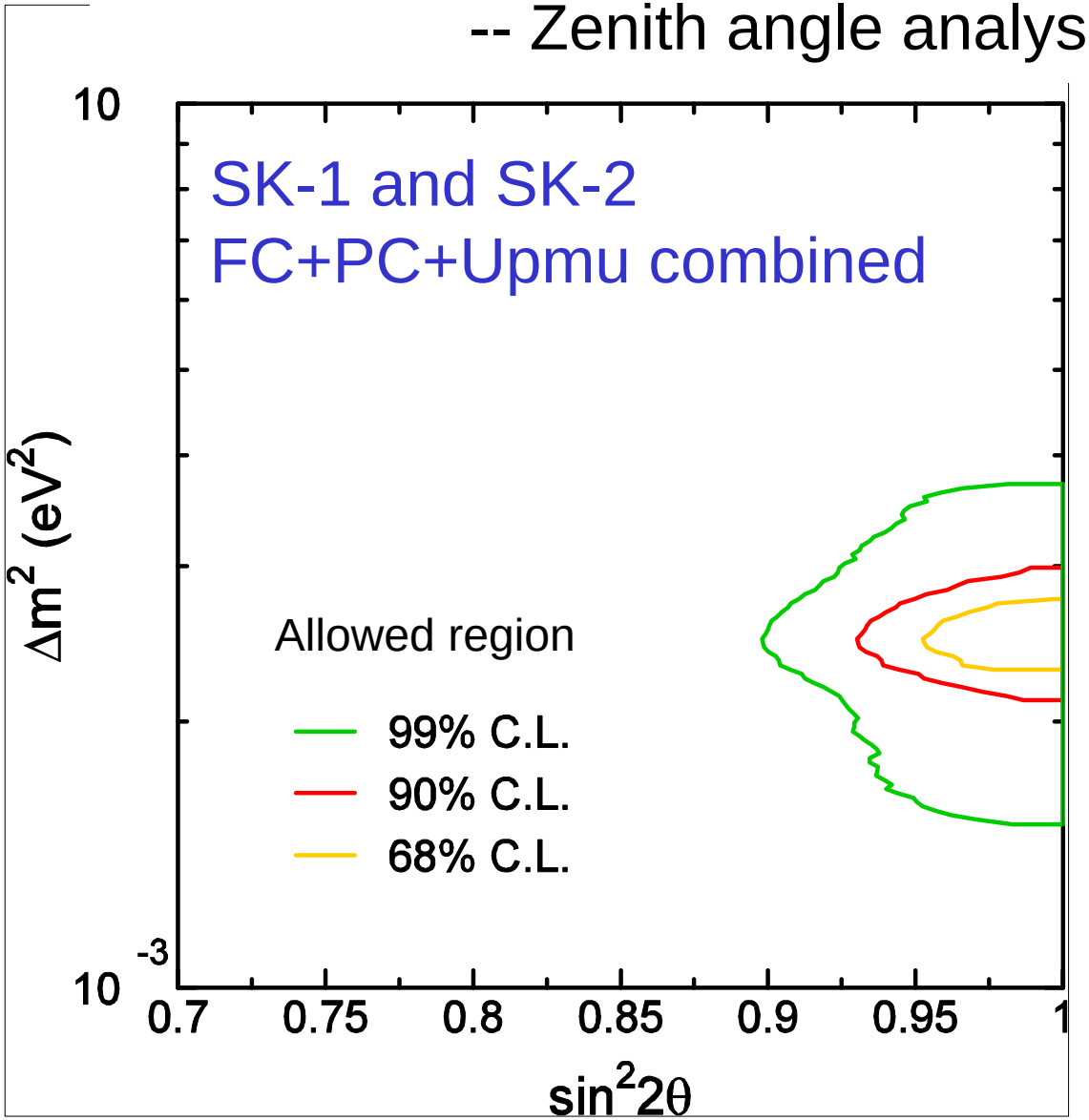
1489days of SK-1 data
627 days of SK-2 data

SK-I + SK-II

Preliminary !



2 flavor neutrino oscillation
-- Zenith angle analysis --



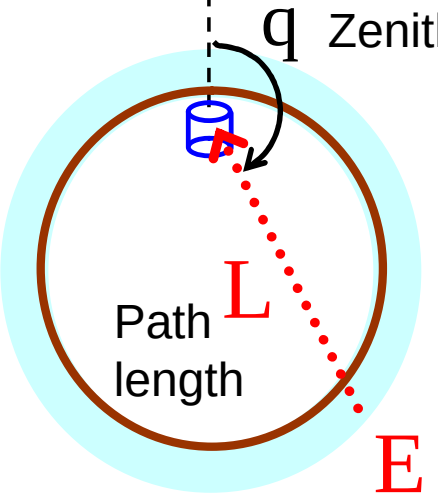
Preliminary !

Best Fit Results:
$\Delta m^2 = 2.5 \times 10^{-3}$ eV²
$\sin^2(2\theta) = 1.0$
χ^2_{min} = 767.5/737 DOF
(physical region)

$2.1 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV²
$\sin^2 2\theta > 0.93$ at 90%C.L.

L/E analysis

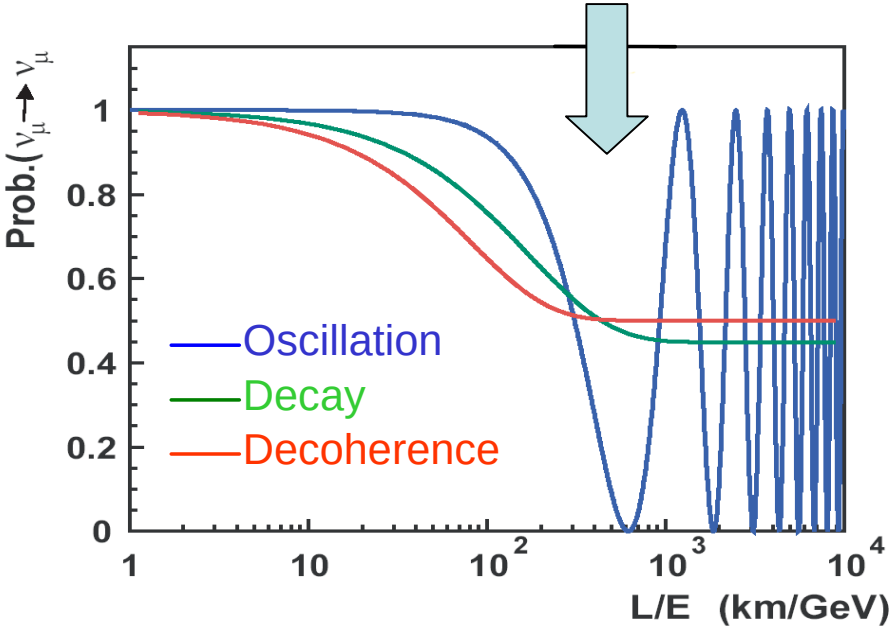
PRL 93 101801 (2004)



Survival probability in neutrino oscillation:

$$P(\nu_m \rightarrow \nu_m) = 1 - \sin^2 2J \sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

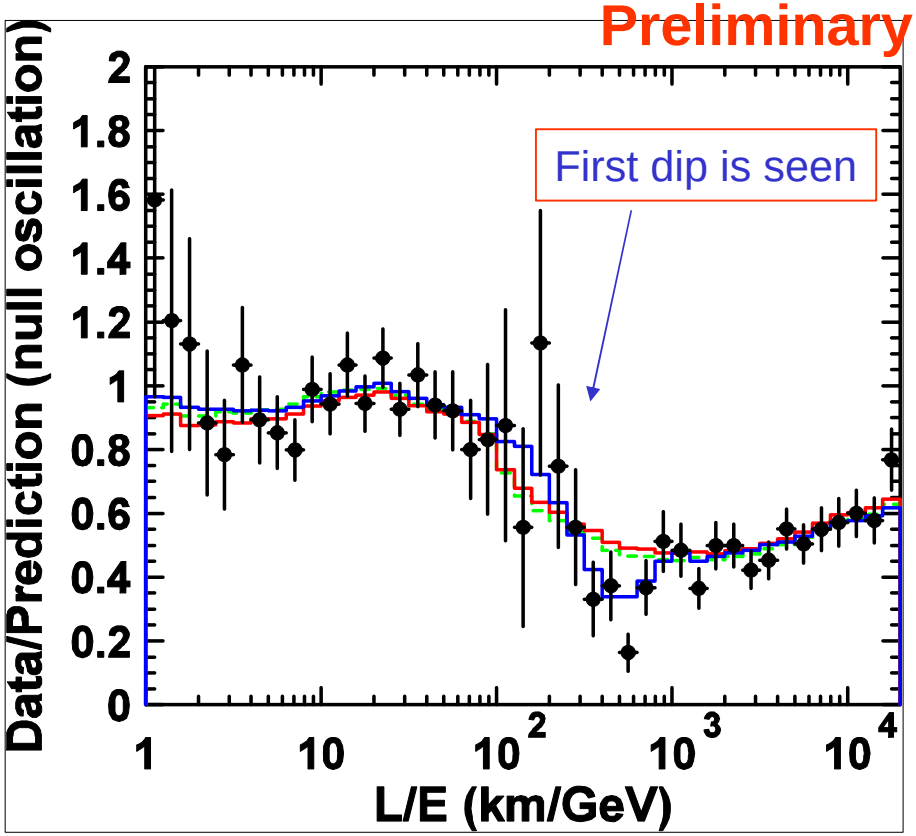
Clear dip, especially appeared in neutrino oscillation



- Try to see the oscillation pattern.
- Strong constraint on Δm^2
- Possible to check some exotic hypothesis.

L/E distribution in SK-1 and SK-2

Preliminary !



—Oscillation

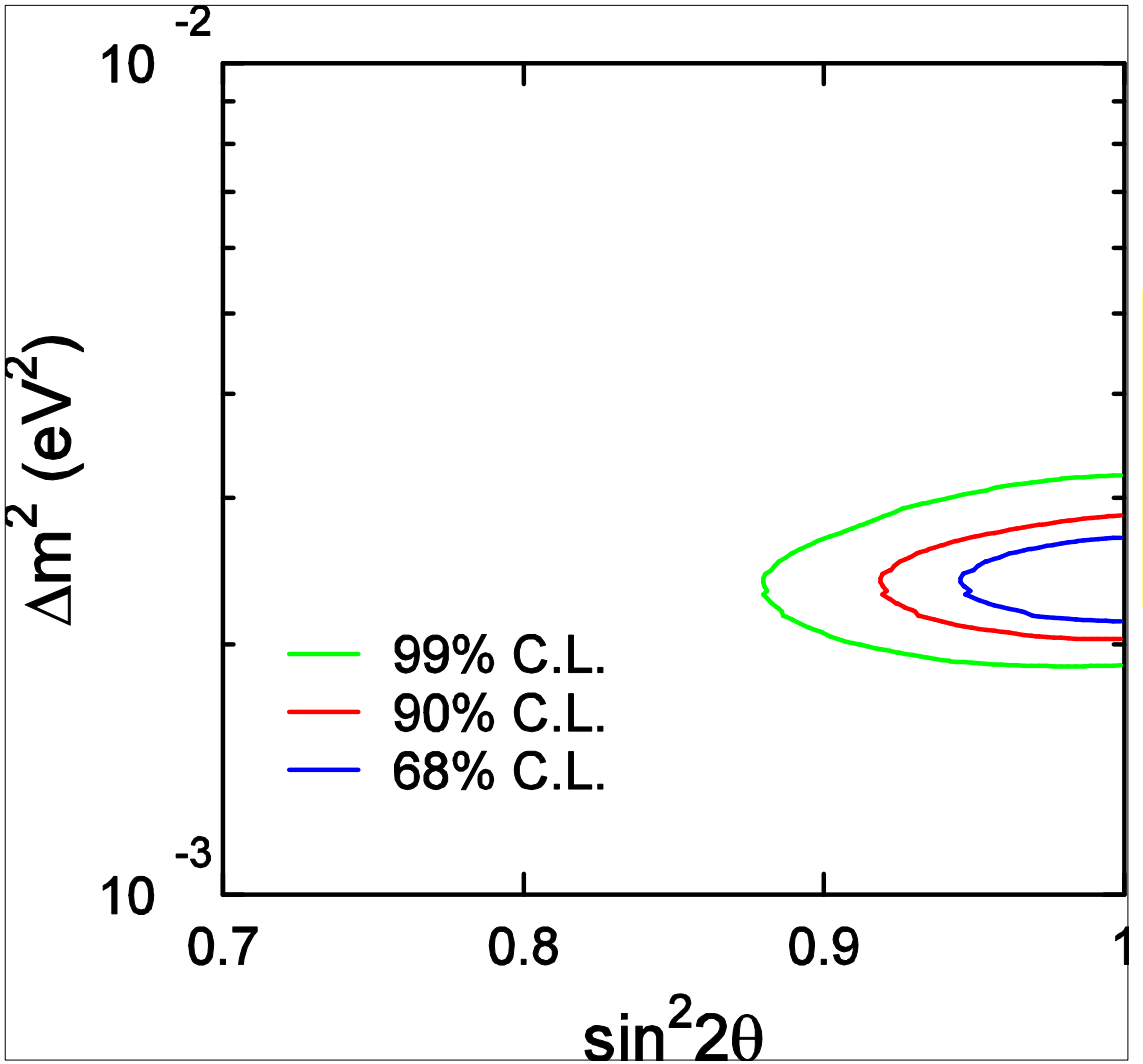
—Decay $\Delta\chi^2$=19.5 → 4.4σ

—Decoherence $\Delta\chi^2$=23.3 → 4.8σ

The first dip cannot be explained by other models

2 flavor neutrino oscillation
-- L/E analysis --

Preliminary !



Best Fit Results:

$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2

$\sin^2(2\theta) = 1.0$

χ^2_{min} = 93.8/83 DOF

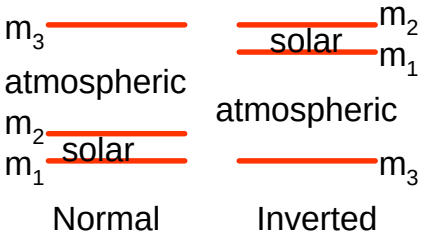
(physical region)

$2.0 \times 10^{-3} < \Delta m^2 < 2.9 \times 10^{-3}$ eV^2

$\sin^2 2\theta > 0.92$ at 90%C.L.

3 flavor neutrino oscillation analysis

Mass difference



Matter effect

	neutrino	anti-neutrino
Normal	enhanced	suppressed
Inverted	suppressed	enhanced

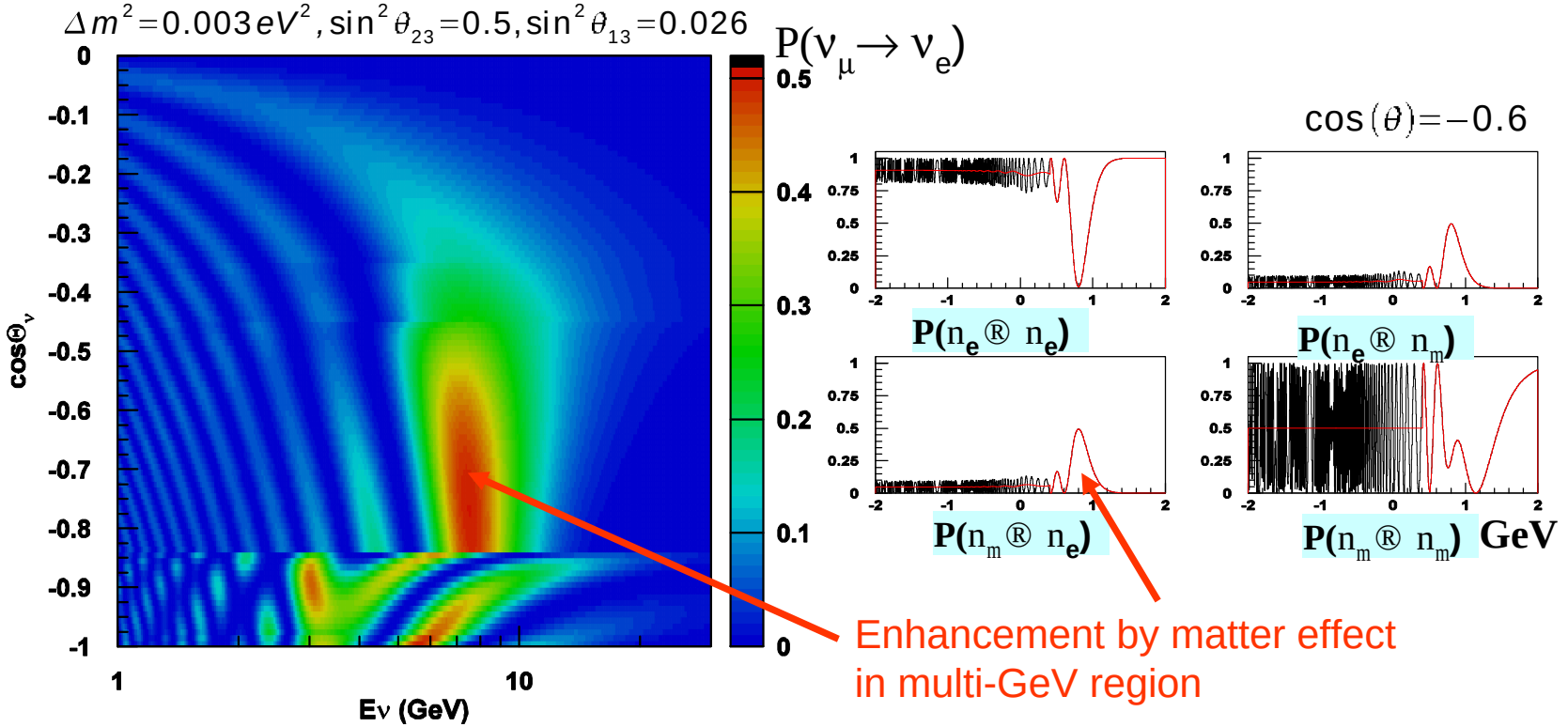
Assume:

- $\Delta m_{atm} >> \Delta m_{solar}$
- $\delta = 0$

Probability is described by 3 parameters:

$$\Delta m^2 \sim \Delta m^2_{13} \sim \Delta m^2_{23}; \theta_{23}; \theta_{13}$$

Enhancement of ν_e probability in the case of non-zero θ_{13}



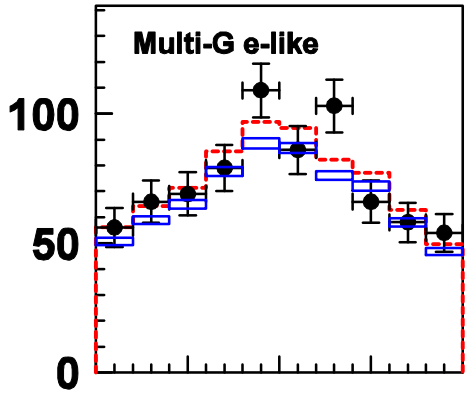
multi-GeV electrons

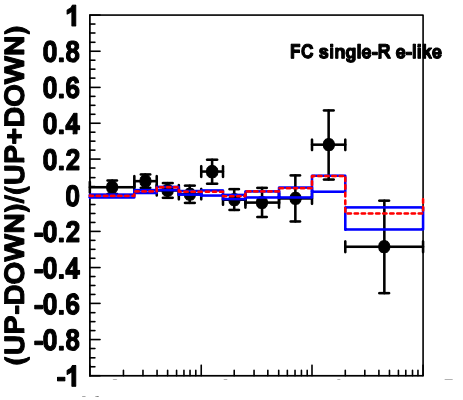
Zenith angle

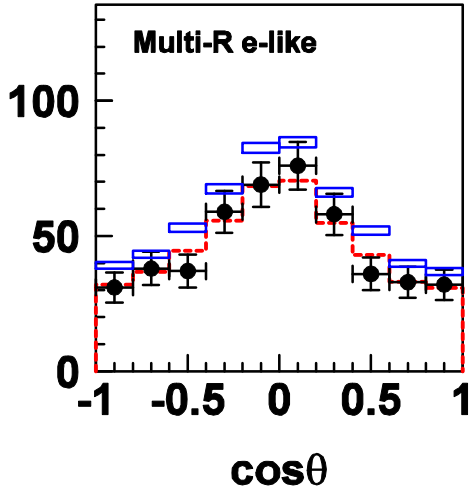
UP/DOWN asymmetry

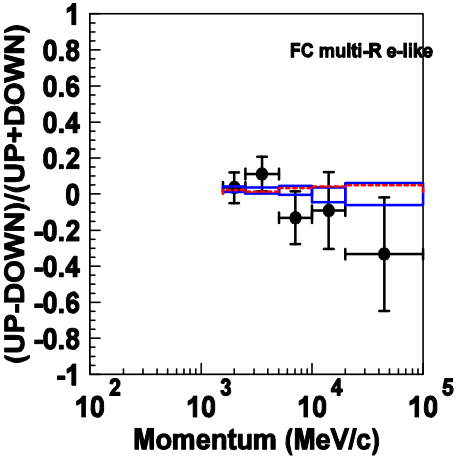
single-R electron

multi-R electron









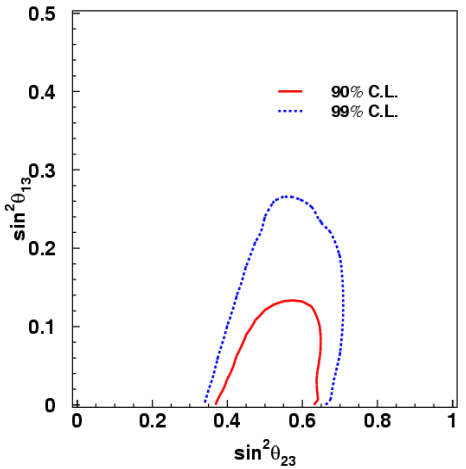
No significant excess due to matter effect was seen in upward-going multi-GeV electron sample

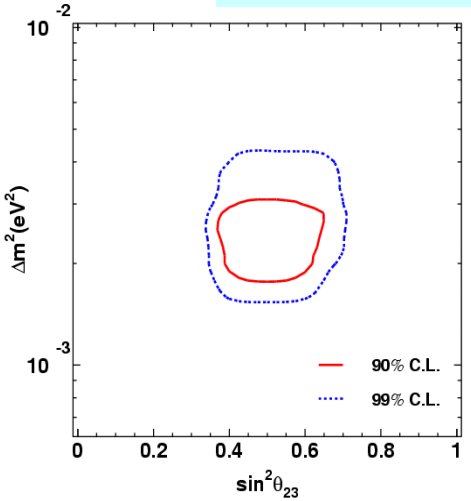
Limits

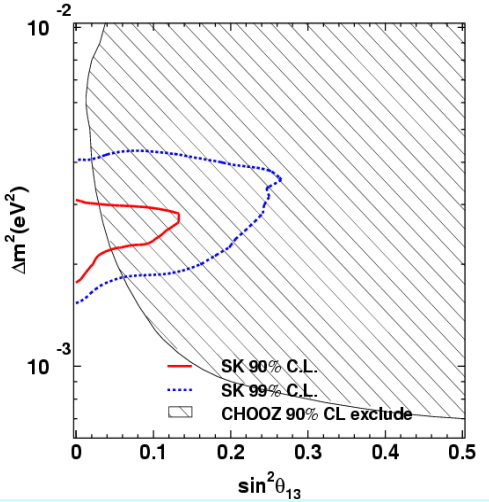
Normal hierarchy

Best Fit: χ^2_{min} = 376.82/368 DOF

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{13} = 0.0$



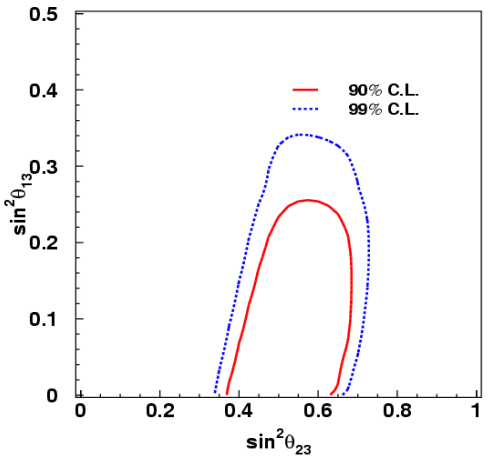


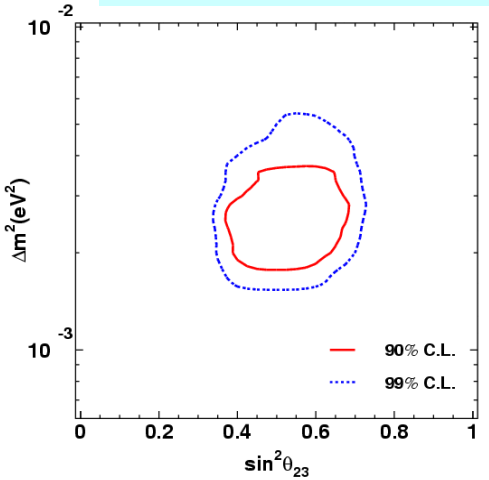


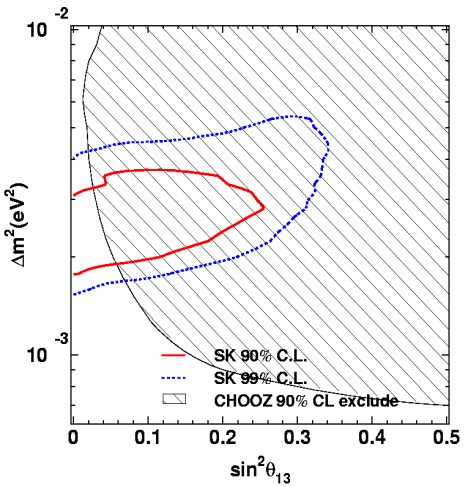
Inverted hierarchy

Best Fit: χ^2_{min} = 376.76/368 DOF

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.525$, $\sin^2\theta_{13} = 0.00625$

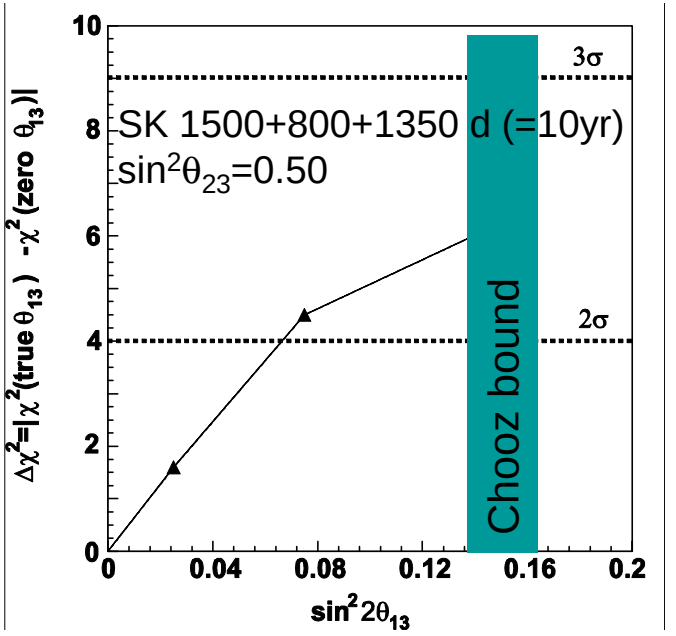






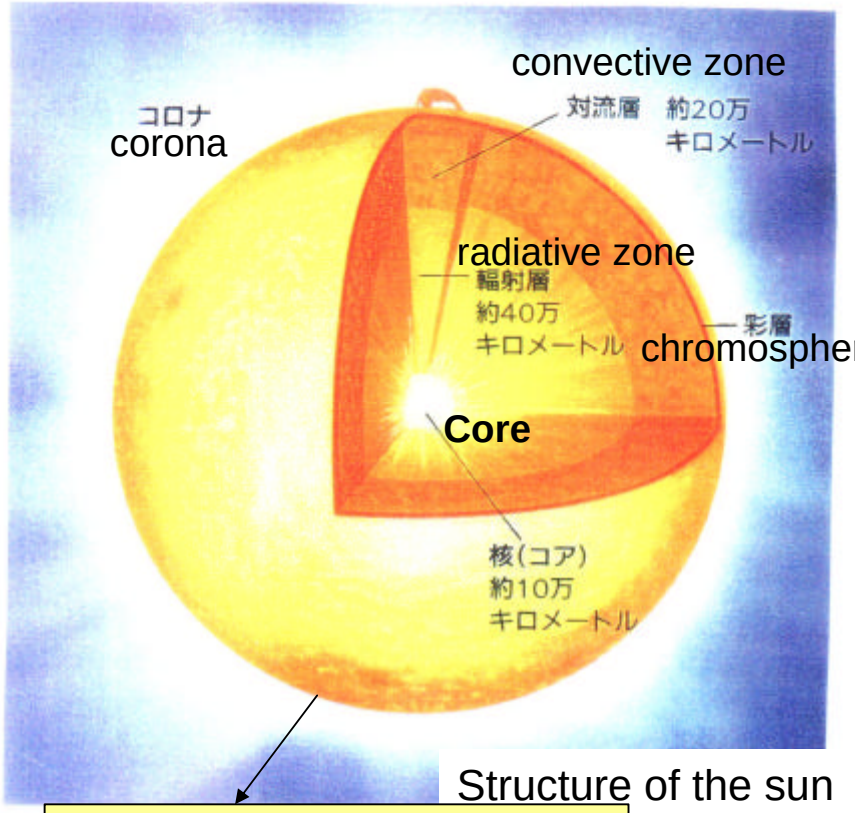
Future prospect for atmospheric neutrinos in SK-3

- Best determination of $\sin^2 2\theta_{23}$
  - The measurement is not systematic limited yet.
    → Improvement with sqrt(exporsure)
  - $\sin^2 2\theta_{23}=1.01 \pm 0.05$(68%CL, 1500+630days)
    → $\sin^2 2\theta_{23}=1.00 \pm 0.038$(1500+800+1350days)
- Search for indication of non-zero θ_{13}
  - Search for upward going multi-GeV ν_e events



Solar neutrinos

How does the sun shine?



Structure of the sun

Photon-measured luminosity

→ ~40000years radiated from the center to the surface.

Nuclear fusion reactions occur deep inside the sun

$4p \; ? \quad {}^4He + 2\,e^+ + 2\,\nu_e + 26.7MeV$

thermal energy

- Flux : ~66 billon neutrinos / sec /cm^2
- Go through the sun immediately (~2sec)

→ Measurements of solar neutrinos can see the current status in the center of the sun.

Neutrino-measured luminosity

Actually, this reaction is realized via pp-chain and CNO cycle

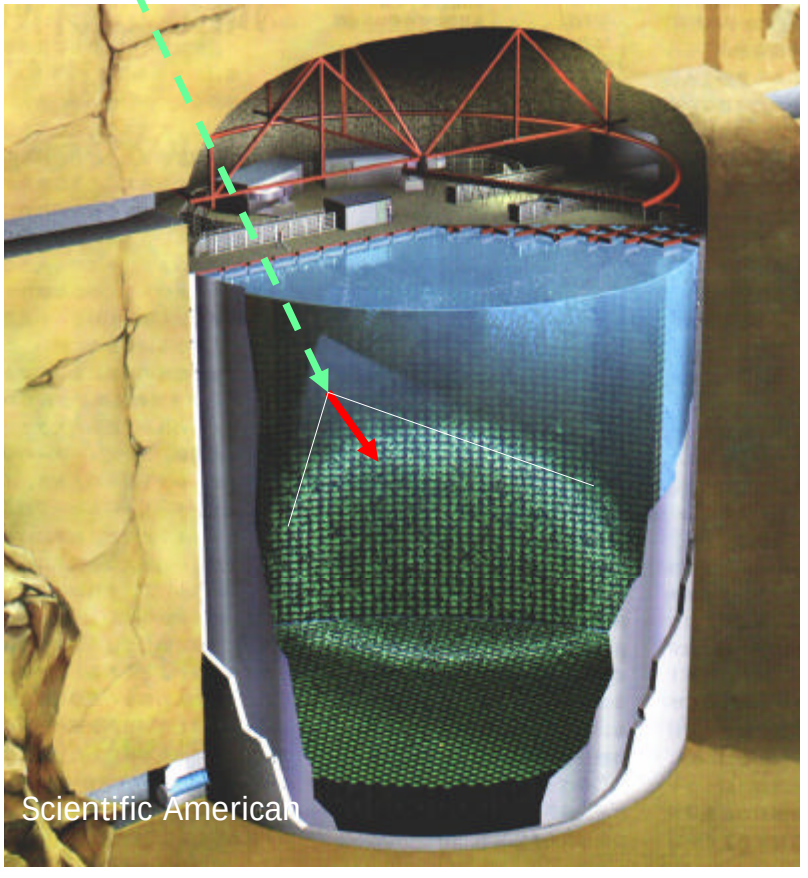
Standard Solar Model (SSM)

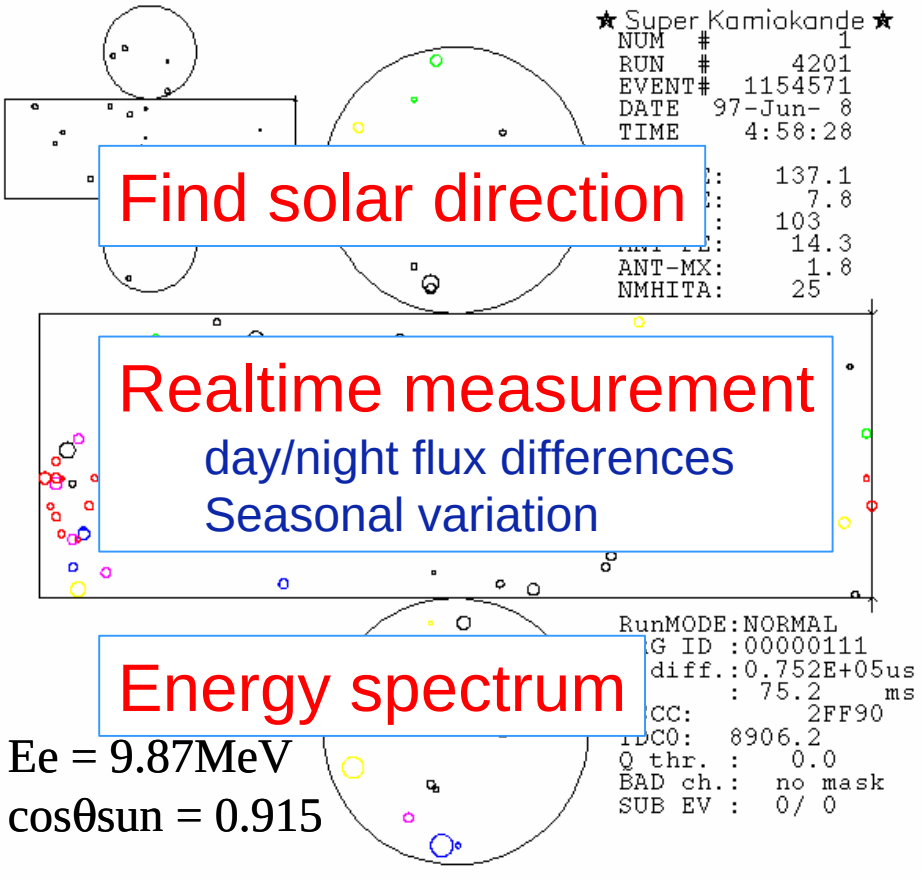
Solar neutrino measurement in SK

ν_{solar}

$\nu_{solar} + e \rightarrow \nu + e$ (elastic scattering)

Strong directionality





Find solar direction

Realtime measurement

day/night flux differences

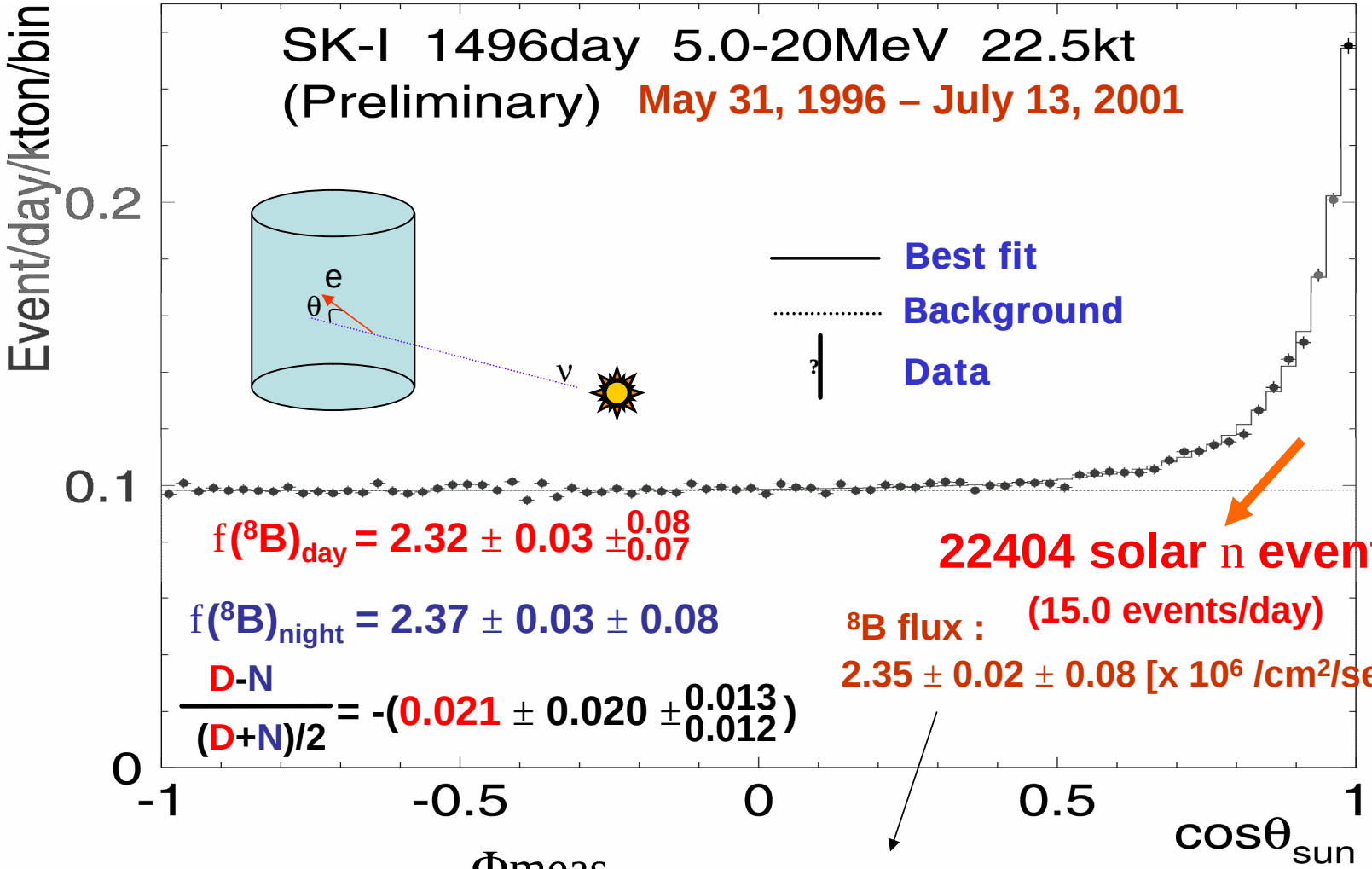
Seasonal variation

Energy spectrum

Ee = 9.87MeV

$\cos\theta_{sun} = 0.915$

Solar neutrino flux in SK-1



$f(^8B)_{day} = 2.32 \pm 0.03 \pm^{0.08}_{0.07}$

$f(^8B)_{night} = 2.37 \pm 0.03 \pm 0.08$

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

22404 solar n events

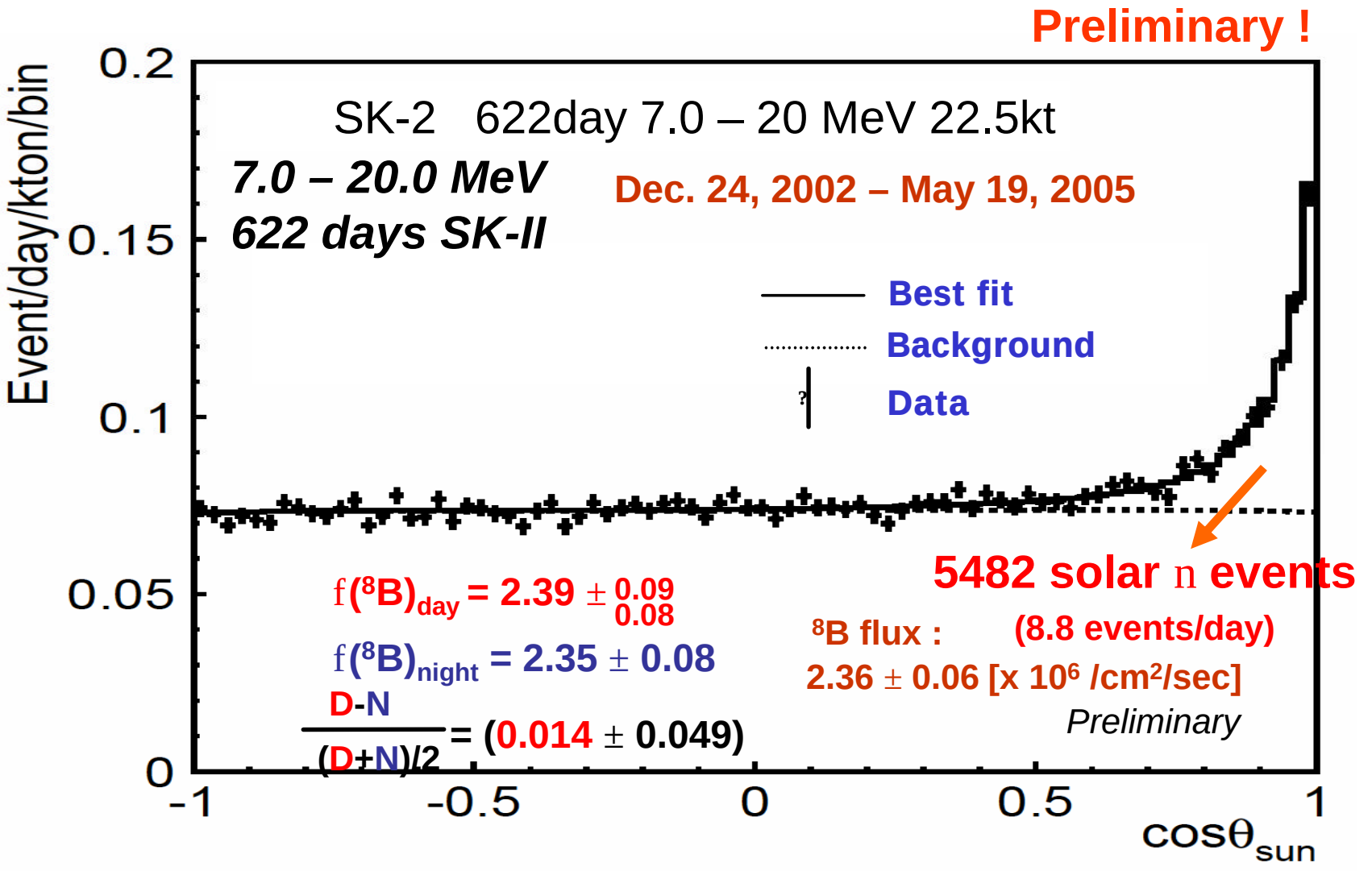
(15.0 events/day)

^{8}B flux :

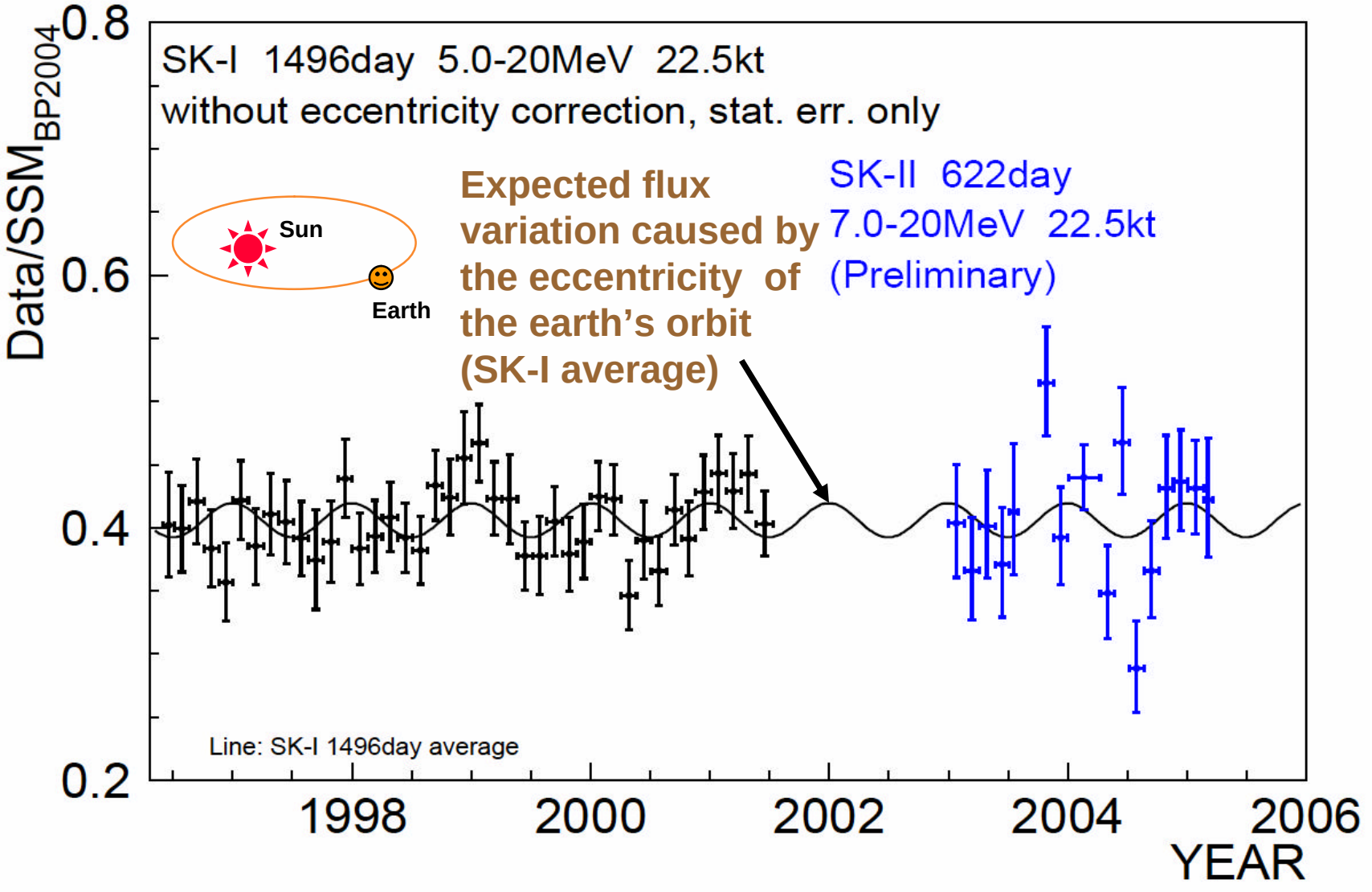
2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

$$\frac{\Phi meas.}{\Phi ssm} = 0.406 \pm 0.003(stat.) \pm 0.014(sys.)$$

Solar neutrino flux in SK-2

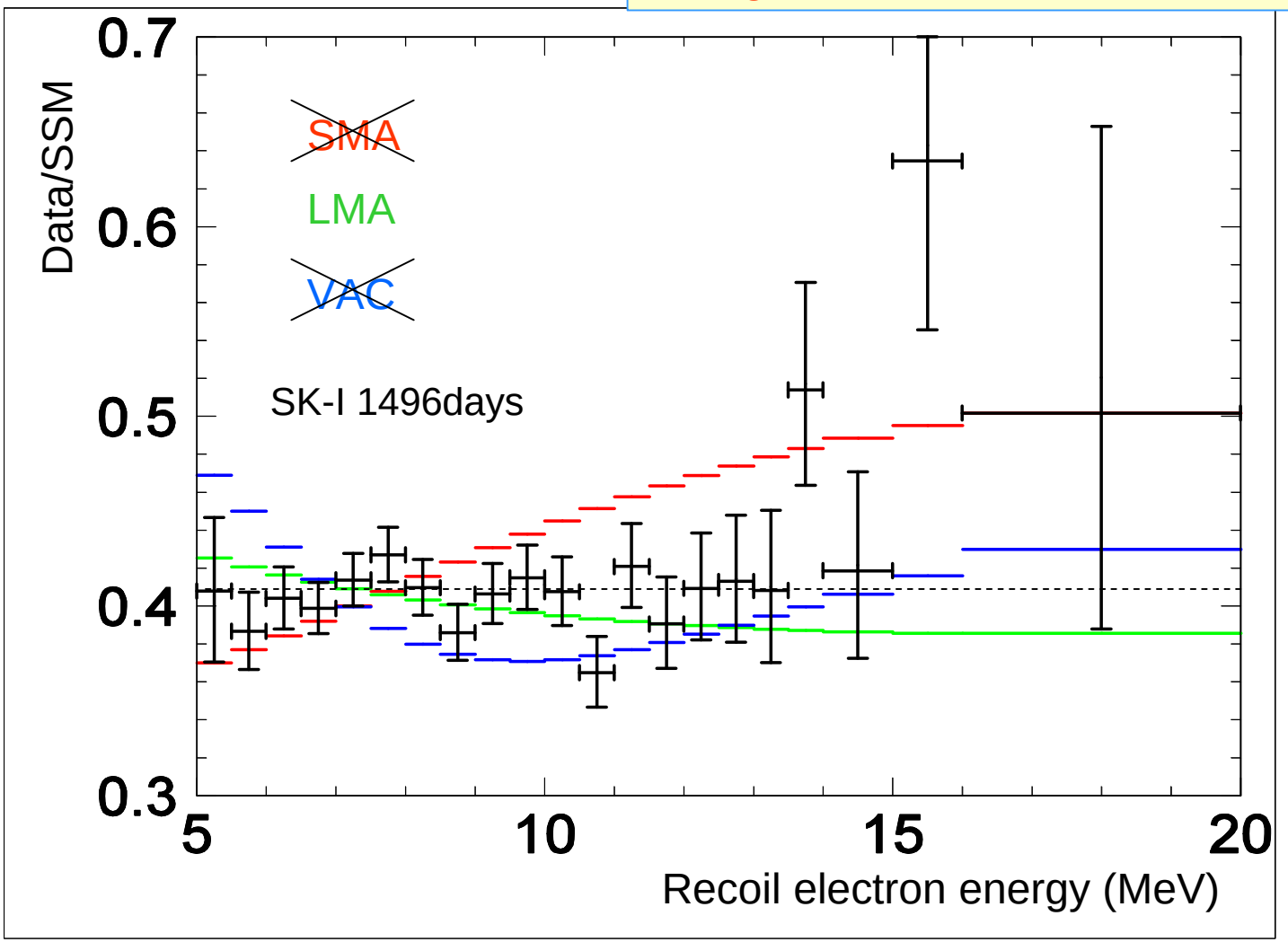


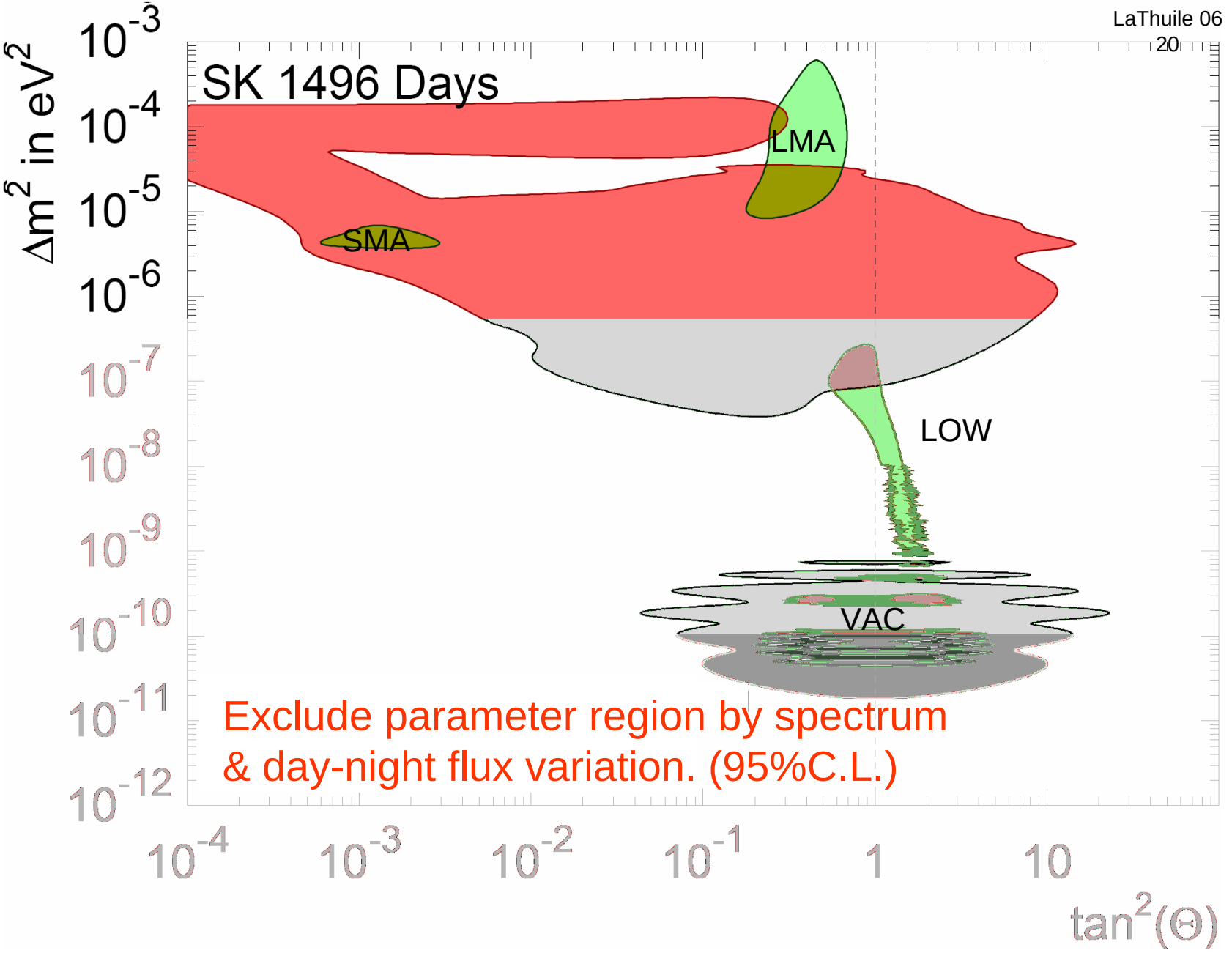
Time variation of solar neutrino flux

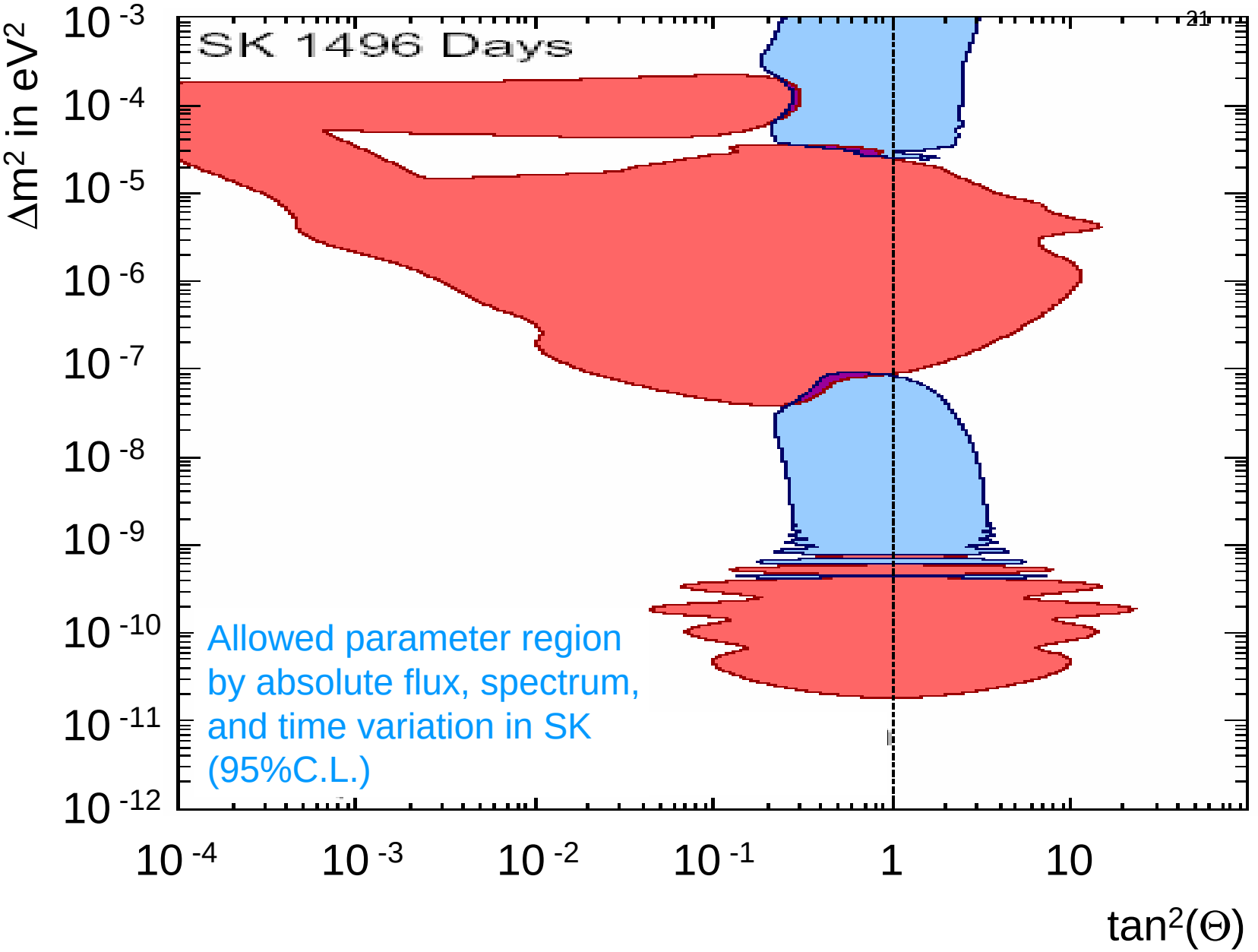


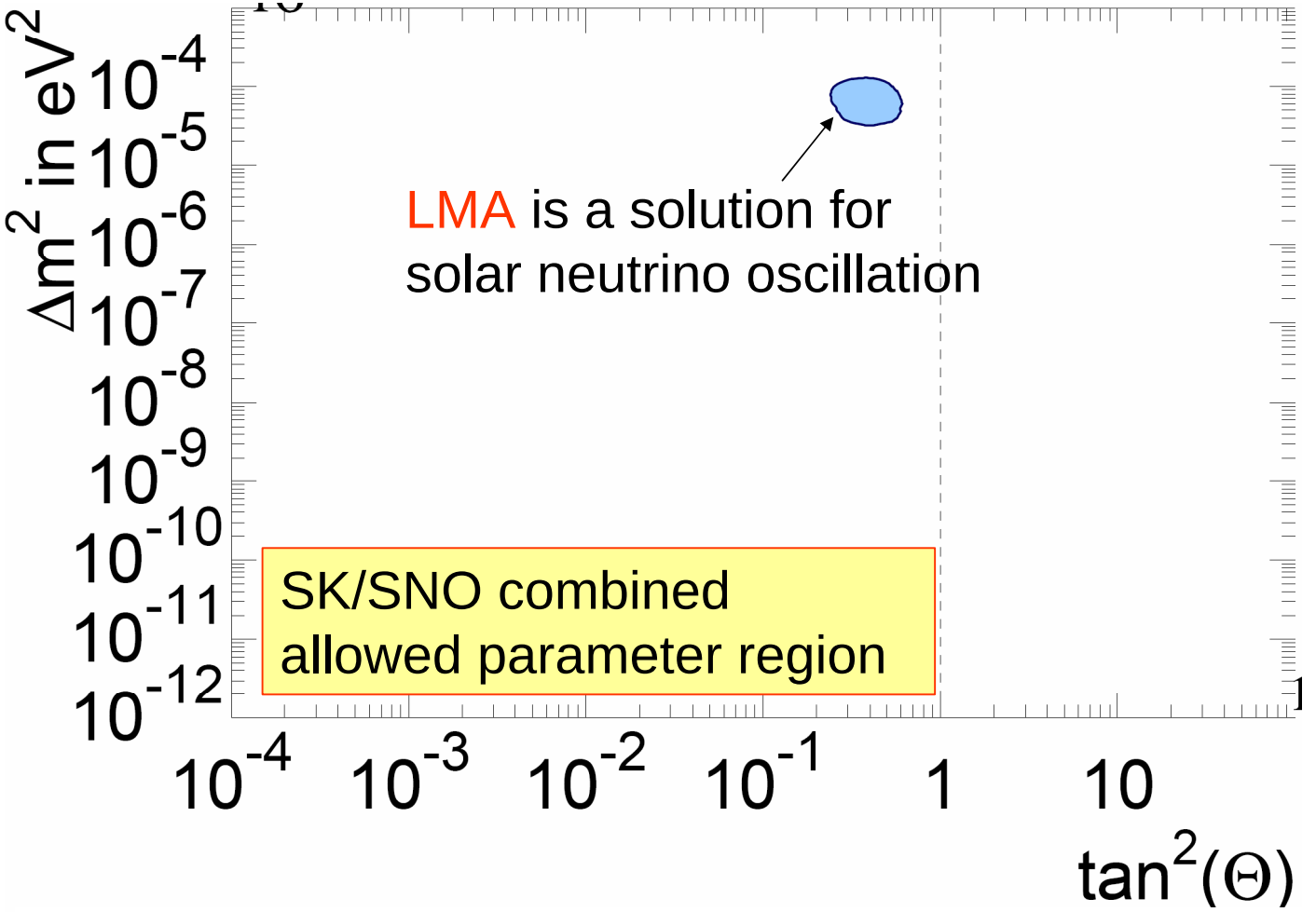
Energy spectrum

No significant distortion can be seen




SK 1496 Days
LMA
SMA
LOW
VAC
Exclude parameter region by spectrum
& day-night flux variation. (95%C.L.)
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
$\tan^2(\Theta)$


SK 1496 Days
Allowed parameter region
by absolute flux, spectrum,
and time variation in SK
(95%C.L.)
Δm^2 in eV^2
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
$\tan^2(\Theta)$


Δm^2 in eV^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
LMA is a solution for
solar neutrino oscillation
SK/SNO combined
allowed parameter region
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
$\tan^2(\Theta)$

Solar neutrino oscillation analysis in SK-1
-- 3 flavor --

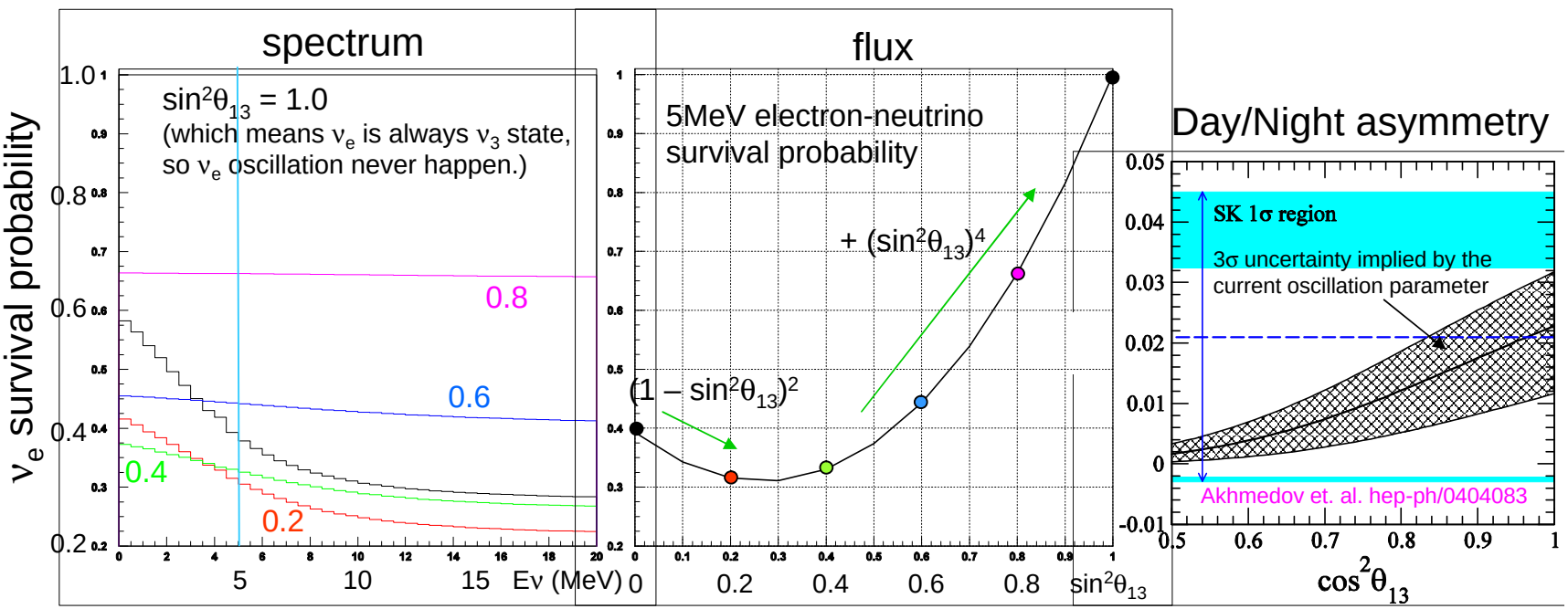
ν_e survival probability for 3 flavor formula can be based on 2 flavor as follows (C.S.Lim et al) ;

$$P^{(3)}(n_e \to n_e; A(x)) = (1-|U_{e3}|^2)^2 P^{(2)}(n_e \to n_e; (1-|U_{e3}|^2)A(x)) + |U_{e3}|^4$$

$\sin^2\theta_{13}$ weaken the matter effect

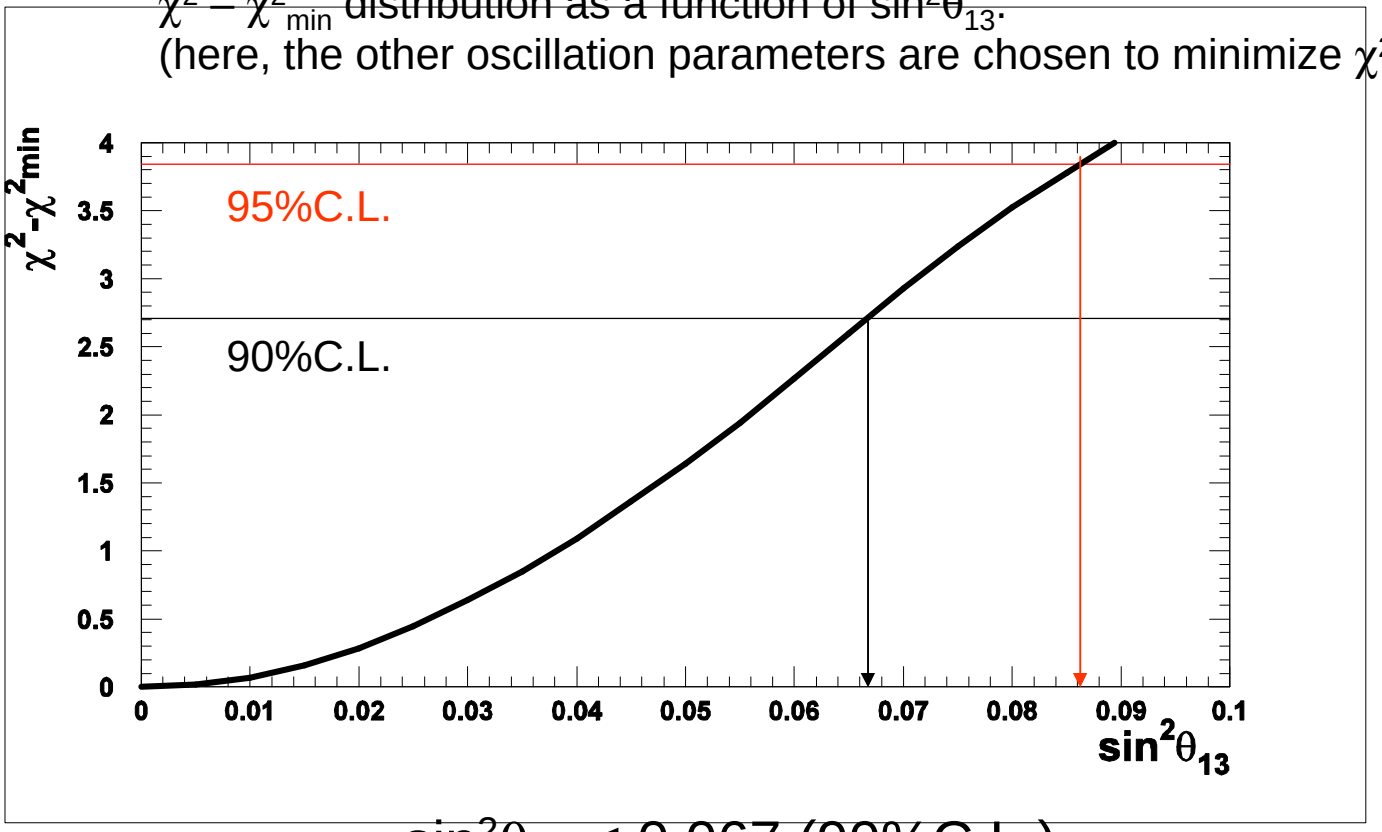
How is the effect ?

($\tan^2\theta_{12}$=0.38, Δm_{12}^2=8.3x10^{-5})



1-dimintional plot using all solar neutrino experiments.

$\chi^2 - \chi^2_{min}$ distribution as a function of $\sin^2\theta_{13}$.
(here, the other oscillation parameters are chosen to minimize χ^2.)

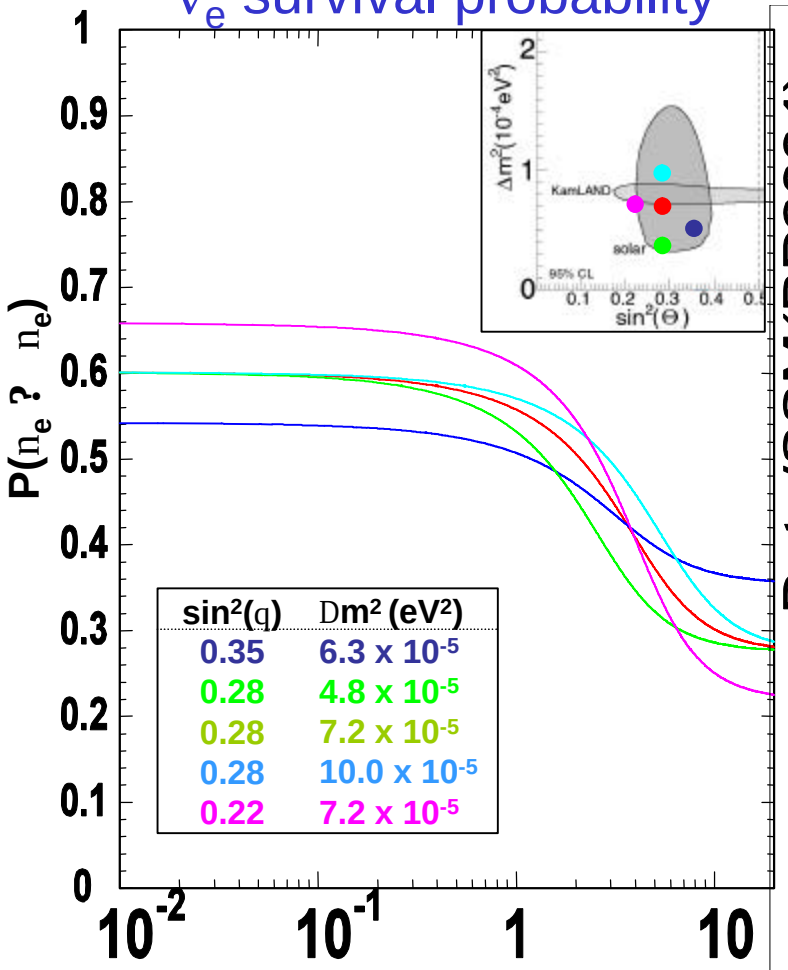


$\sin^2\theta_{13} < 0.067$ (90%C.L.)

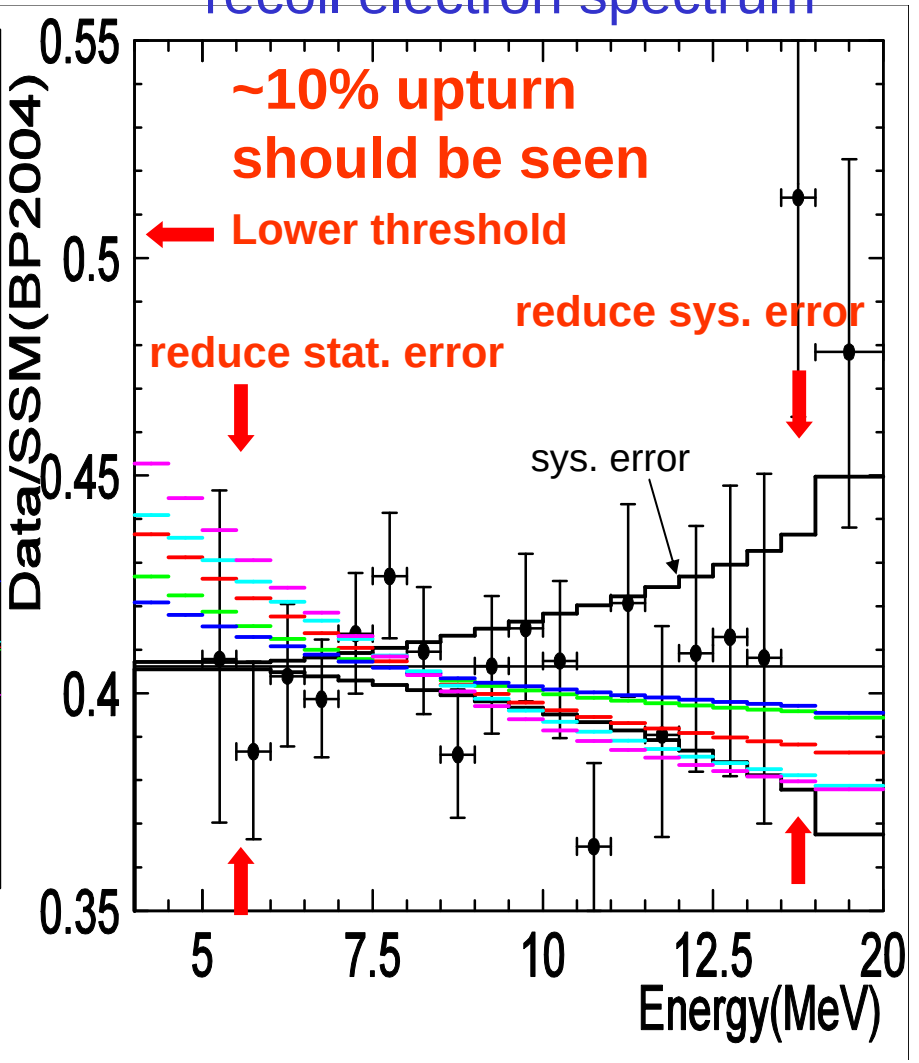
$\sin^2\theta_{13} < 0.086$ (95%C.L.)

Future prospect for solar neutrinos in SK-3

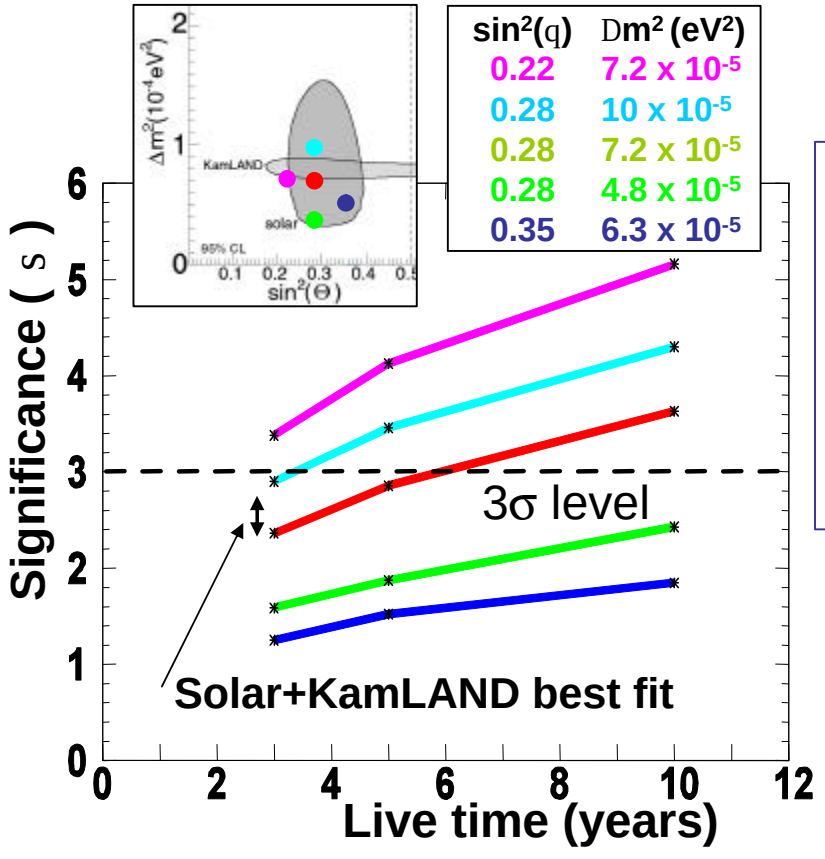
ν_e survival probability



recoil electron spectrum



Significance of spectrum distortion



sin²(q)	Dm² (eV²)
0.22	7.2 x 10⁻⁵
0.28	10 x 10⁻⁵
0.28	7.2 x 10⁻⁵
0.28	4.8 x 10⁻⁵
0.35	6.3 x 10⁻⁵

Assumptions:

4.0 MeV energy threshold

Systematic error (energy correlated): x 0.5

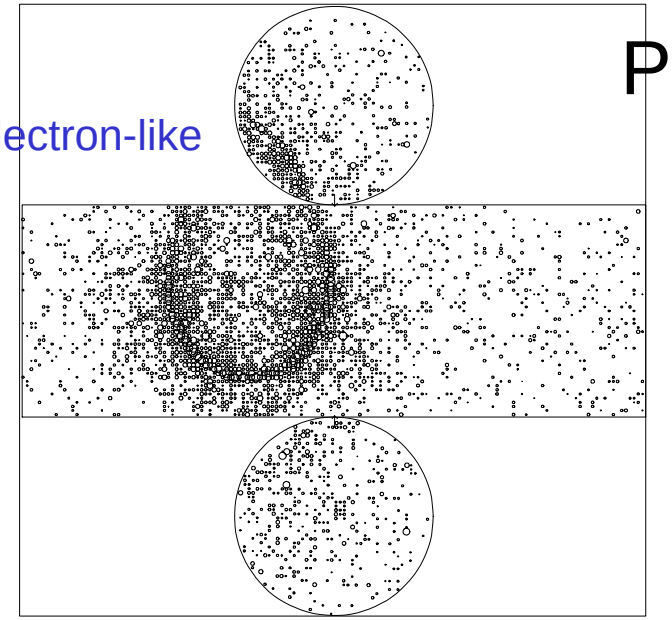
4.0-5.5MeV background: x 0.3 (same BG as SK-I above 5.5MeV)

Summary

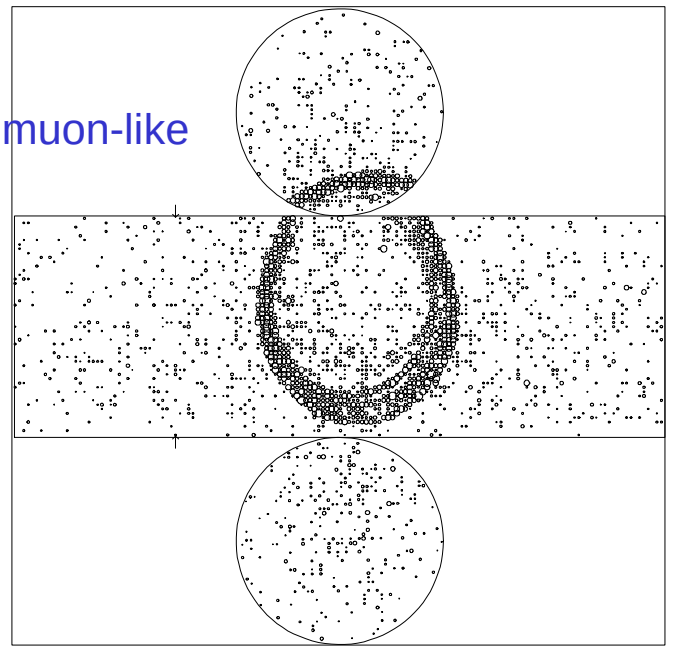
- The results of atmospheric and solar neutrinos in Super-Kamiokande phase 1 and 2 appear.
- In atmospheric neutrino oscillation analysis, not only zenith angle analysis, but L/E analysis has been done. L/E analysis gives tighter Δm^2 region. The SK-2 results of those are consistent with SK-1.
- The ν_τ appearance effect is observed about 3σ level.
- In 3 flavor analysis, it is consistent with $\theta_{13}=0$, and gives limit to the θ_{13} parameter.
- In solar neutrino analysis, no significant time variation and energy distortion appear. SK-2 results are consistent with SK-1.
- Solar neutrino oscillation studies in SK-1:
  - The results of SK-1 (flux, spectrum and day/night flux differences) favors Large neutrino mixing angle at 95%C.L.
  - The data combined with all the solar neutrino and KamLAND are constraint to the very small LMA region.
  - 3 flavor analysis in solar neutrino oscillation is done, the upper limit for $\sin^2\theta_{13}$ (90%C.L.) is 0.067.
- The spectrum distortion of solar neutrinos are important issue in SK-3.
- SK-3 will start from June 2006.

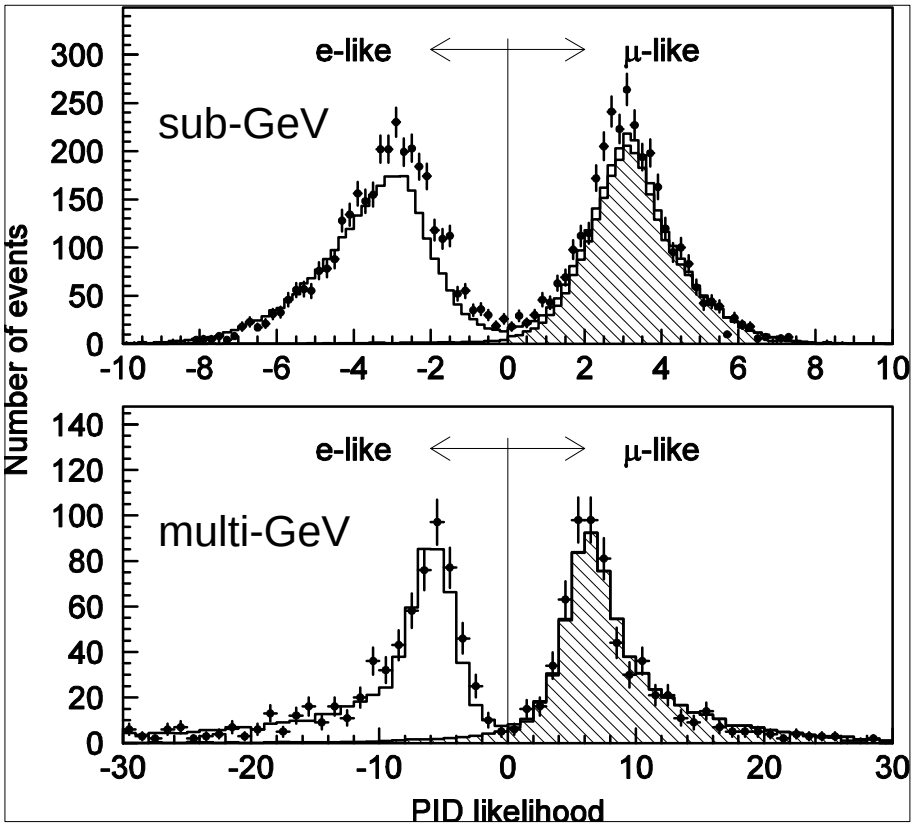
Particle ID

electron-like



muon-like

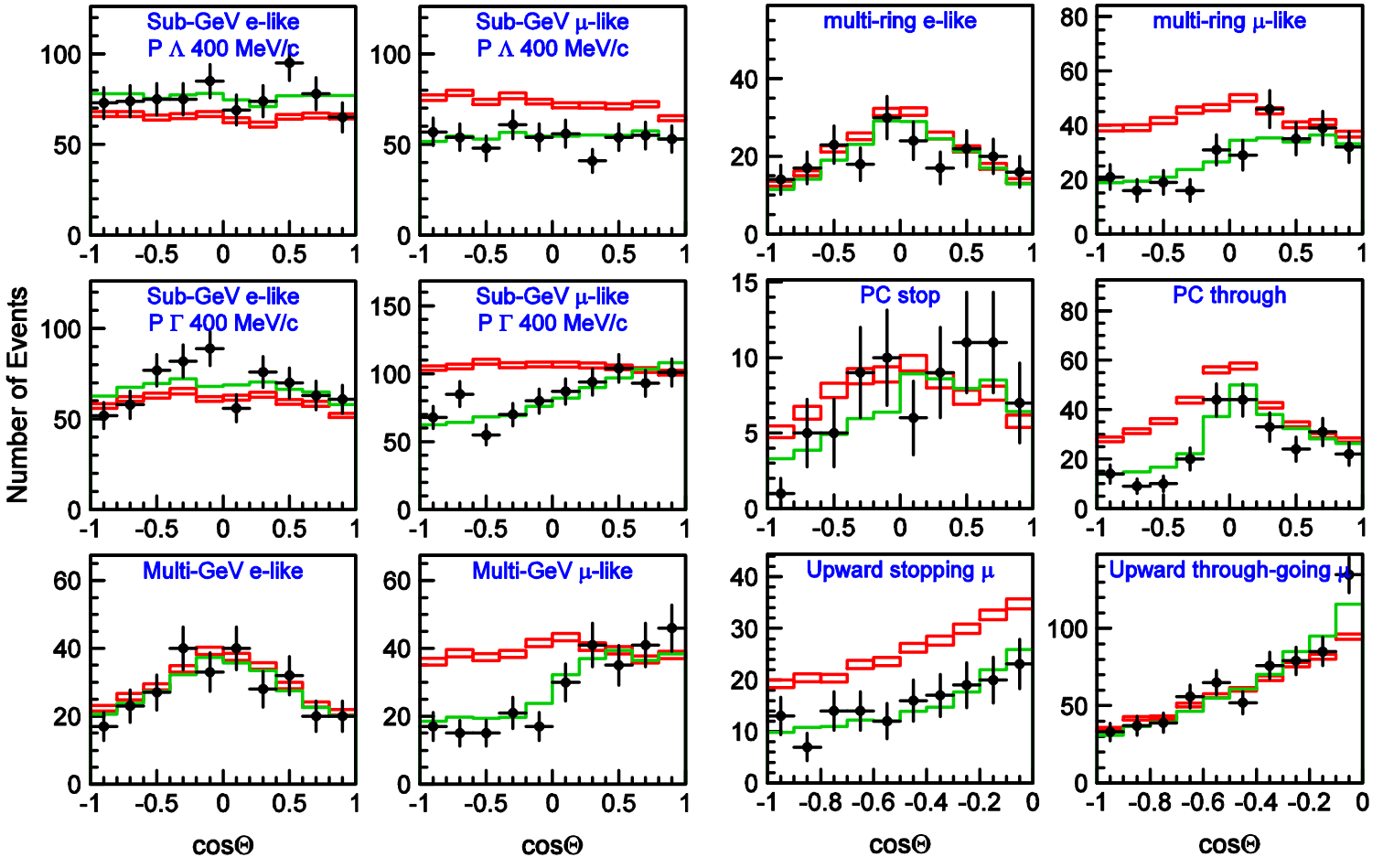




Zenith angle distribution in SK-2

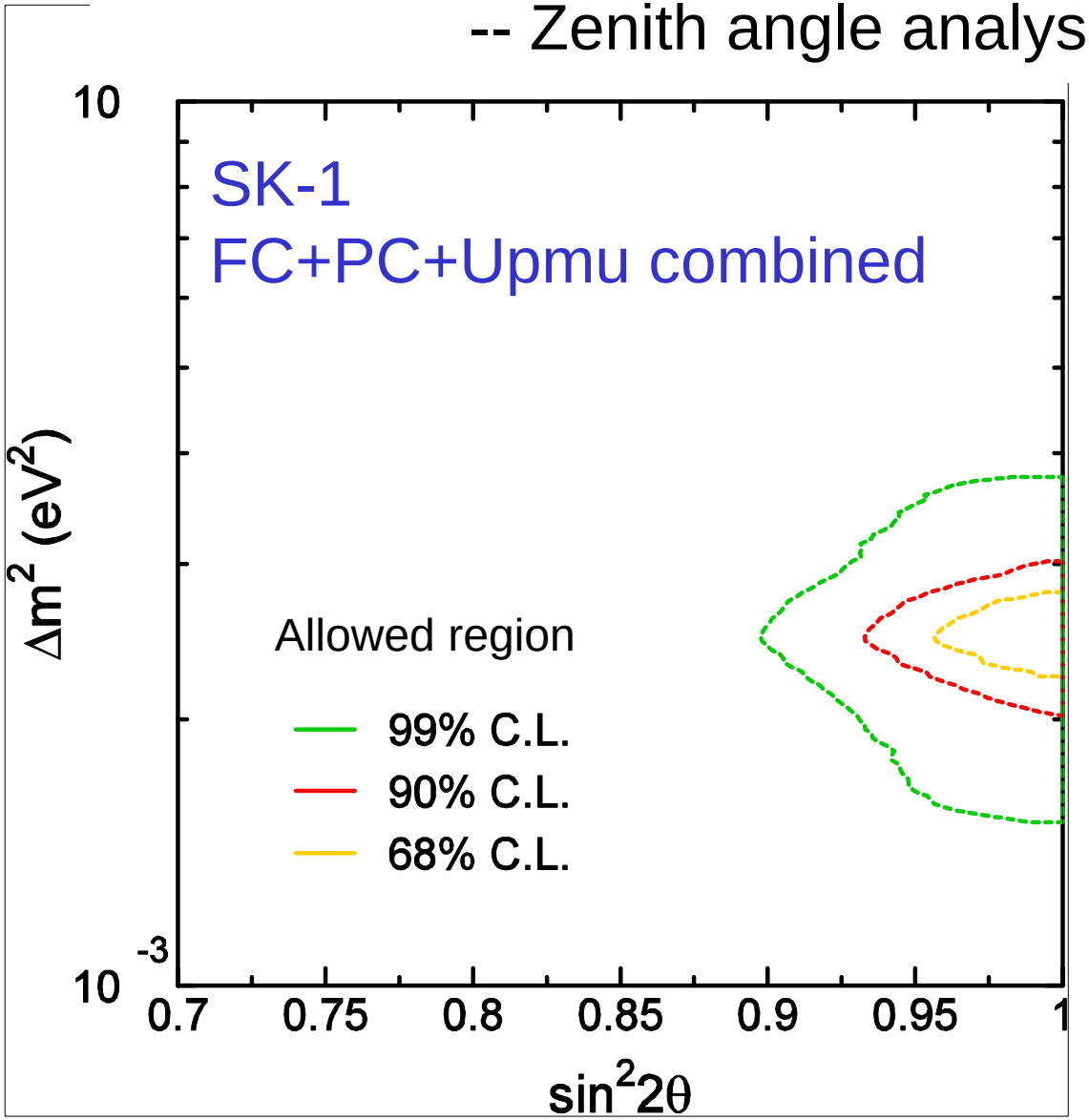
627 days for FC/PC
609 days for upmu

Preliminary !



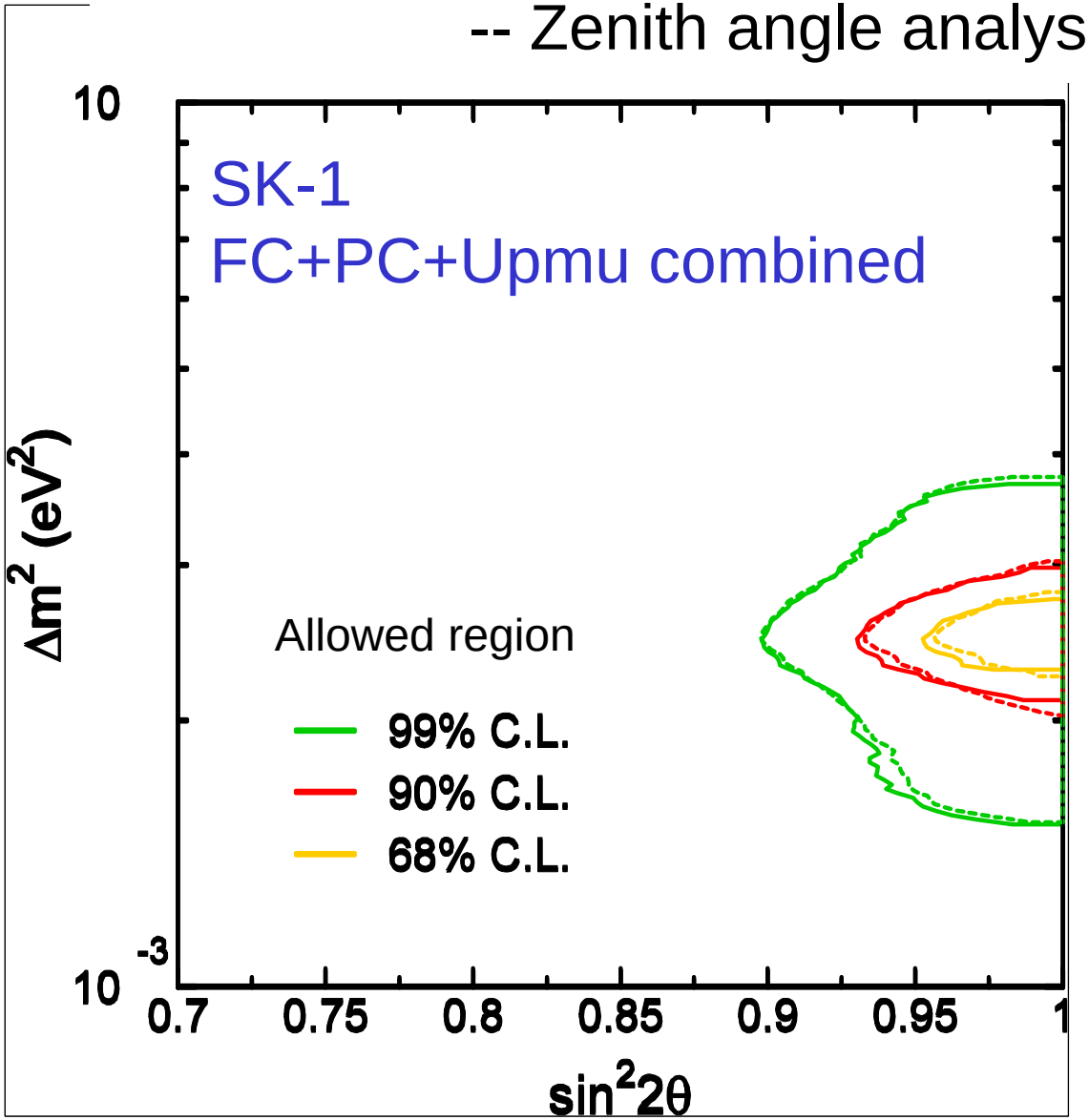
2 flavor neutrino oscillation

-- Zenith angle analysis --



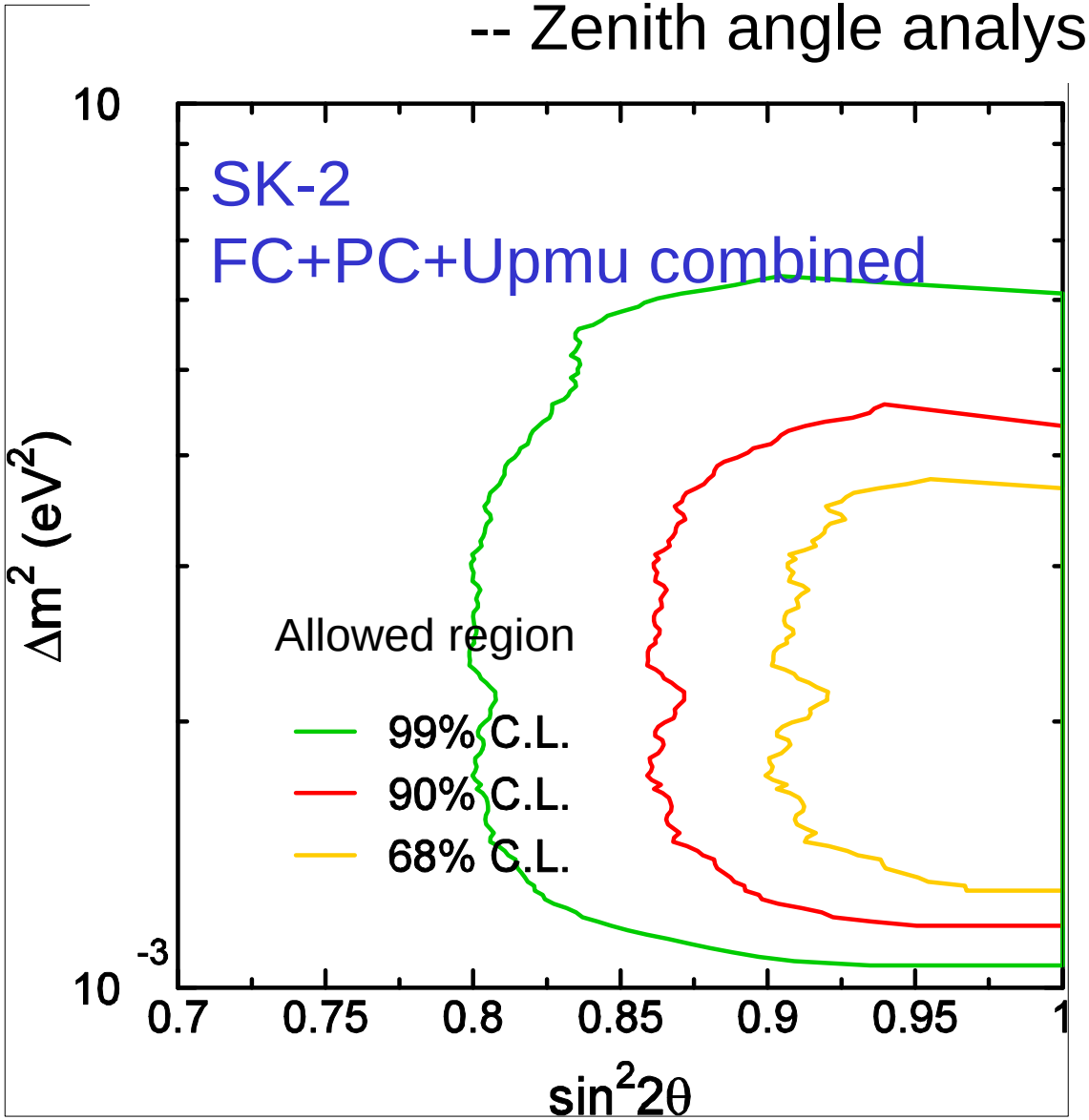
2 flavor neutrino oscillation

-- Zenith angle analysis --



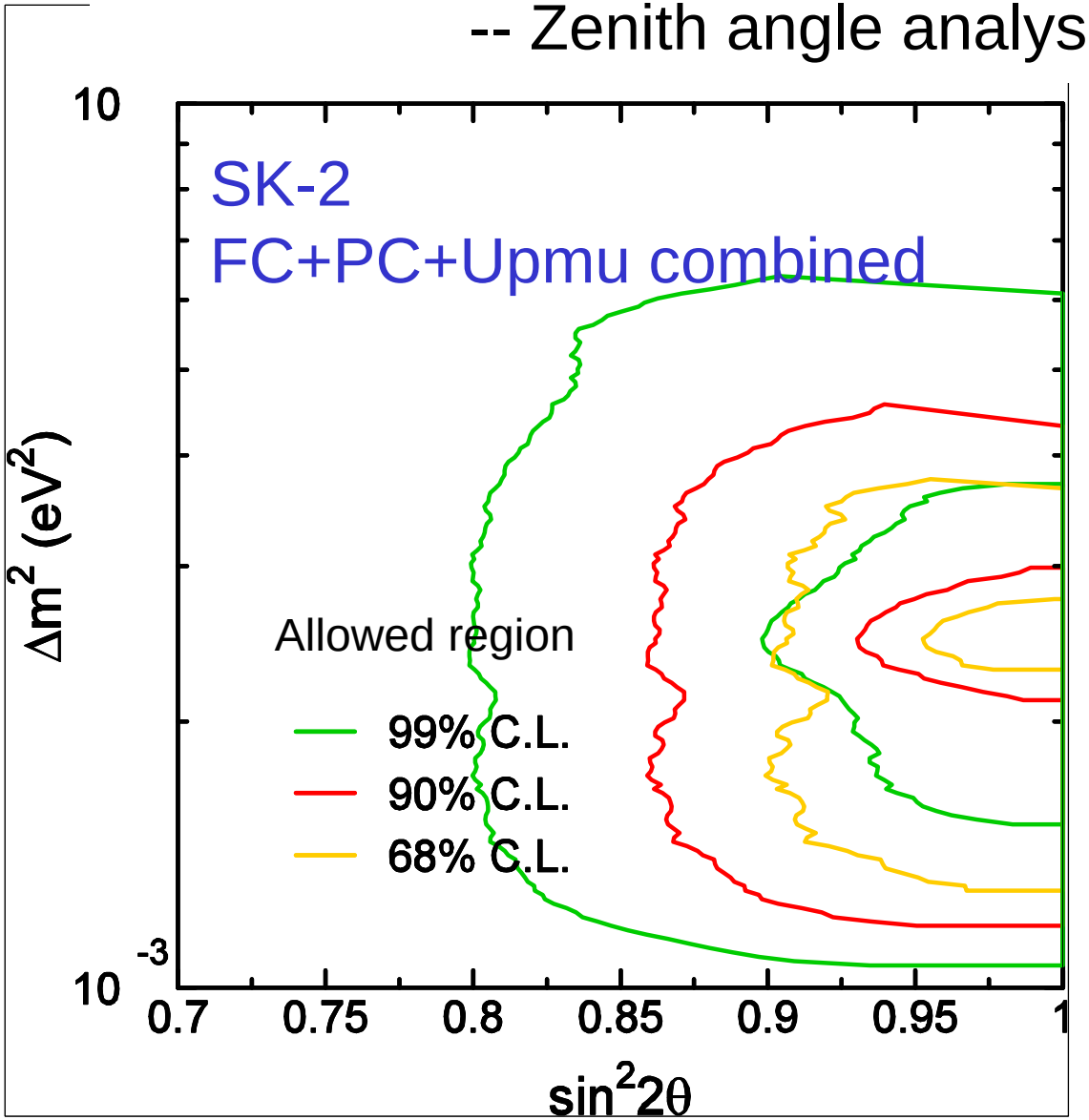
2 flavor neutrino oscillation

-- Zenith angle analysis --



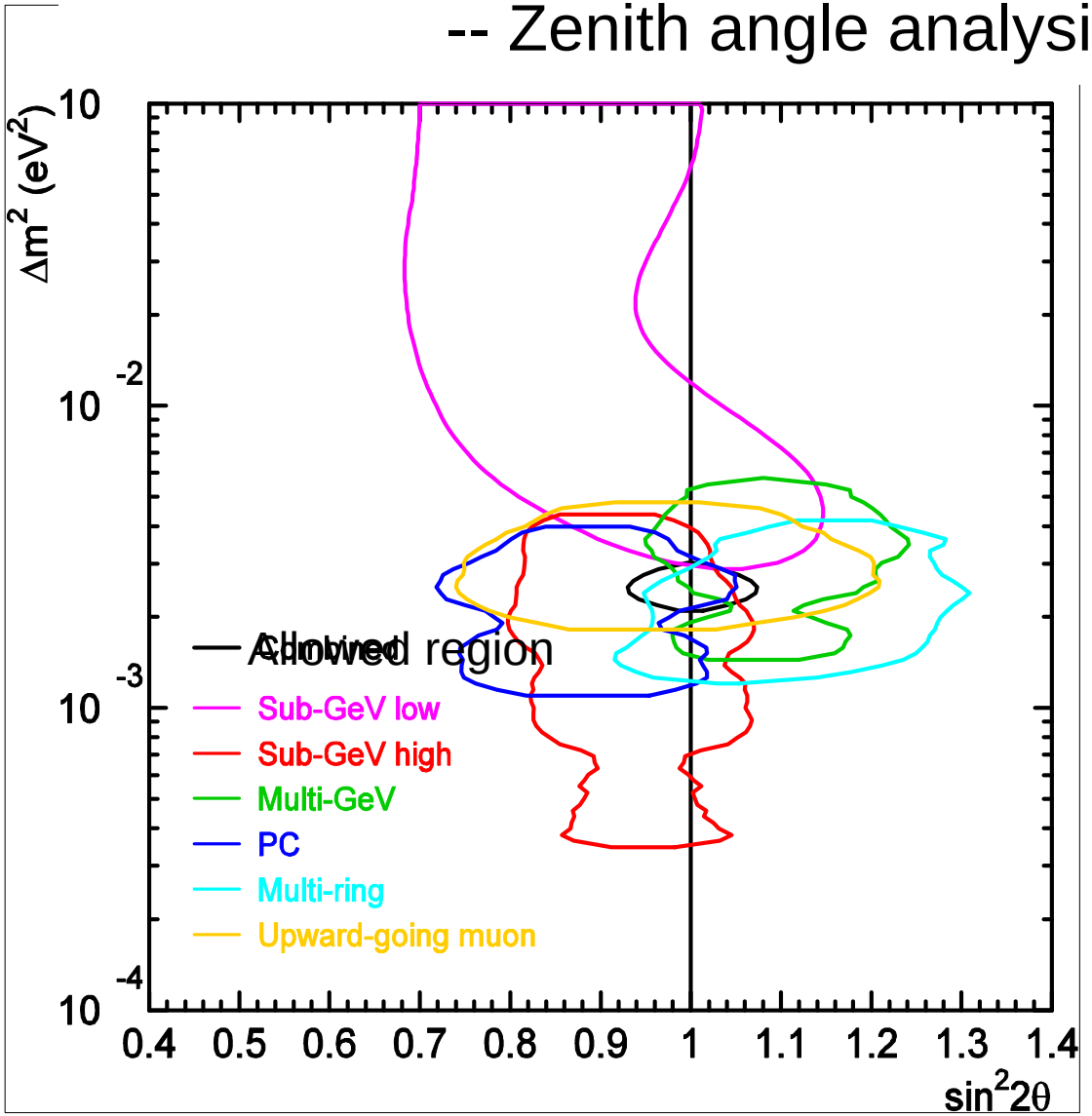
2 flavor neutrino oscillation

-- Zenith angle analysis --

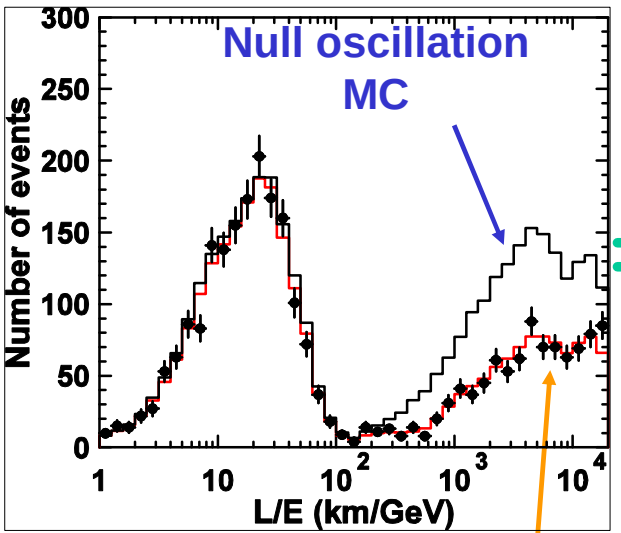


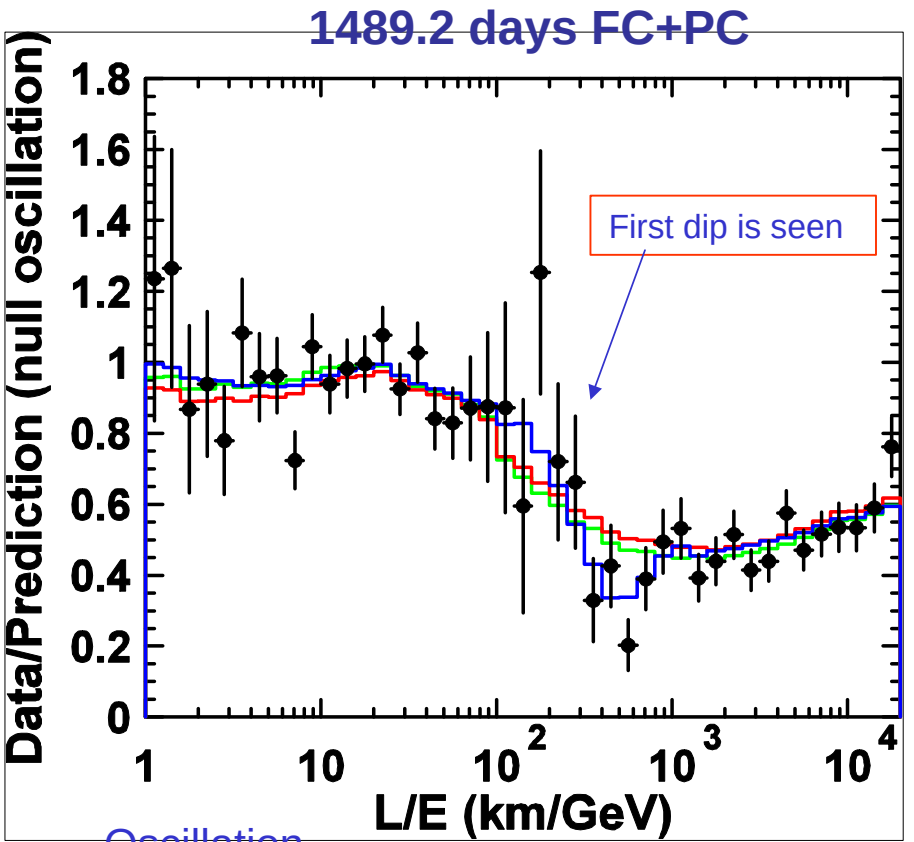
2 flavor neutrino oscillation

-- Zenith angle analysis --



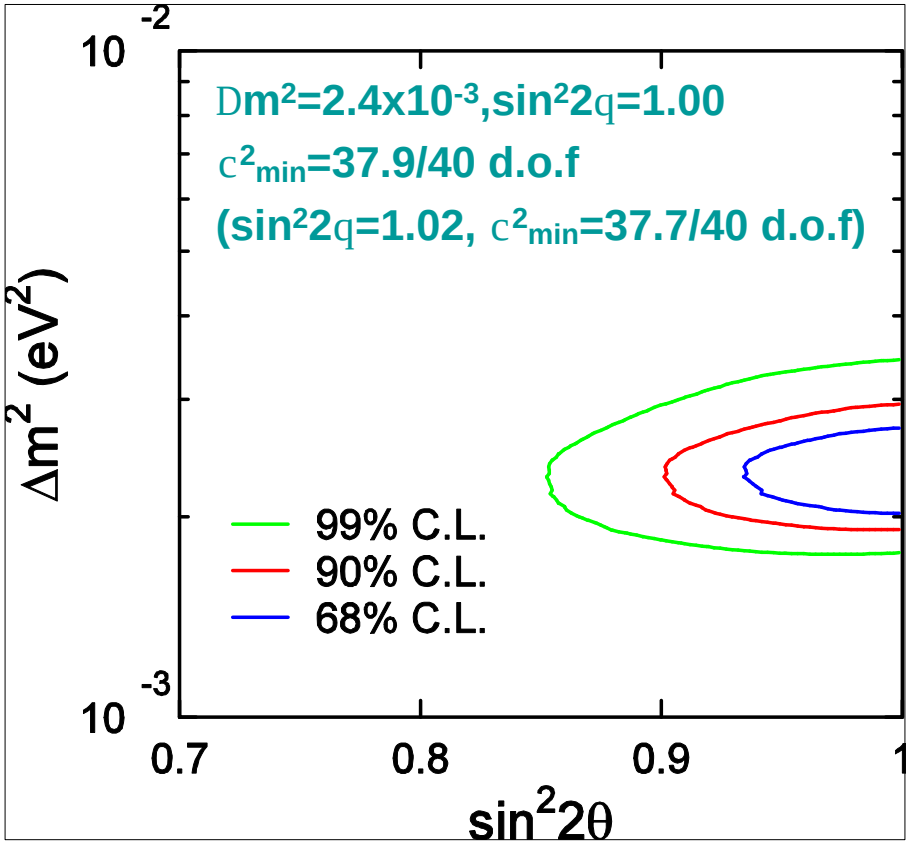
L/E distribution in SK-1

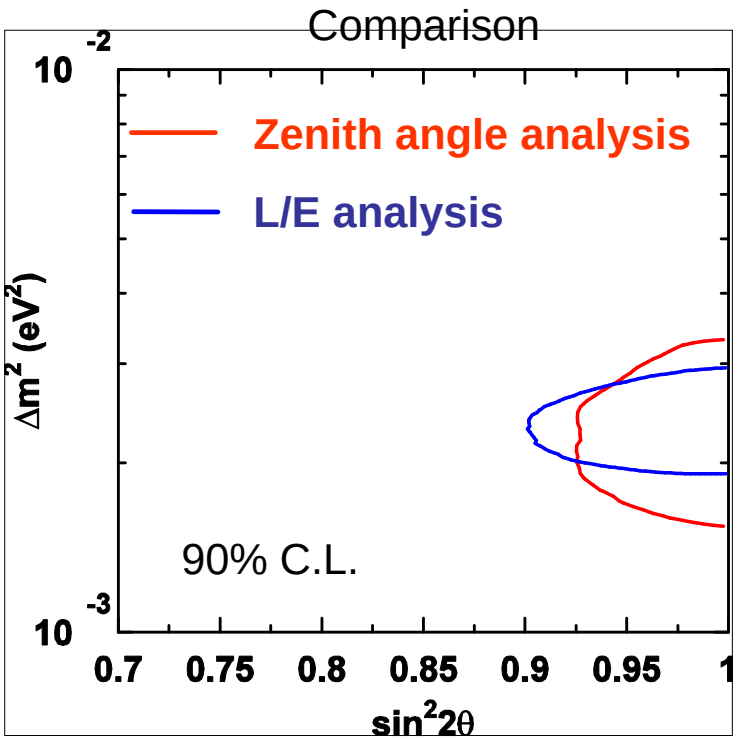




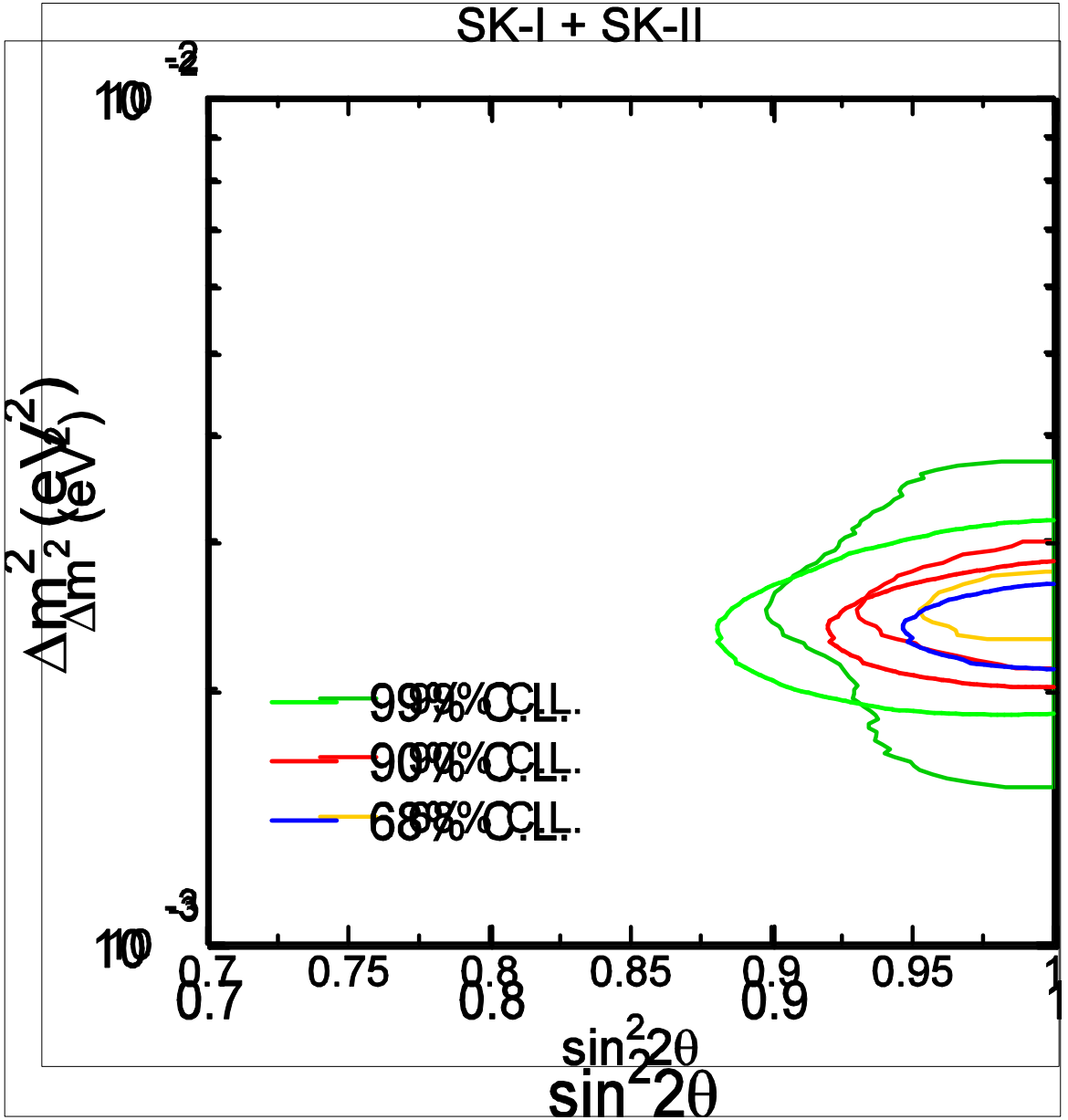
The first dip cannot be explained by other models

2 flavor neutrino oscillation in SK-1
-- L/E analysis --

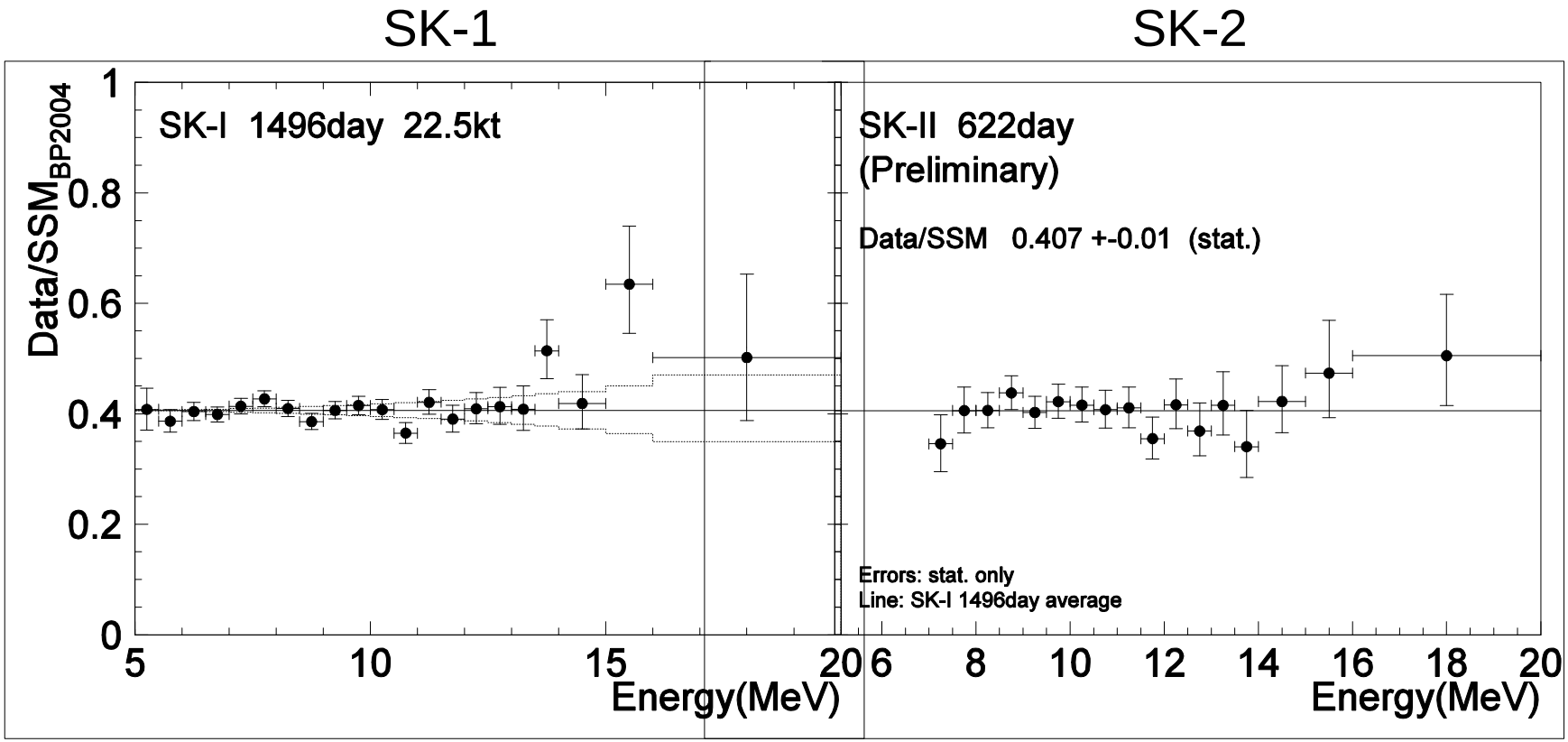




1.9x10⁻³ < Dm² < 3.0x10⁻³ eV²
0.90 < sin²2q at 90% C.L.

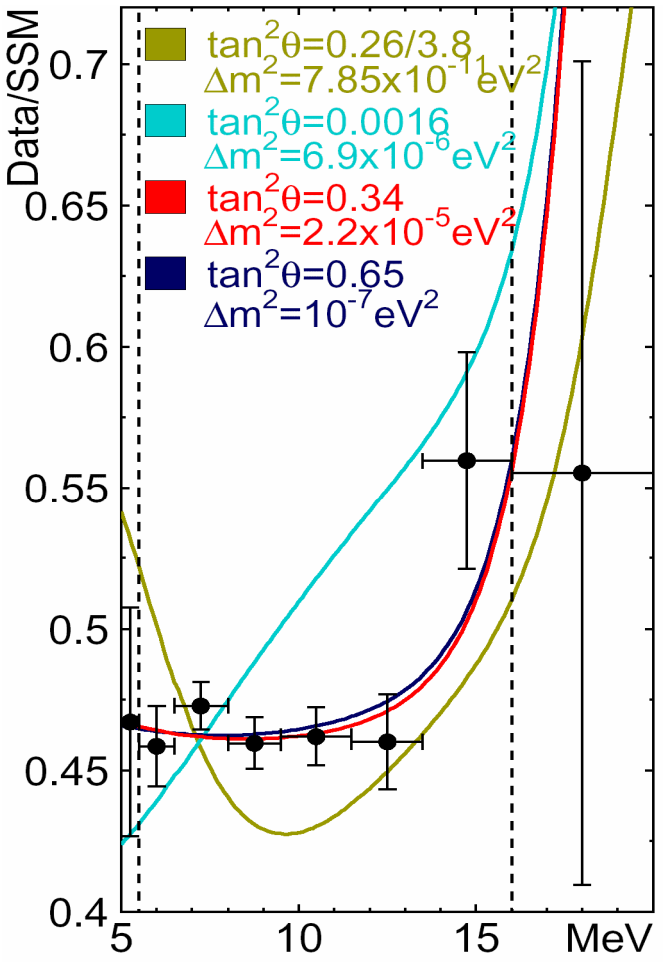

SK-I + SK-II
Δm^2 (eV^2)
$\sin^2 2\theta$
99% C.L.
90% C.L.
68% C.L.

Spectrum

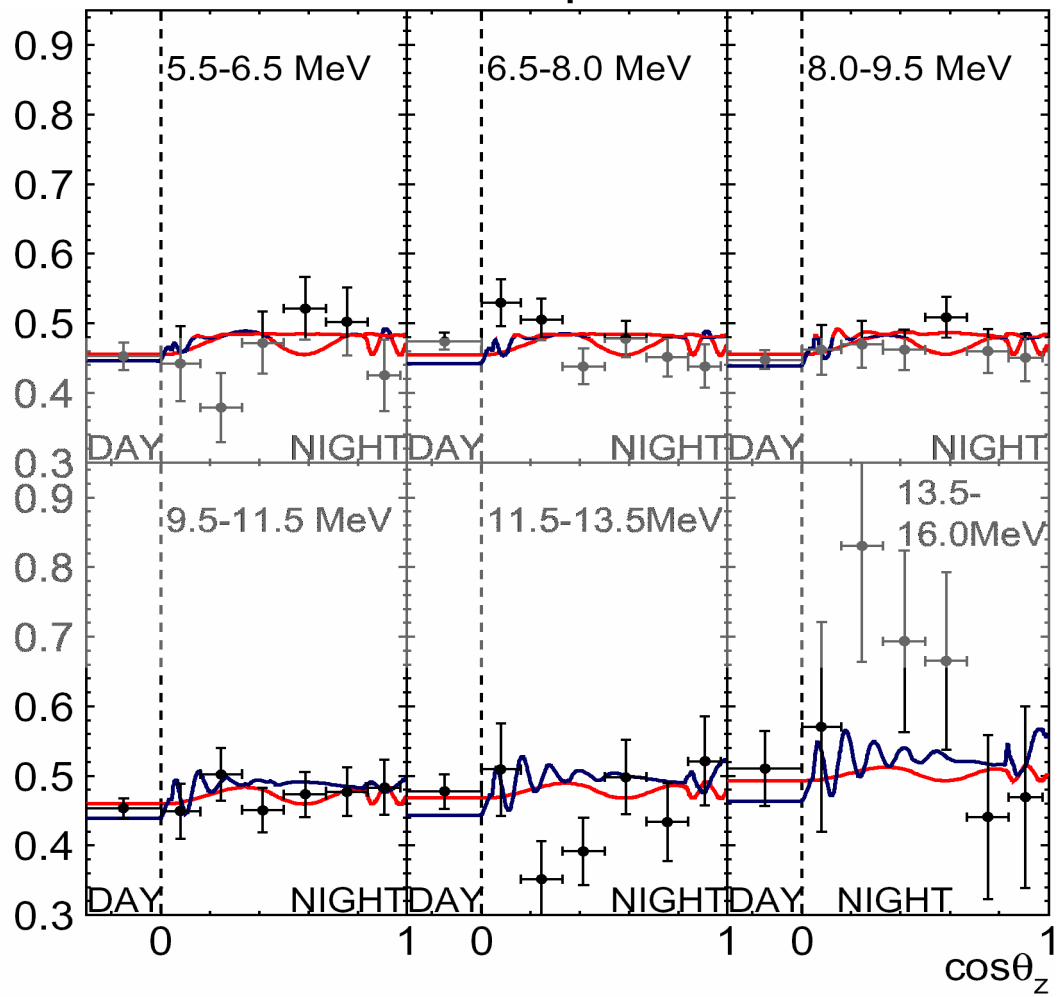


Consistent between SK-1 and SK-2

Solar neutrino oscillation analysis in SK-1
-- 2 flavor --



Zenith spectrum



Un-binned time variation method

Likelihood for solar neutrino extraction

 # Backgrounds in each energy bins

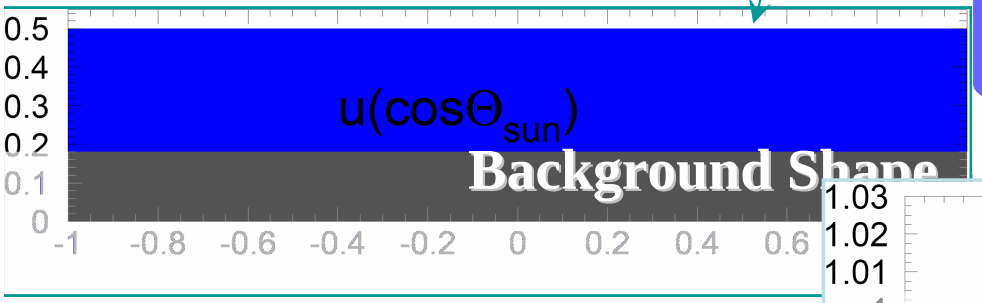
 # Signal Events

Event Energy

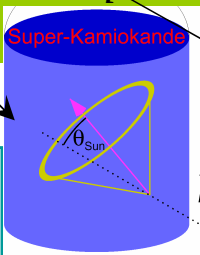
Event "Time"

$$\mathbf{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{n=1}^{n_i} \left(B_i \cdot u_i(c_n) + m_i S \cdot p(c_n, E_n) \right)$$

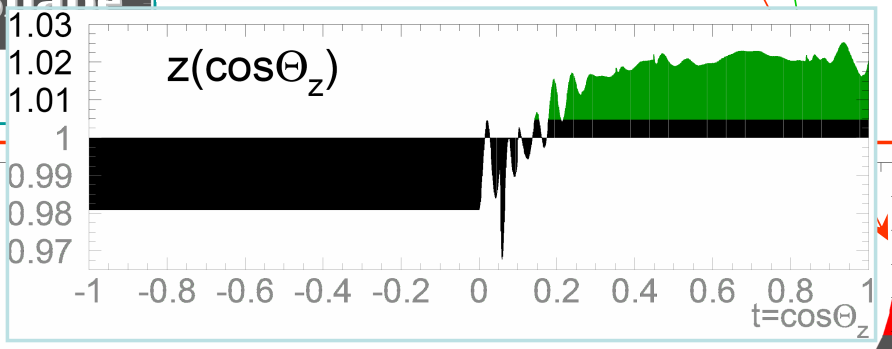
21 Energy bins

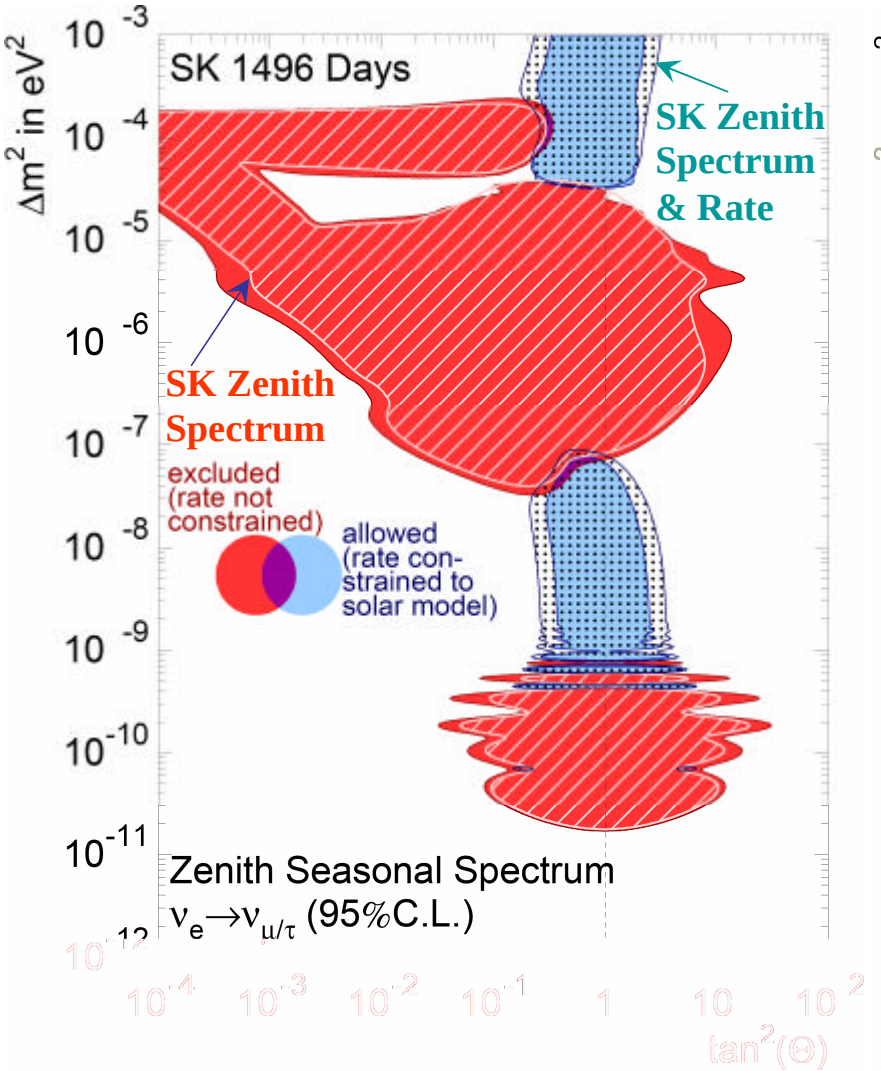


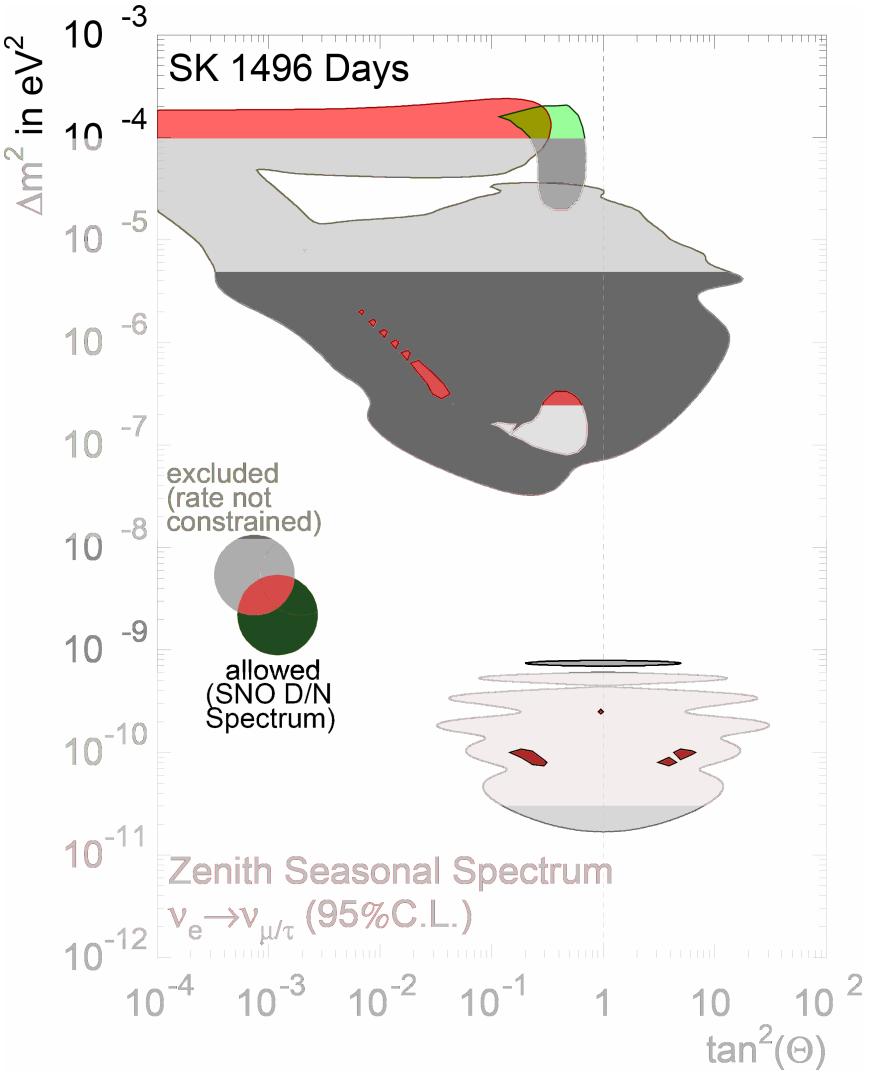
Background Shape



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

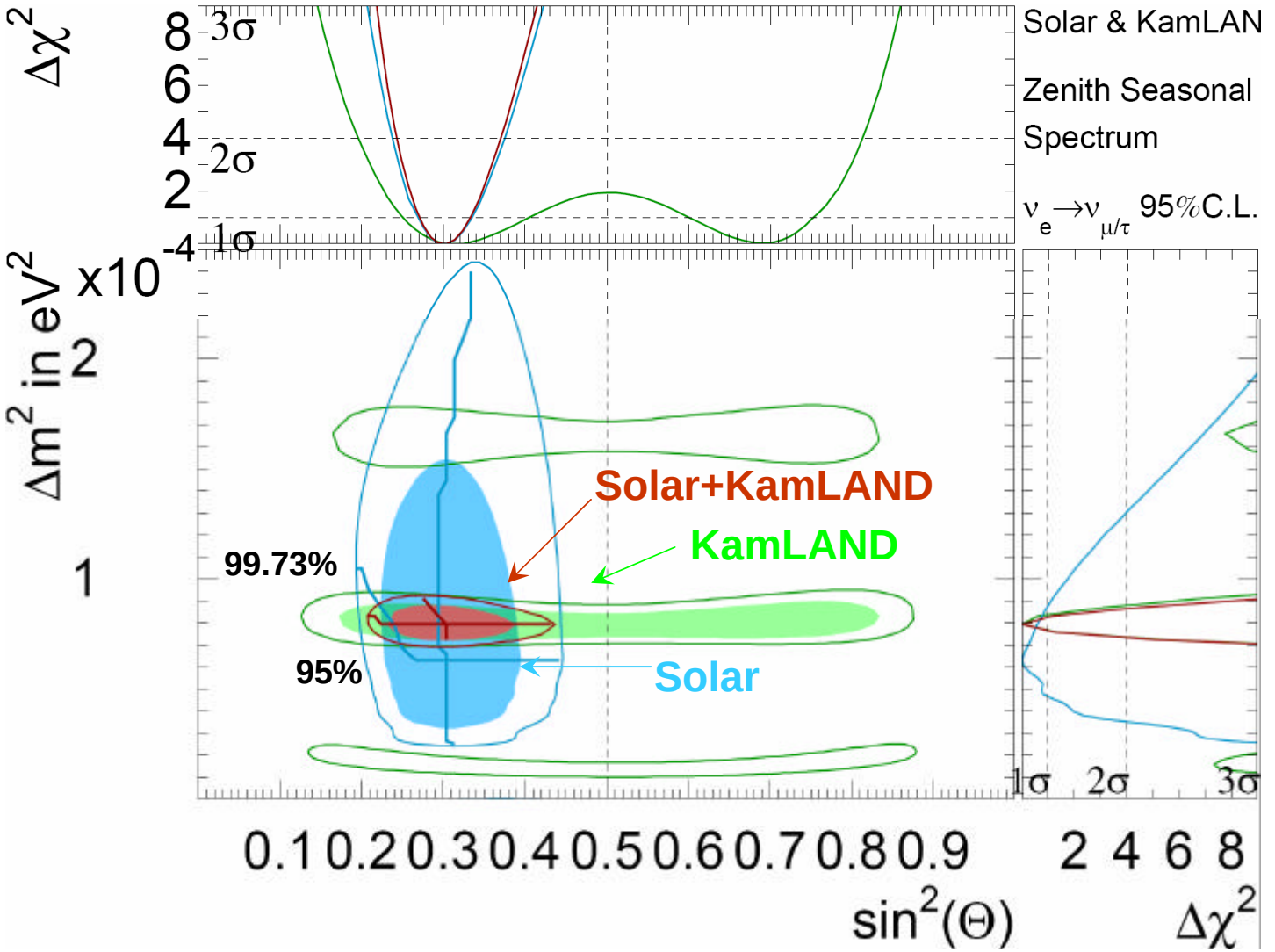




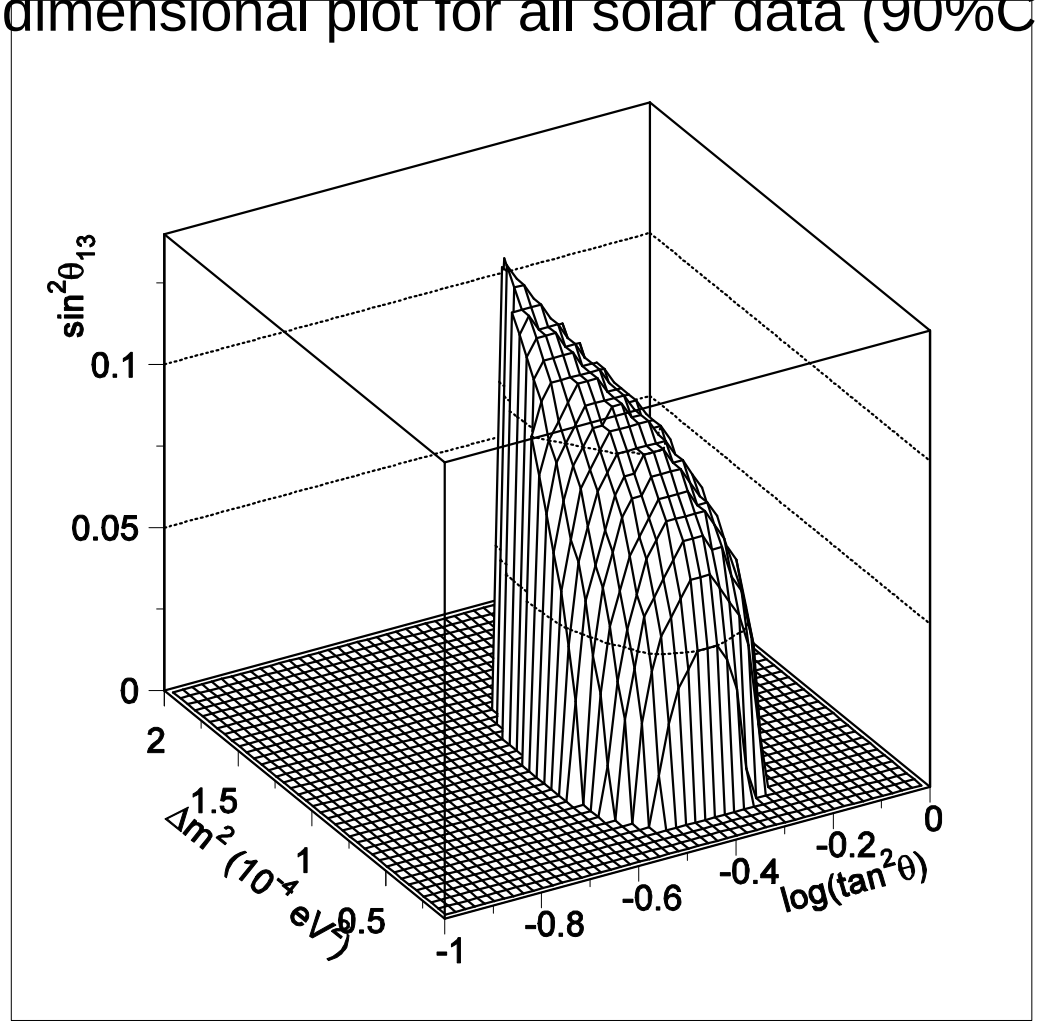


SK excludes all small mixing angles, disfavor LOW

Oscillation parameters from solar neutrino and KamLAND experiments

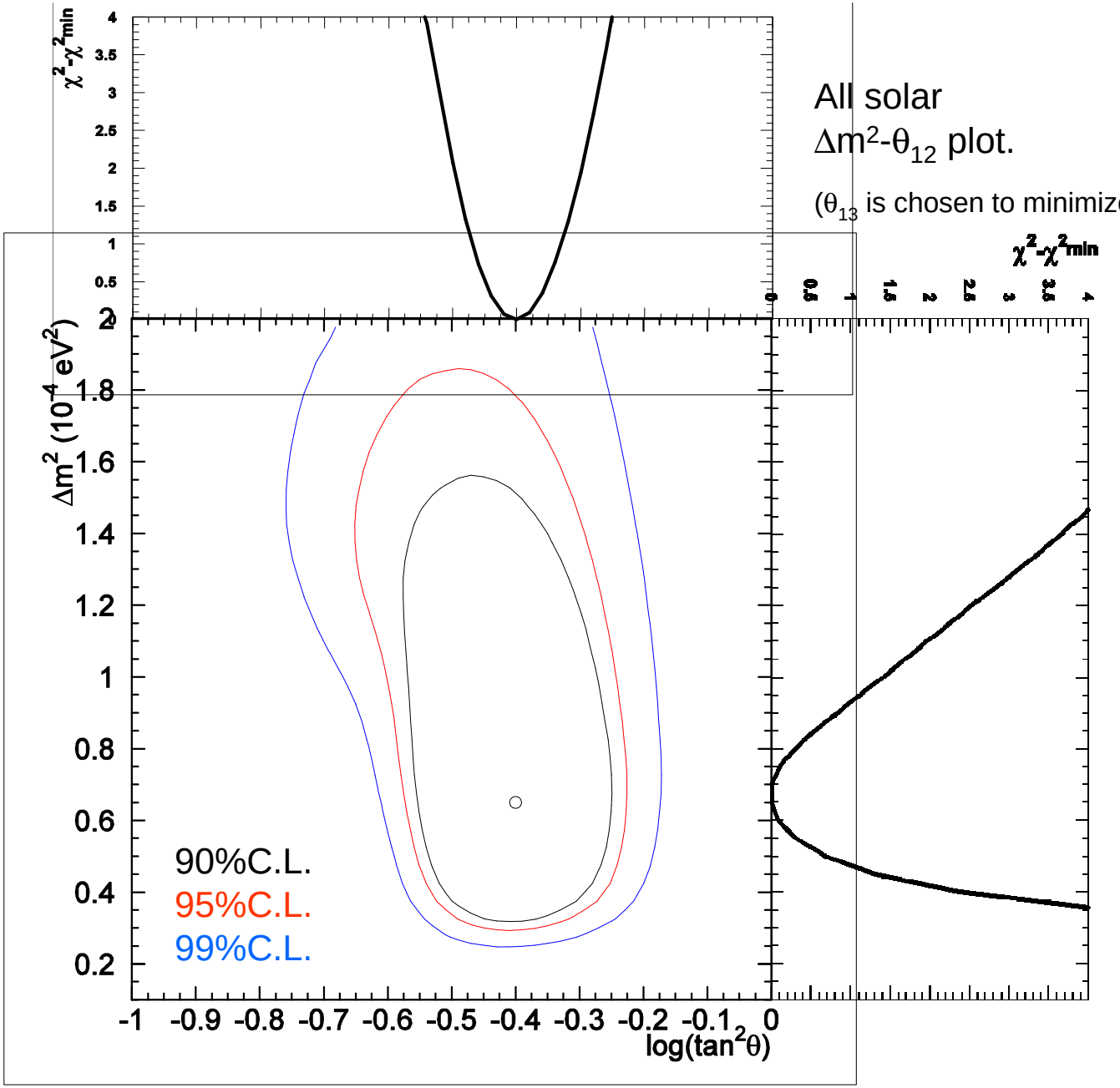


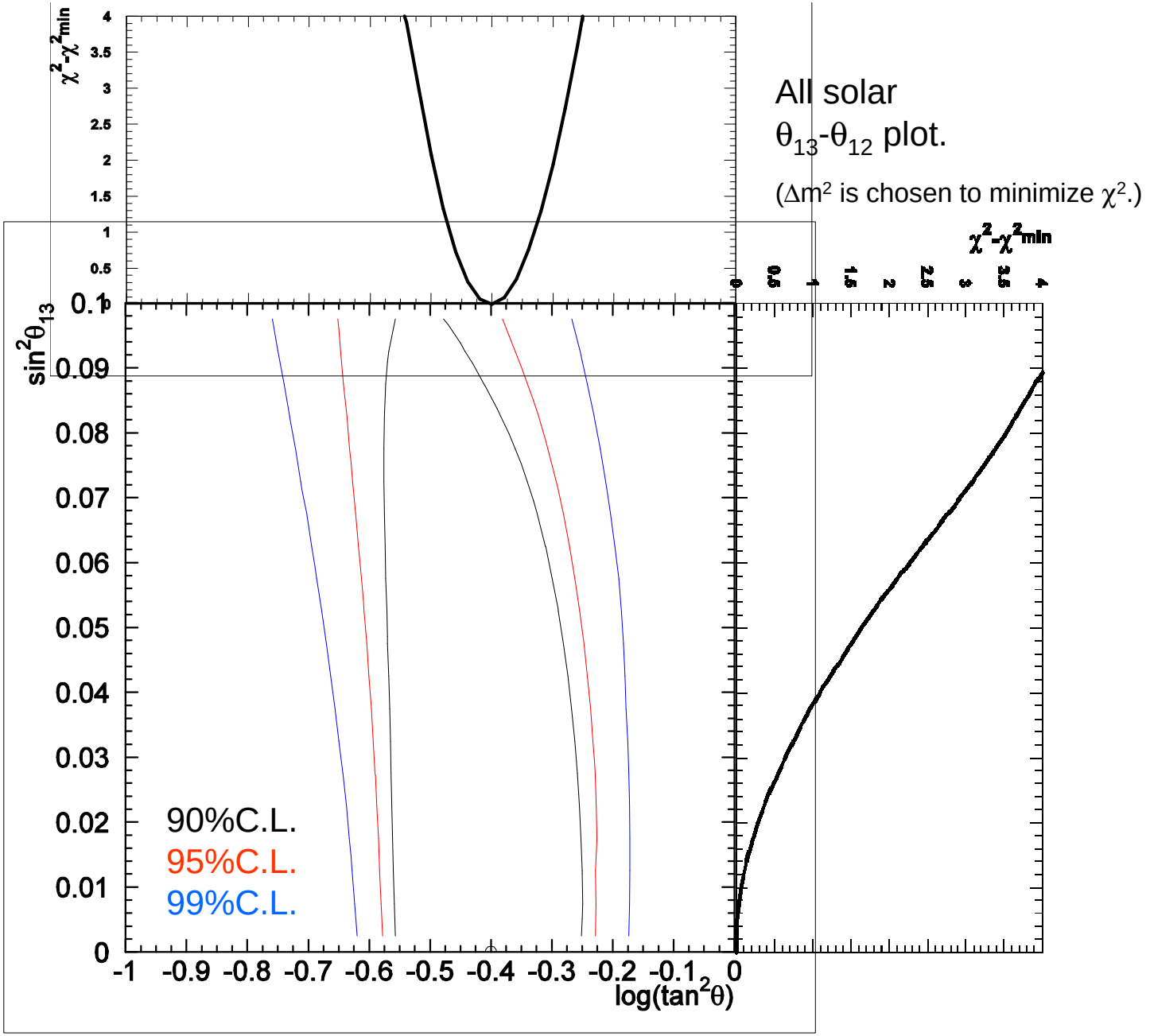
3 dimensional plot for all solar data (90%C.L.)

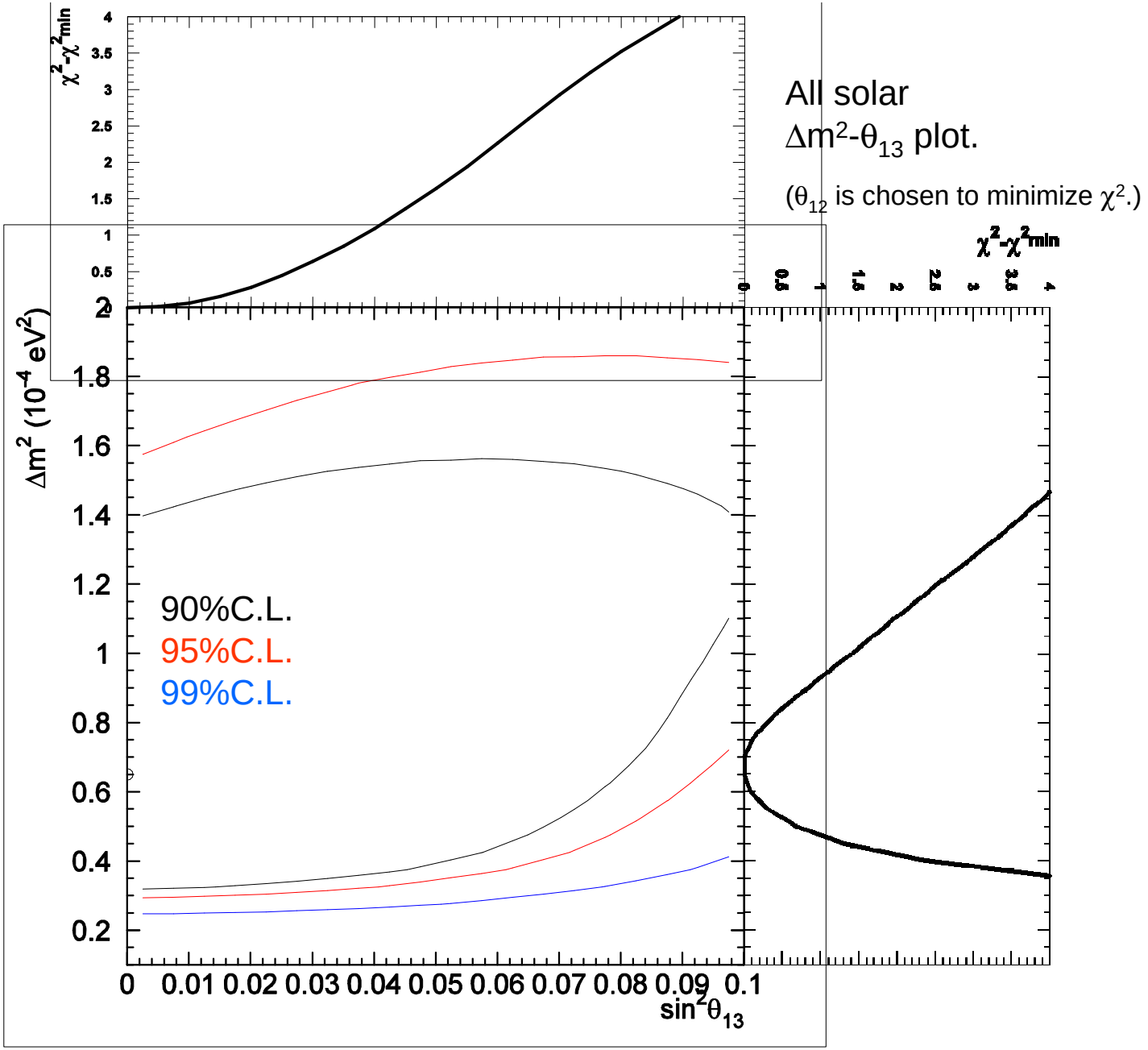


All solar
Δm^2-θ_{12} plot.

(θ_{13} is chosen to minimize χ^2.)




All solar
θ_{13}-θ_{12} plot.
(Δm^2 is chosen to minimize χ^2.)
$\chi^2-\chi^2_{min}$
$\sin^2\theta_{13}$
$\log(\tan^2\theta)$
90%C.L.
95%C.L.
99%C.L.


All solar
Δm^2-θ_{13} plot.
(θ_{12} is chosen to minimize χ^2.)
χ^2-χ^2_{min}
Δm^2 (10^{-4} eV^2)
90%C.L.
95%C.L.
99%C.L.
$\sin^2\theta_{13}$

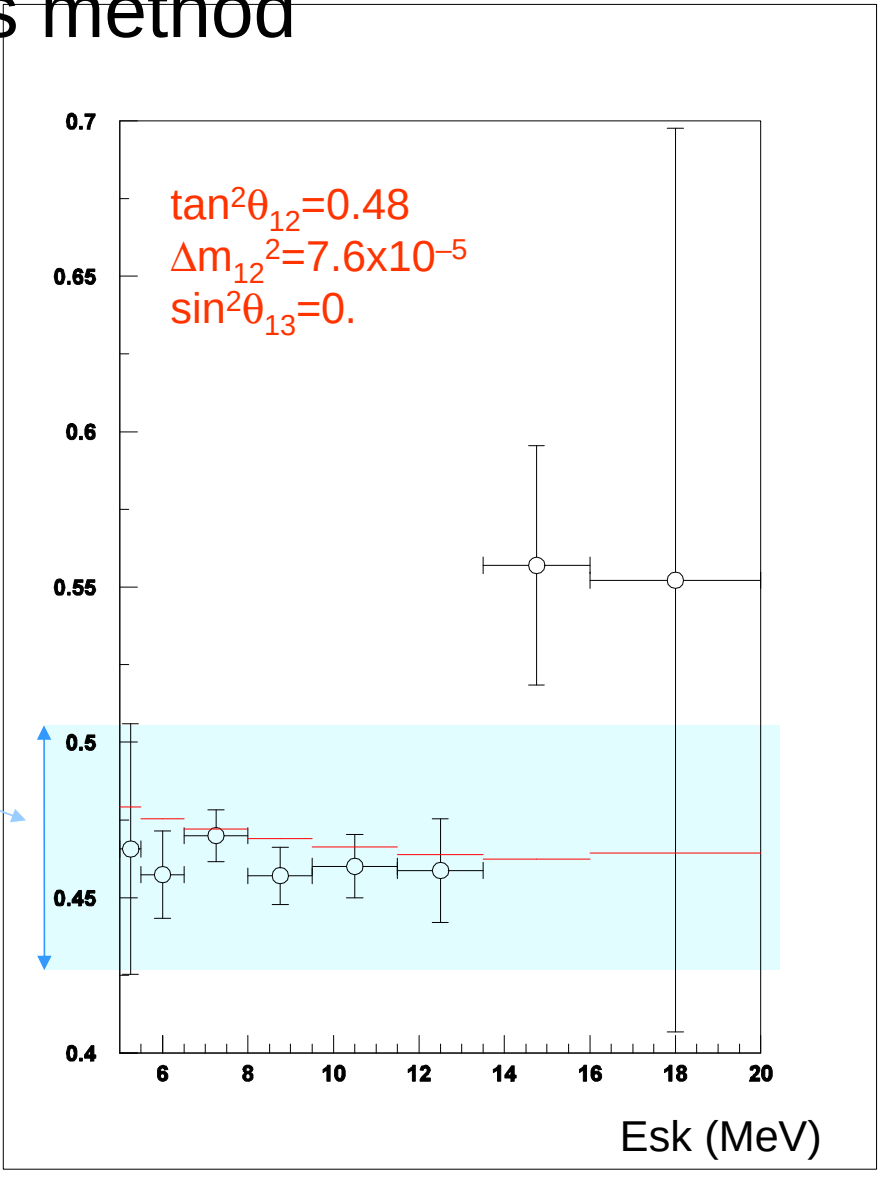
Analysis method

- Zenith spectrum for SK
  - 8 bins for spectrum and 7 bins for zenith angle.

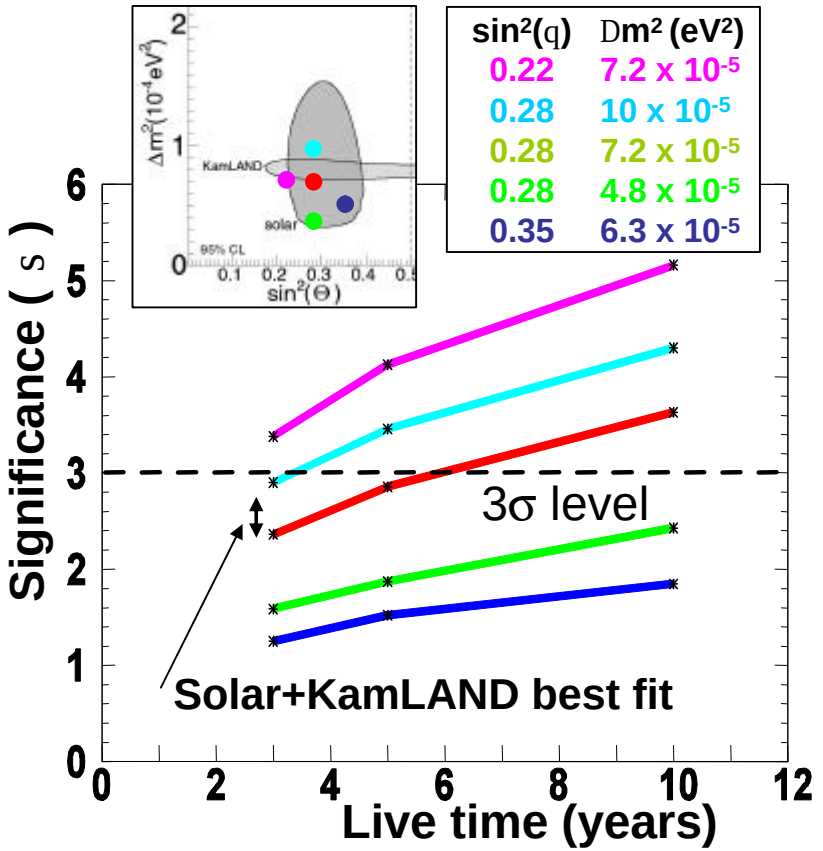
1. SK flux constraint by SNO NC salt phase data.

   $4.94\ (1^{+0.081}_{-0.088}) \times 10^6\ /cm^2/sec$

2. SK/SNO (NC,CC)
3. All solar data, Ga and Cl, BP2004 neutrino fluxes for pp, pep, CNO and ^{7}Be are used.



Significance of spectrum distortion



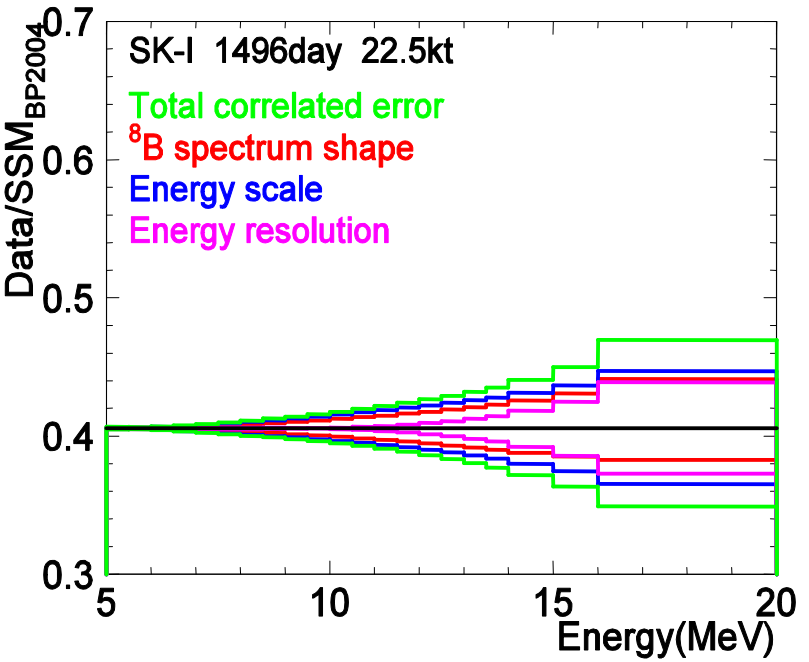
Assumptions:

Correlated systematic error: x 0.5

4.0-5.5MeV background: x 0.3

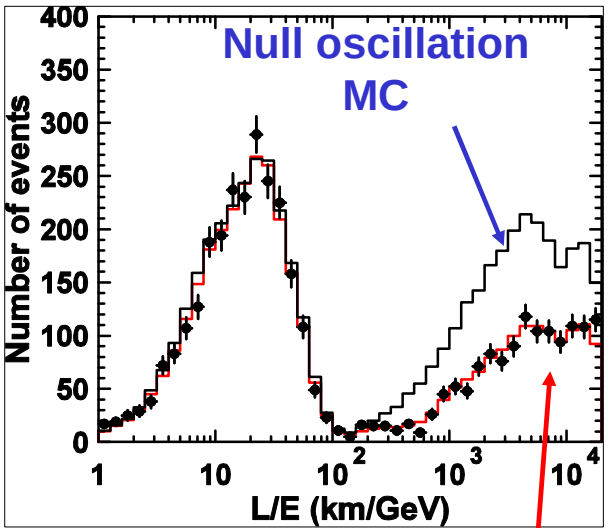
(same BG as SK-I above 5.5MeV)

Current breakdown of correlated systematic errors

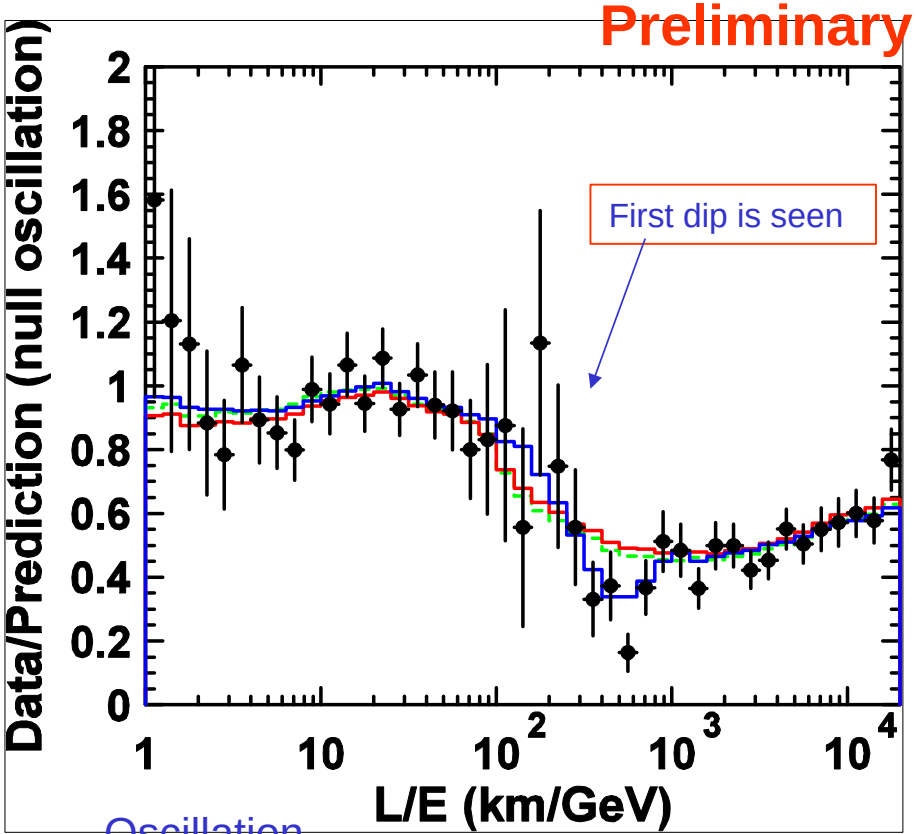


- Better Energy scale calibration (~ ± 0.4%) is needed.
- Better ^{8}B spectrum shape from nuclear physics is needed.

L/E distribution in SK-1 and SK-2



Preliminary !

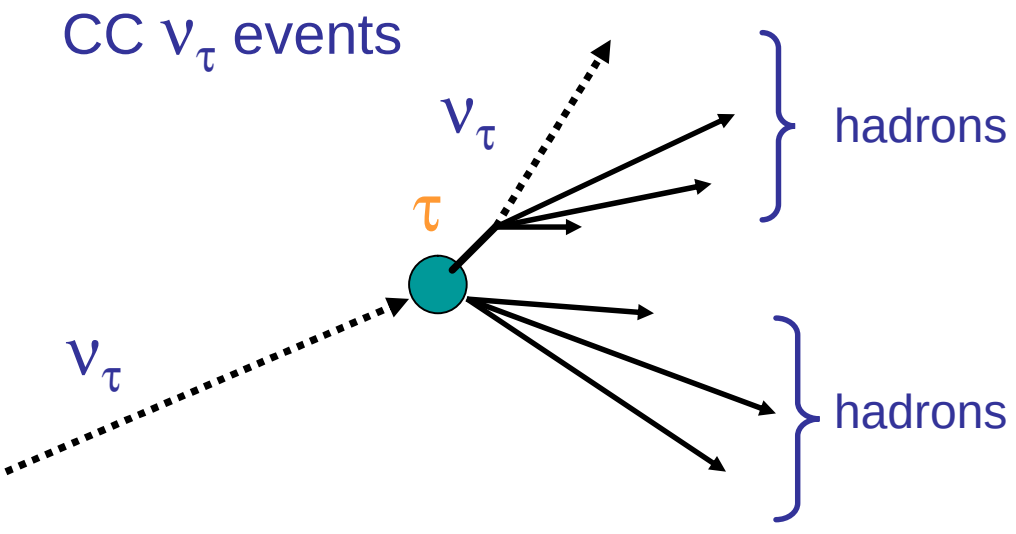


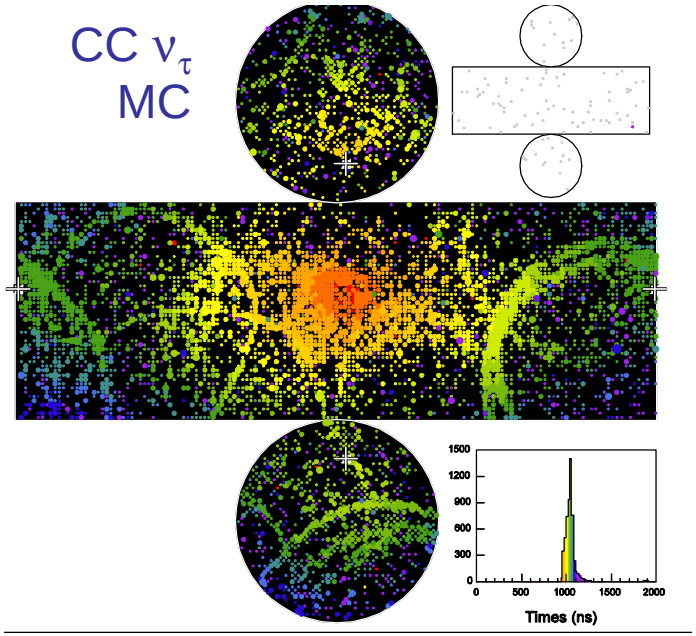
$\Delta\chi^2$=19.5 → 4.4σ

$\Delta\chi^2$=23.3 → 4.8σ

The first dip cannot be explained by other models

Search for CC ν_τ events





? Many hadrons . . . .
(But no big difference with other (NC) events.)

→ τ- likelihood analysis

? Upward going only

→ Zenith angle dependence

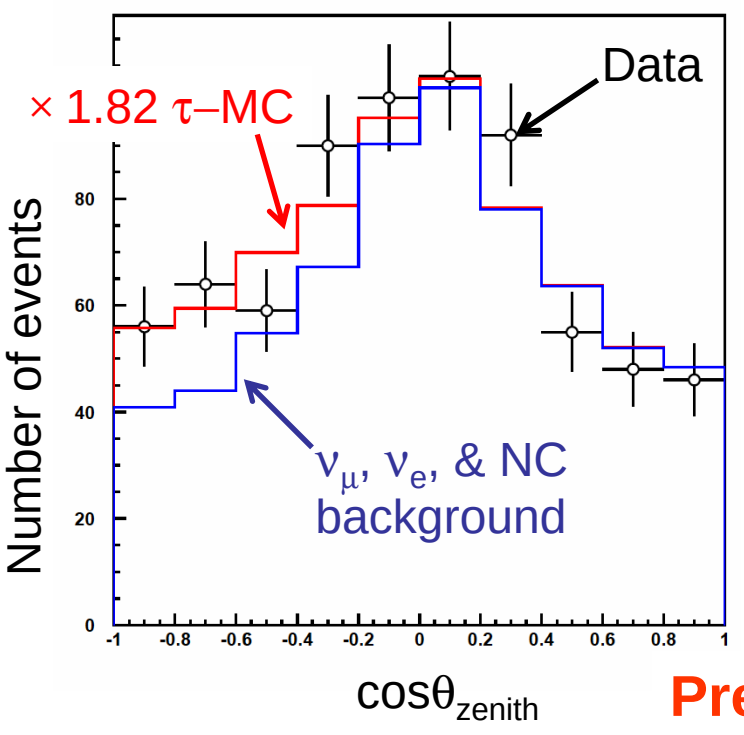
Only ~ 1.0 CC ν_τ FC events/kton· yr

⇕

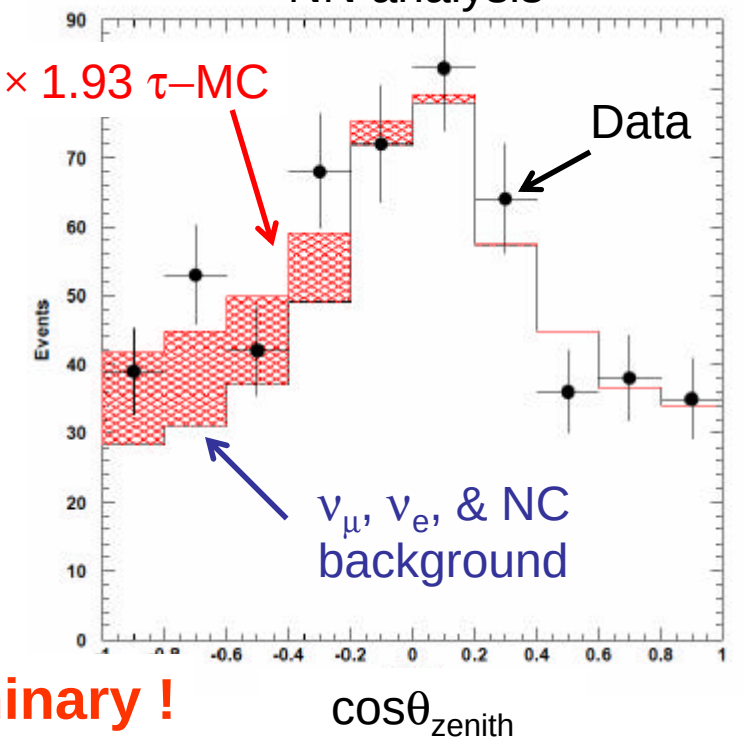
(BG (other ν events) ~ 130 ev./kton· yr)

Zenith angle distribution and fit results

Likelihood analysis



NN analysis



Preliminary !

	Likelihood analysis	NN analysis
Fitted # of τ events	145 ± 48(stat) +9 / -36 (osc. para. uncertainty)	152 ± 47(stat) +12 / -27 (osc. para. uncertainty)
Expected # of τ events	79 ± 31(stat)	79 ± 31 (stat)