Super-Kamiokande's Solar Neutrino results

M. Nakahata
Kamioka observatory,
ICRR, Univ. of Tokyo

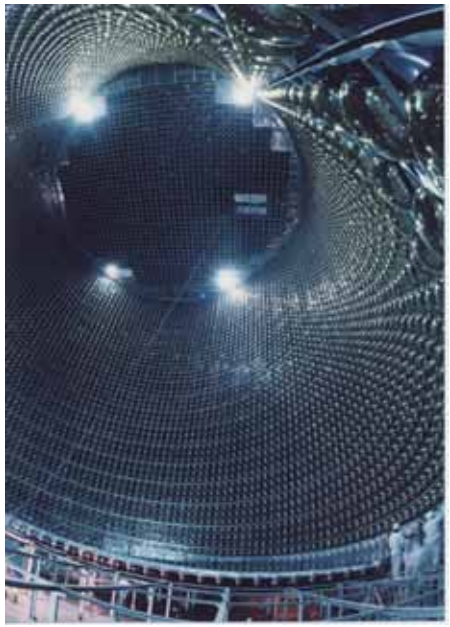
- Super-Kamiokande(SK) detector
- Day/night and energy spectrum in SK-I
- Oscillation analysis
- Preliminary results from SK-II
- Future prospects

Super-Kamiokande detector

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007

SK-I — accident — SK-II — SK-III

SK full reconstruction (plan)



50kton total,

22kton fiducial volume

1000m underground

Water Cherenkov detector

11,146	Number of ID(*) PMTs	5,182
40%	Photocathod coverage	19%
~6 p.e./MeV	Cherenkov light yield	~2.8 p.e./MeV
		Acrylic+FRP cases

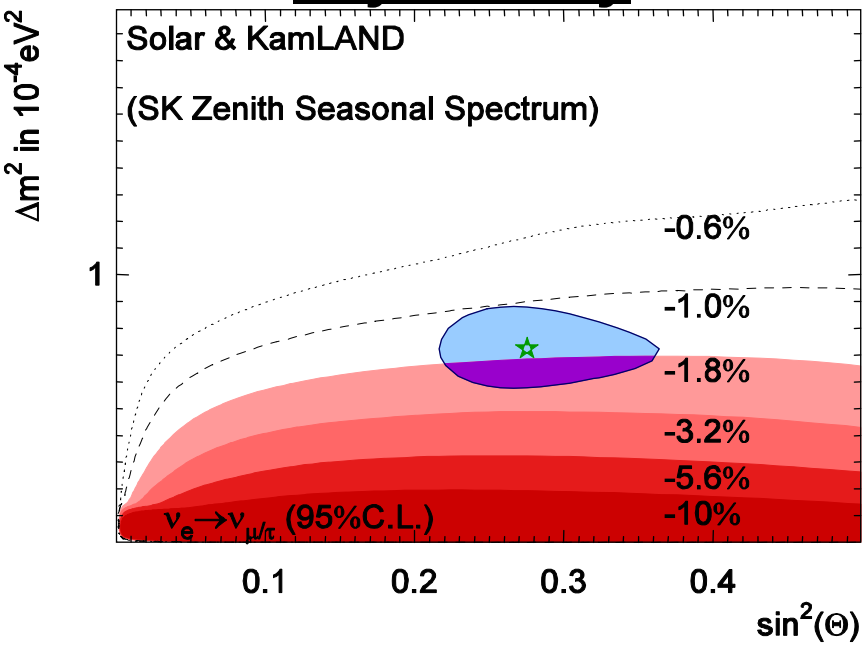
Number of ID PMTs will be back to 11,146 in SK-III.

(*) Inner Detector

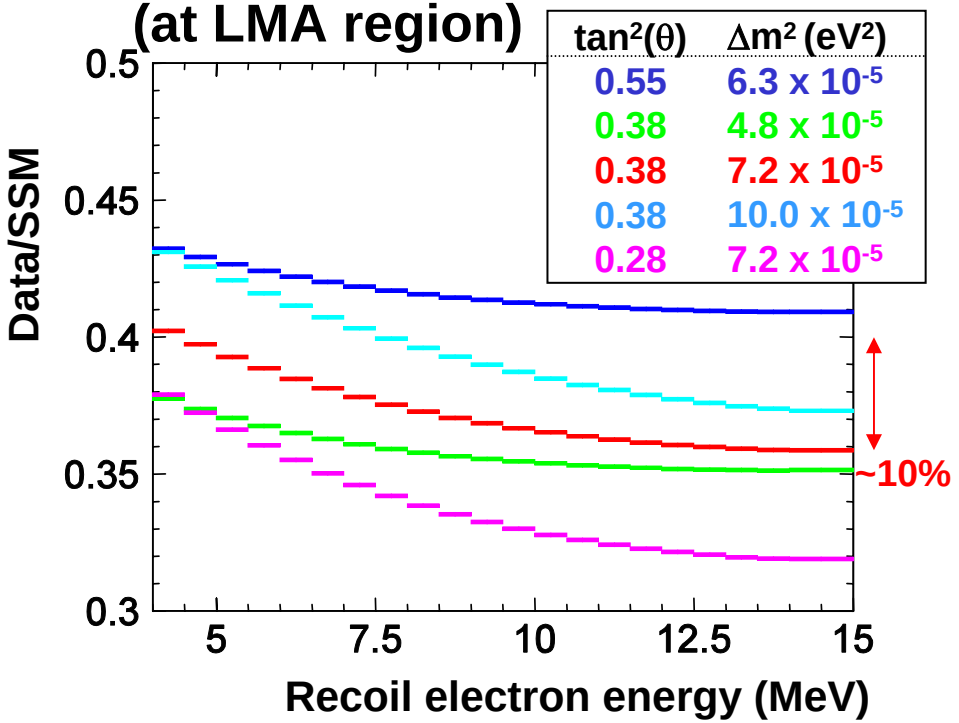
Solar neutrino measurement in SK

- ^{8}B neutrino measurement by $\nu + e^- \rightarrow \nu + e^-$
- Sensitive to ν_e, ν_μ, ν_τ $\sigma(\nu_{\mu(\tau)}+e^-) = \sim 0.15 \times \sigma(\nu_e+e^-)$
- High statistics ~15ev./day with $E_e > 5$MeV
- Real time measurement. Studies on time variations.
- Studies on energy spectrum.
- Precise energy calibration by LINAC and ^{16}N.

Expected day/night asymmetry

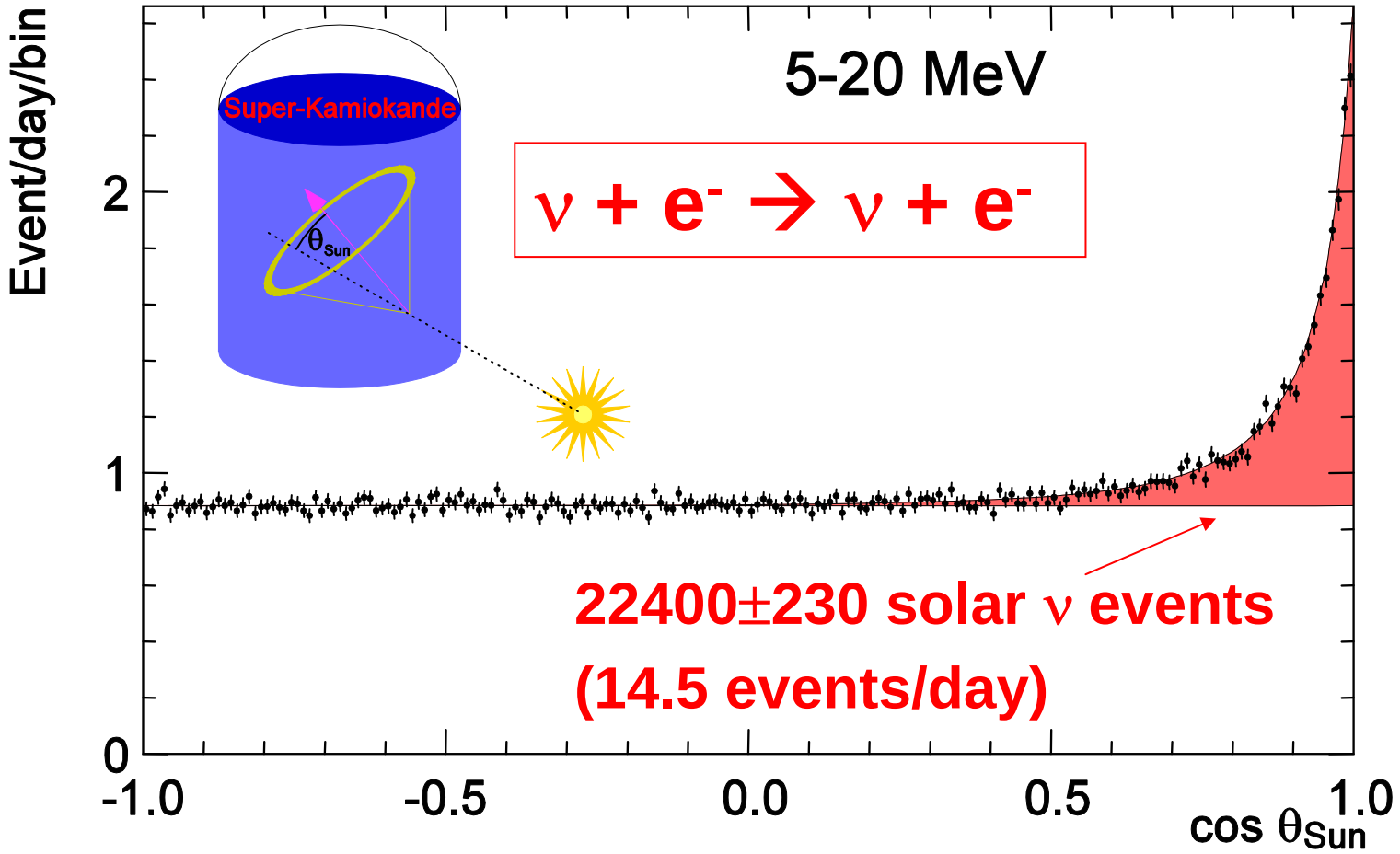


Expected spectrum distortion (at LMA region)



Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)

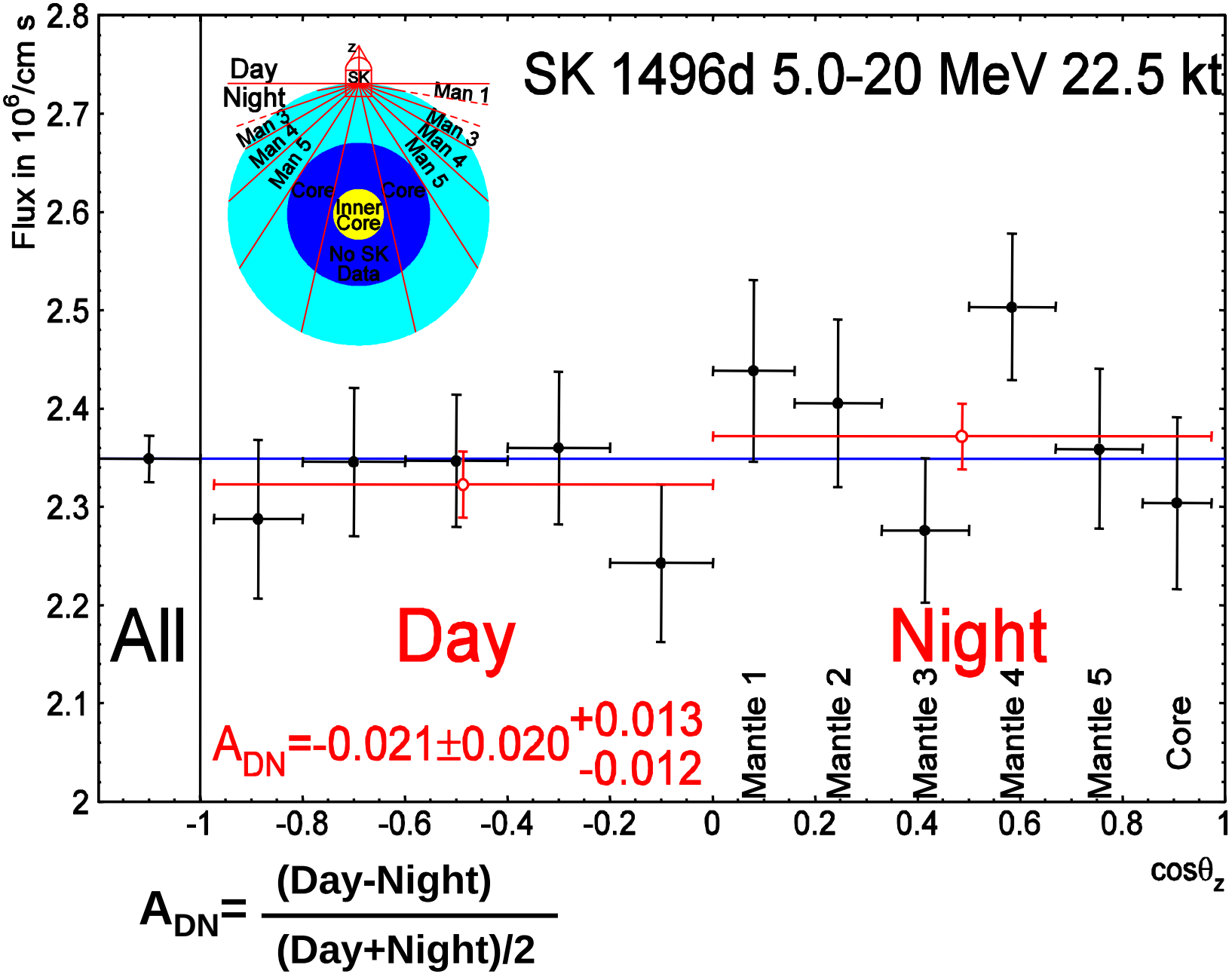


^{8}B flux : $2.35 \pm 0.02 \pm 0.08$ [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \; {}^{+0.014}_{-0.013}$$

(Data/SSM(BP2000) = 0.465 ±0.005 +0.016/-0.015)

SK-I day/night difference

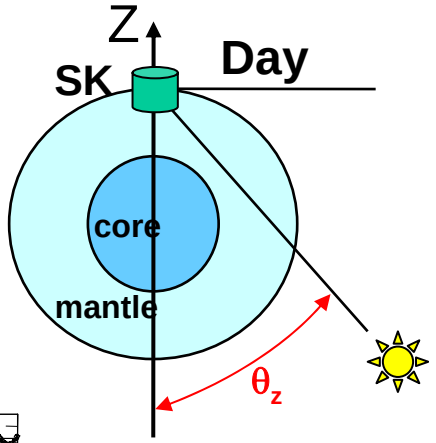


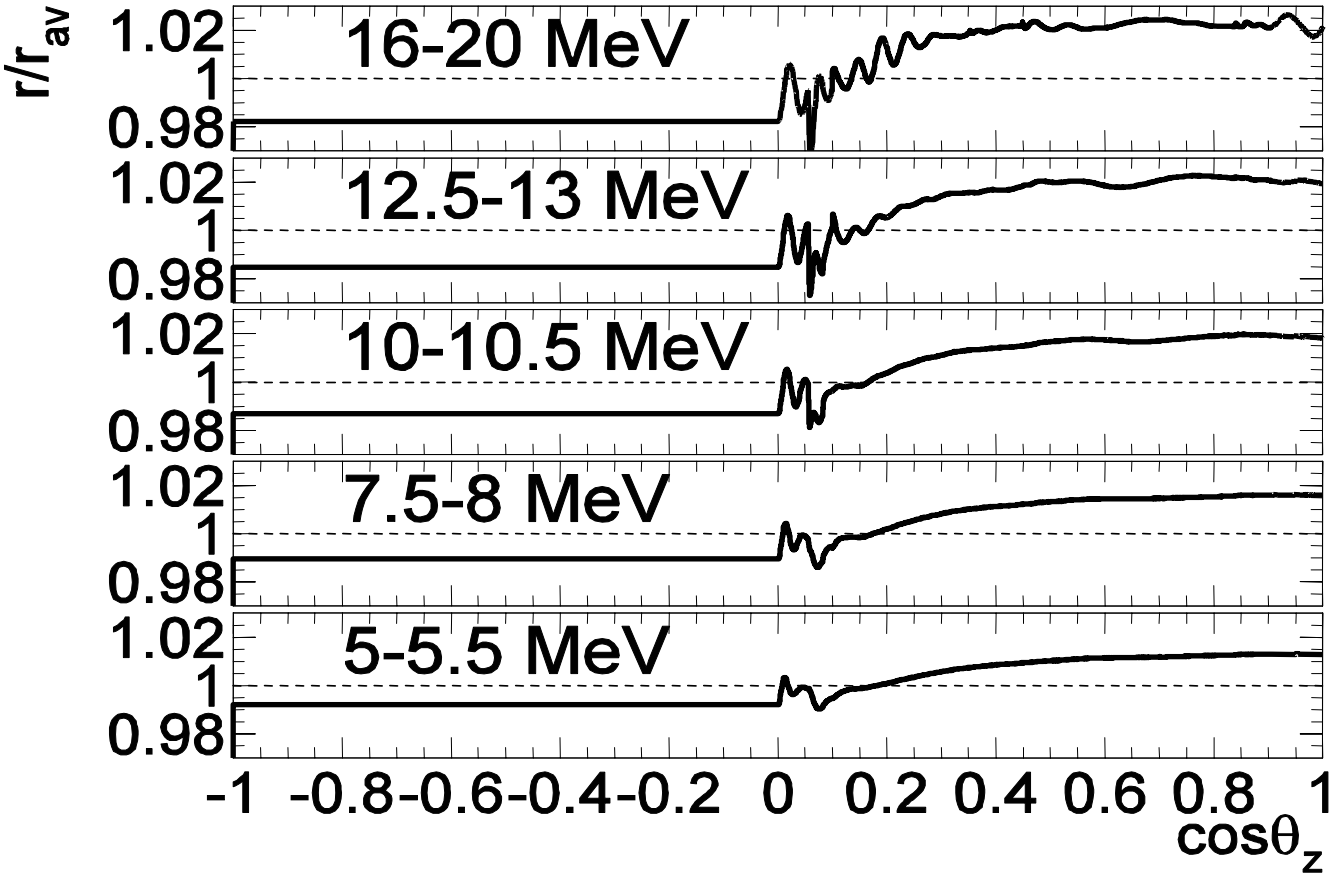
$$A_{DN} = \frac{\text{(Day-Night)}}{\text{(Day+Night)/2}}$$

Un-binned day/night analysis

Energy and zenith angle dependence of event rate variation.

Example for $\Delta m^2=6.3\times10^{-5}eV^2$, $\tan^2\theta=0.55$





Un-binned time variation method

Likelihood for solar neutrino extraction

Backgrounds in each energy bins

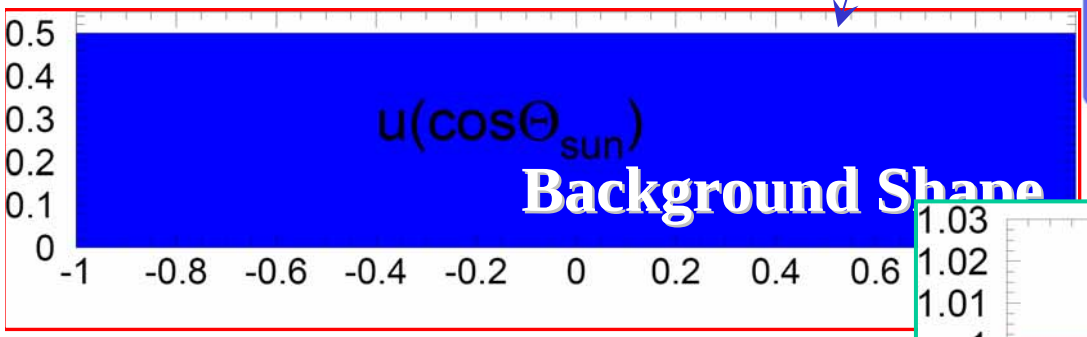
Signal Events

Event Energy

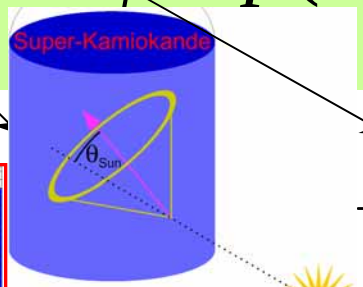
Event "Time"

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

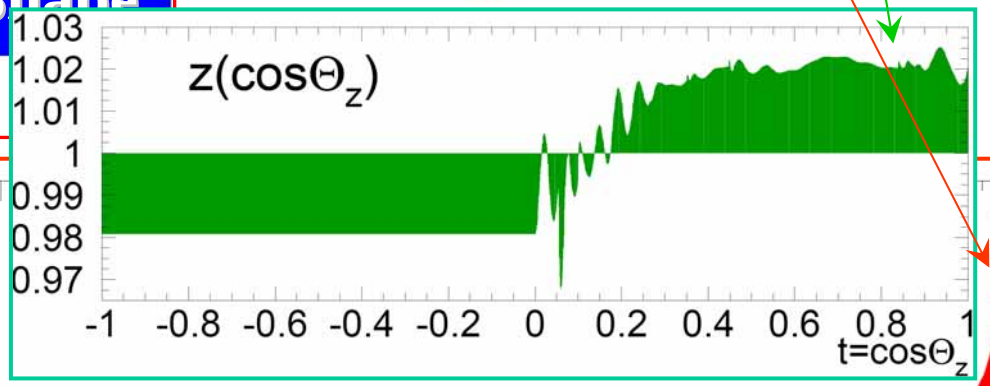
21 Energy bins



Background Shape

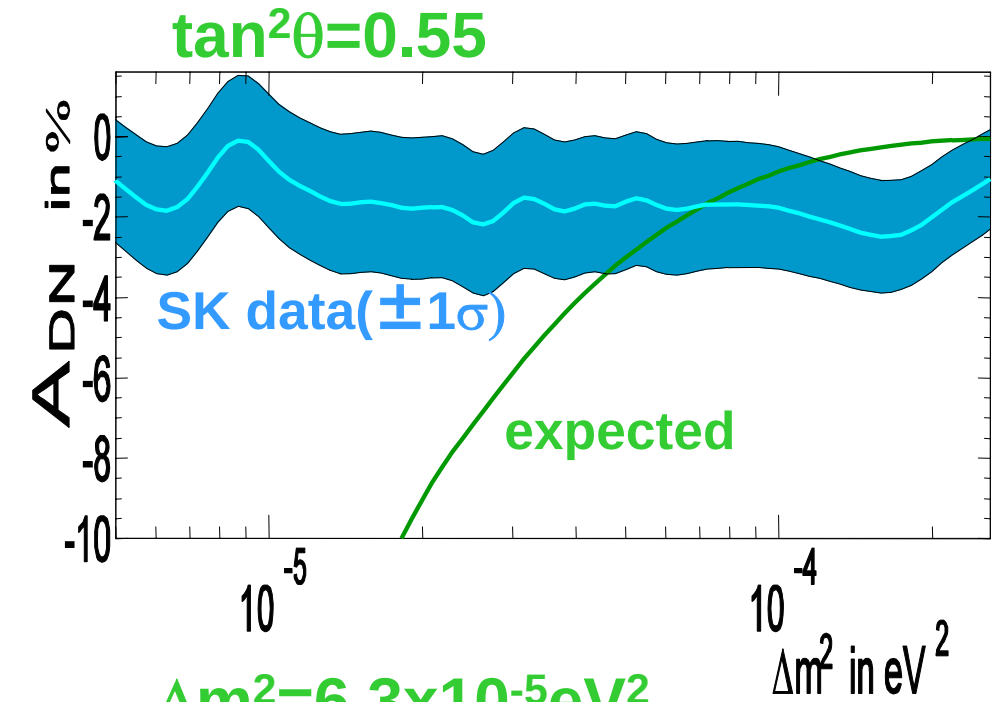


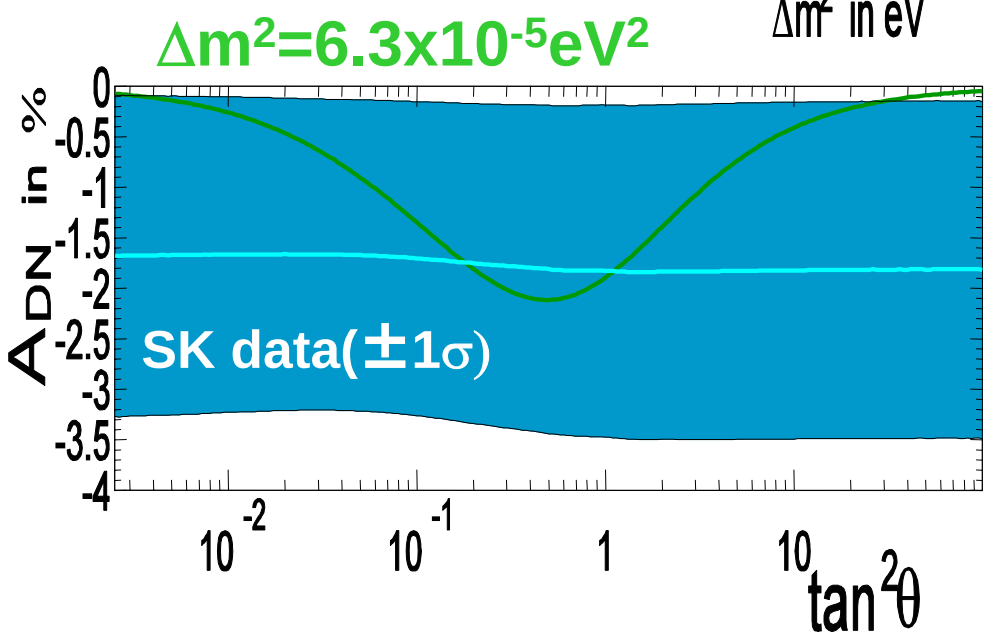
$$\frac{MC_i}{\sum_j MC_j}$$



Solar Signal Shape

Day/night asymmetry





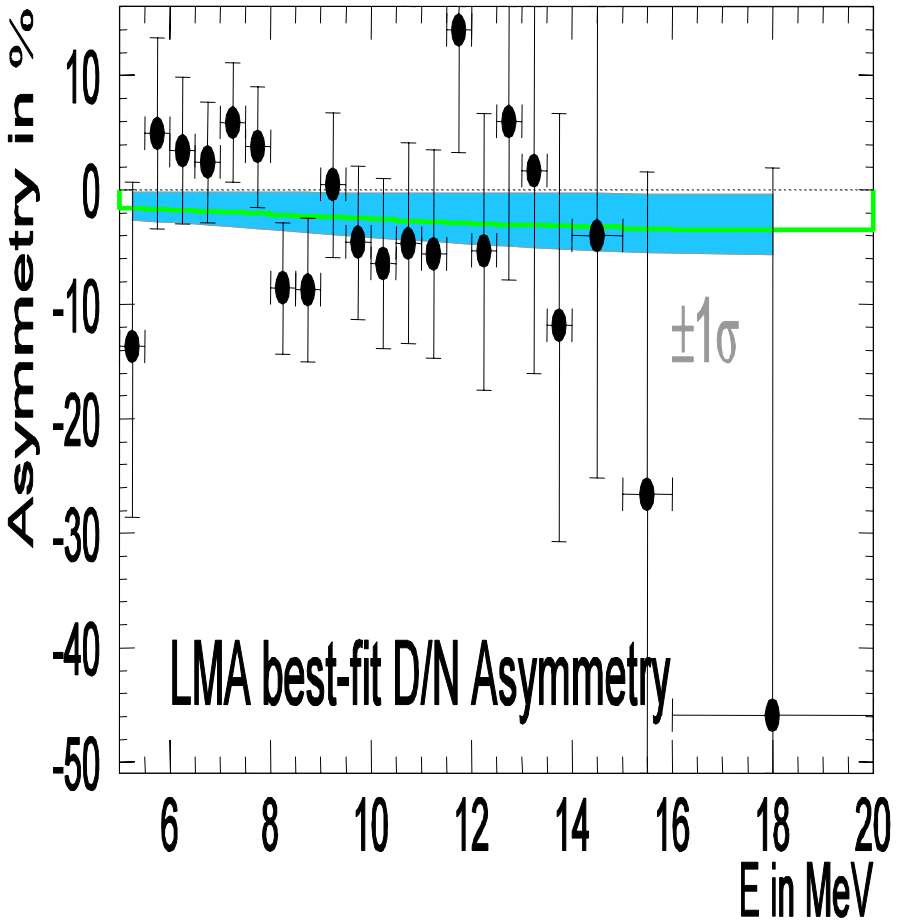
LMA best fit

(Assuming BP2000 flux and error)

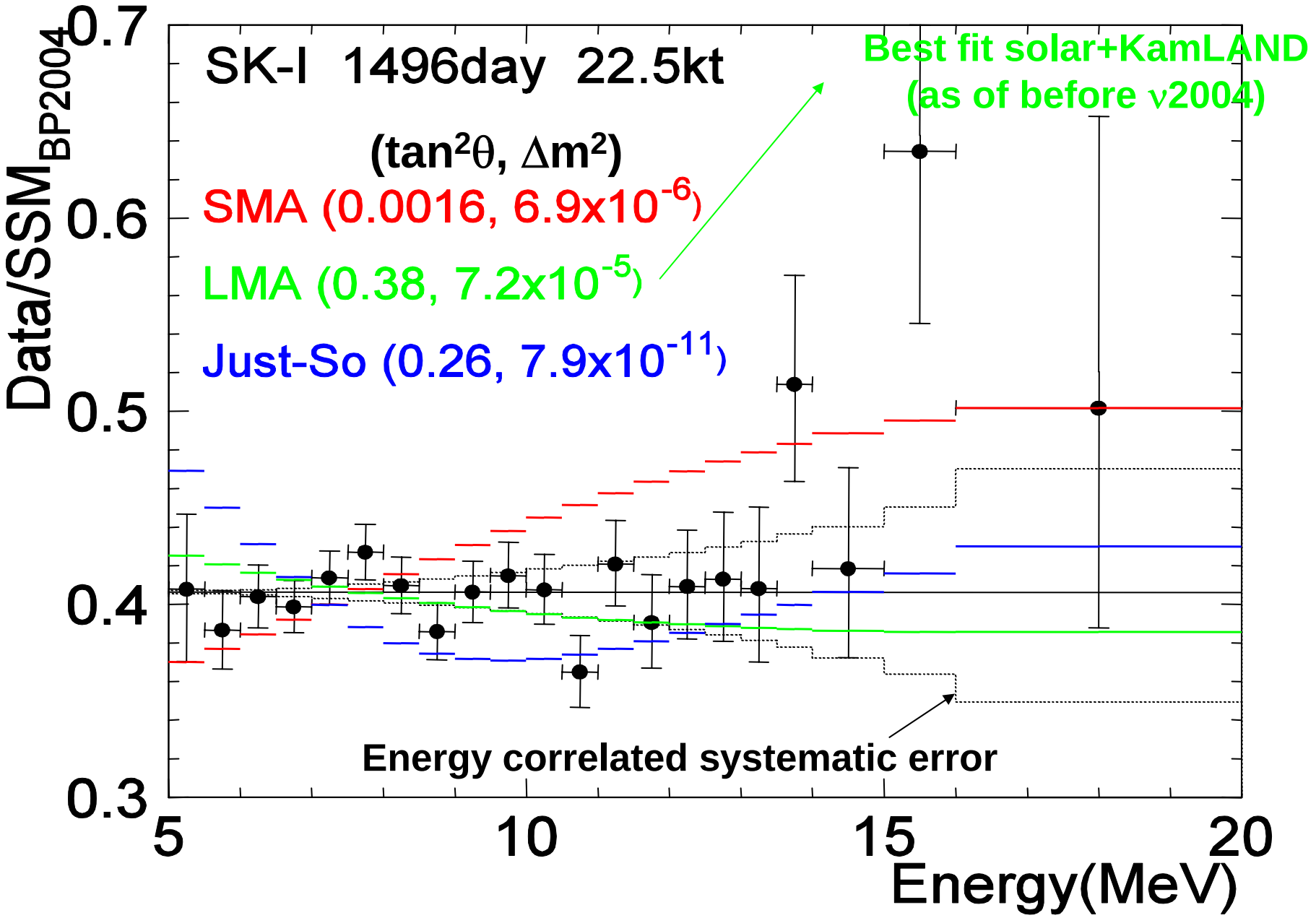
$\Delta m^2 = 6.3 \times 10^{-5} eV^2$

$\tan^2\theta = 0.55$

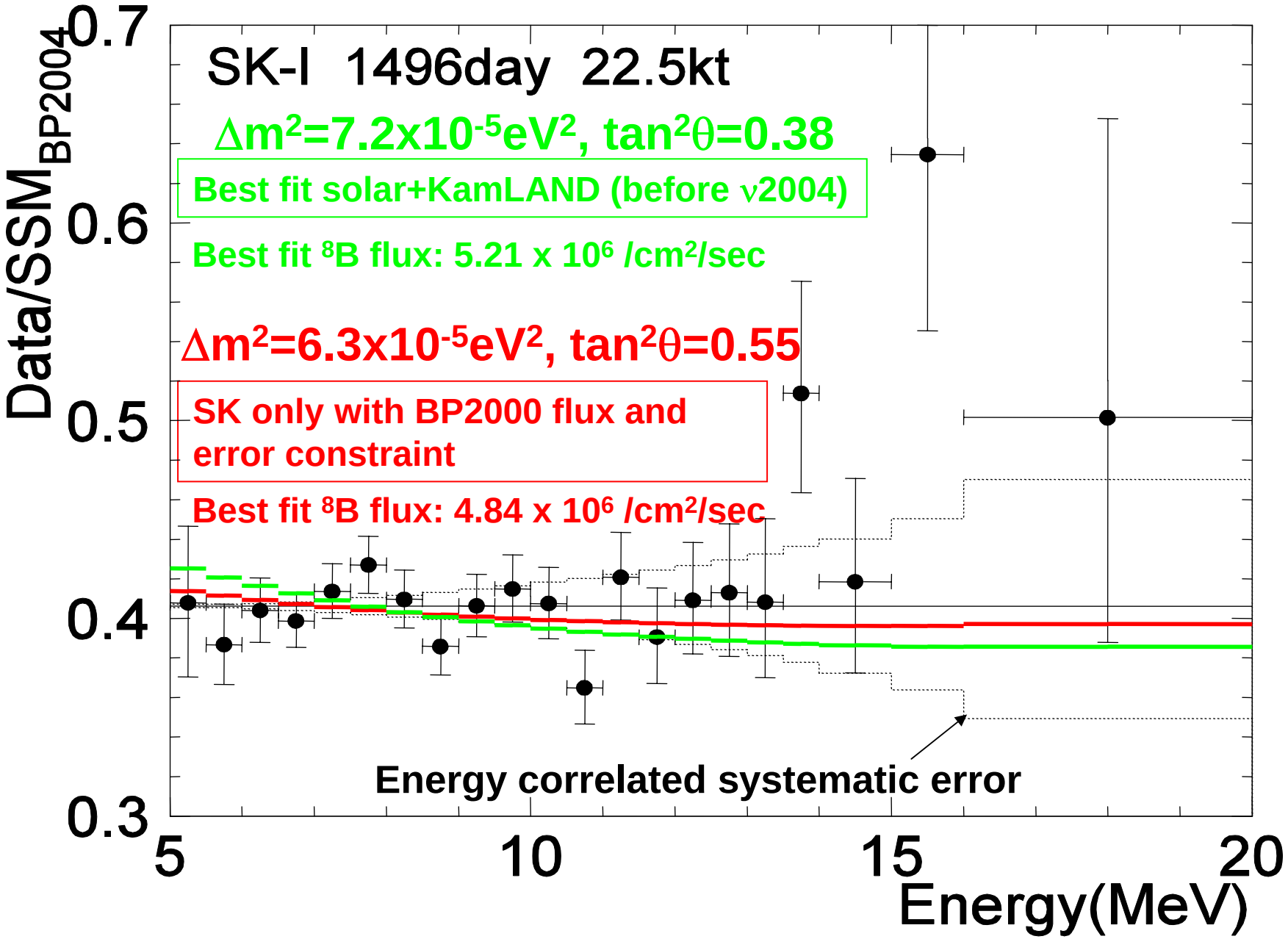
$$A_{DN} = -1.8 \pm 1.6\ ^{+1.3}_{-1.2}\ \%$$



Energy spectrum of SK-I



Energy spectrum of SK-I



Oscillation analysis

$$\chi^2 = \sum_{i=1}^{N_{bin}} \frac{(d_i - \rho_i)^2}{\sigma_i^2} + \frac{\delta_B^2}{\sigma_B^2} + \frac{\delta_S^2}{\sigma_S^2} + \frac{\delta_R^2}{\sigma_R^2} - 2\Delta\log\mathbf{L}_{\text{timevar}}$$

Spectrum

Energy correlated systematic error

Time variation

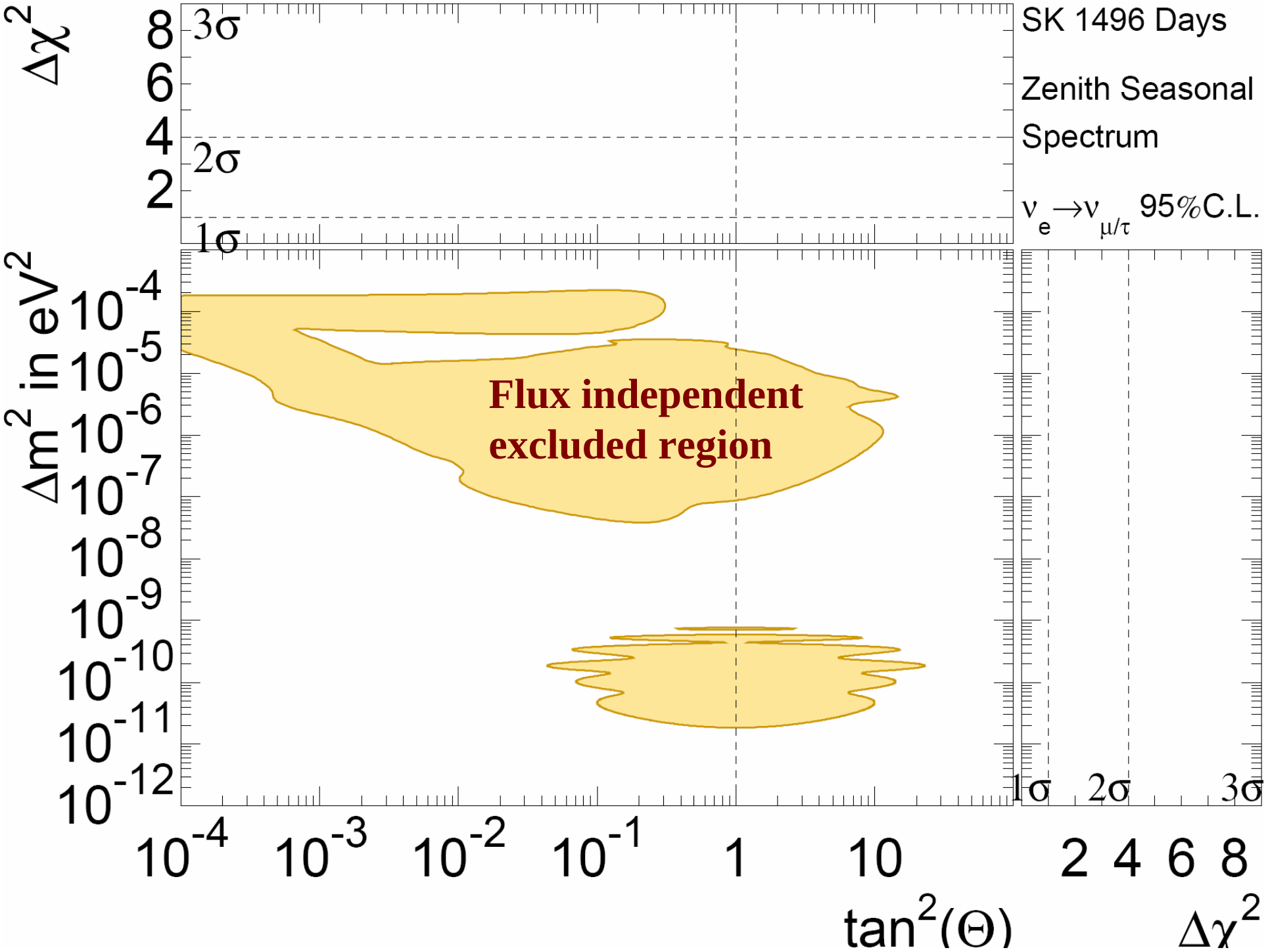
$$\mathrm{d}_i = \frac{\mathrm{Data}_i}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}, \quad \rho_i = \frac{\beta b_i + \eta h_i}{f_i}$$

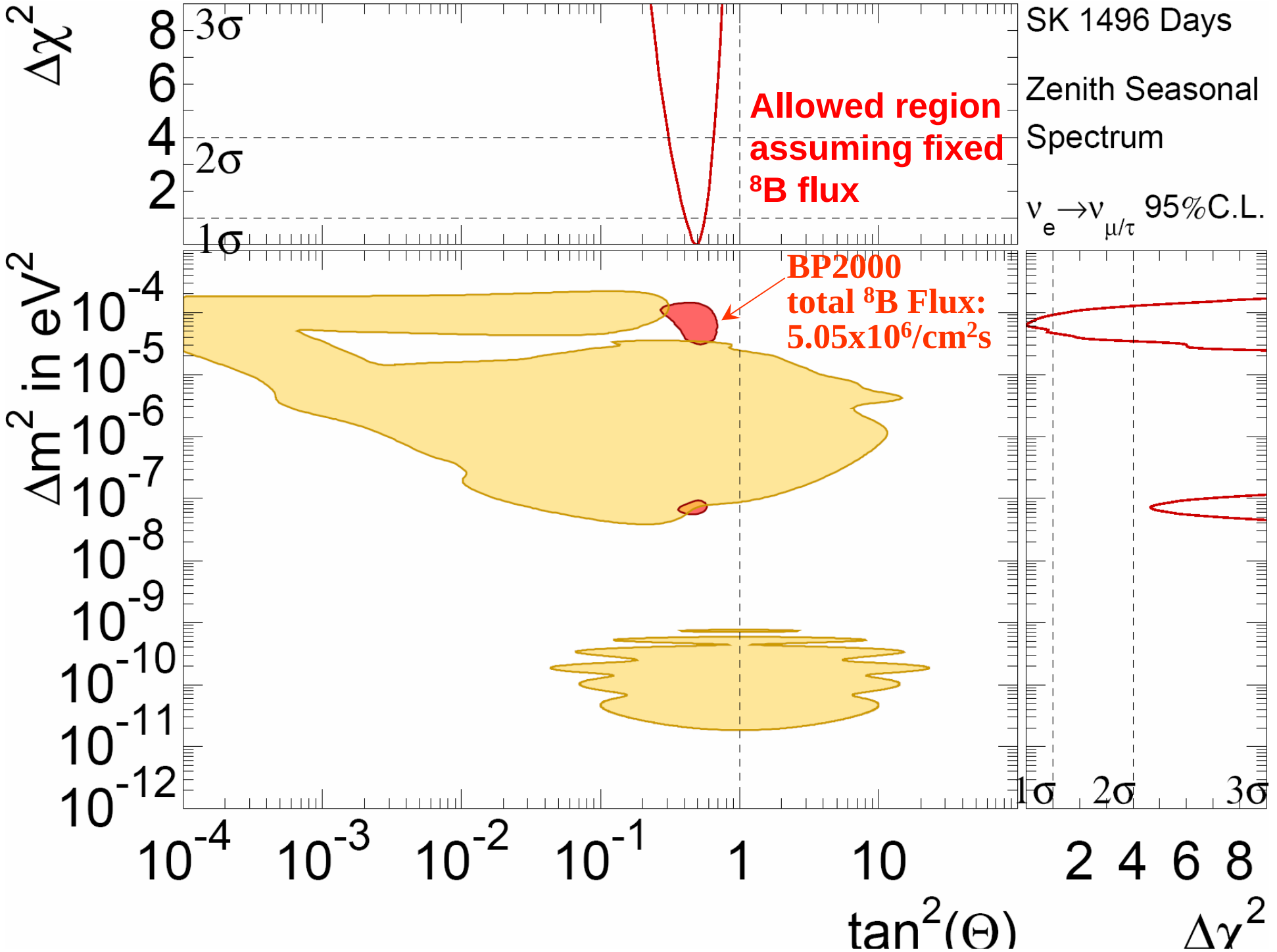
$$b_i = \frac{{}^8\mathrm{B}_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}, \quad h_i = \frac{hep_i^{\mathrm{osc}}(\Delta m^2, \tan^2\theta)}{{}^8\mathrm{B}_i^{\mathrm{SSM}} + hep_i^{\mathrm{SSM}}}$$

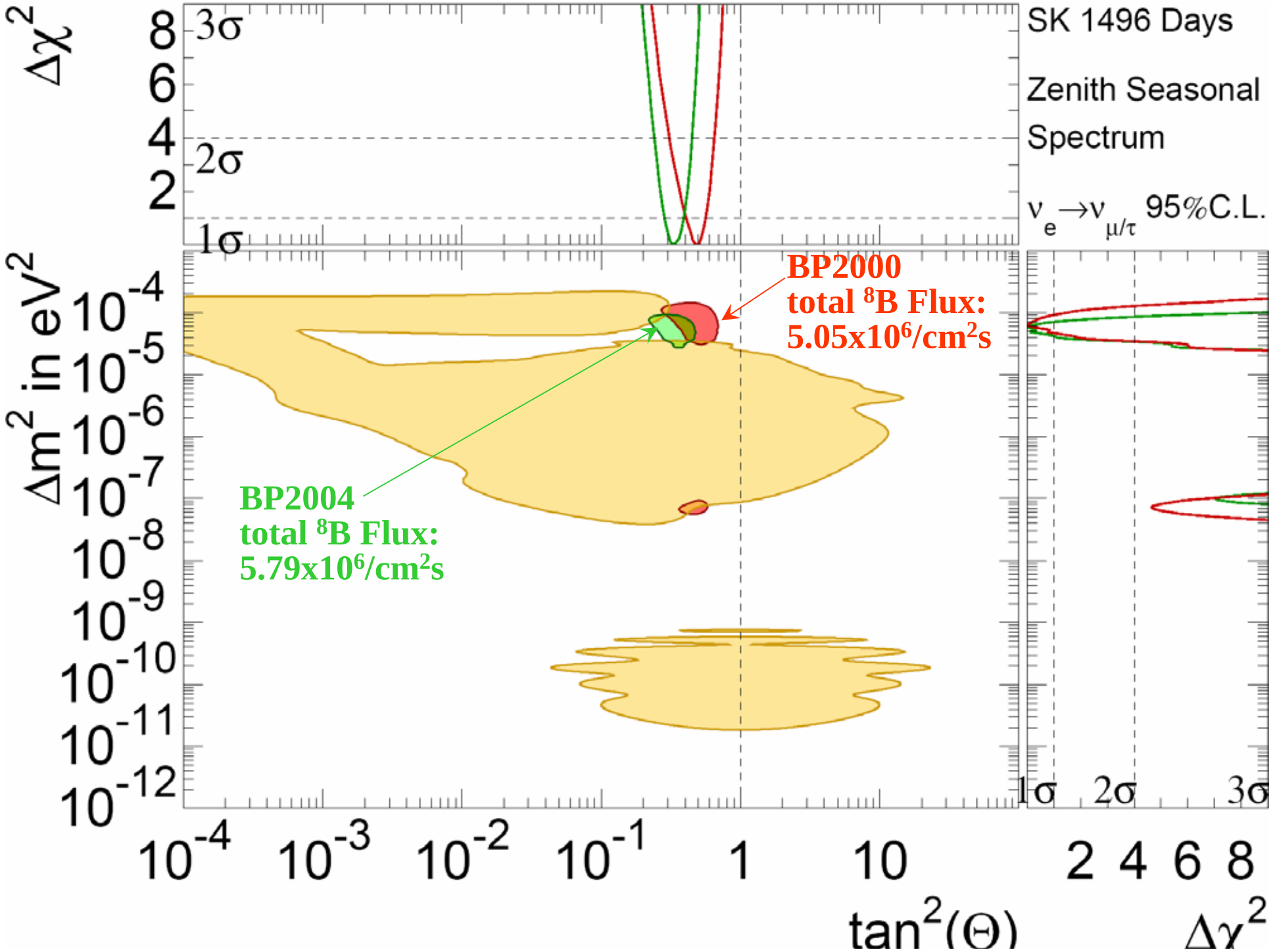
$$f_i(\delta_B, \delta_S, \delta_R) = f_i^B(\delta_B) \times f_i^S(\delta_S) \times f_i^R(\delta_R)$$

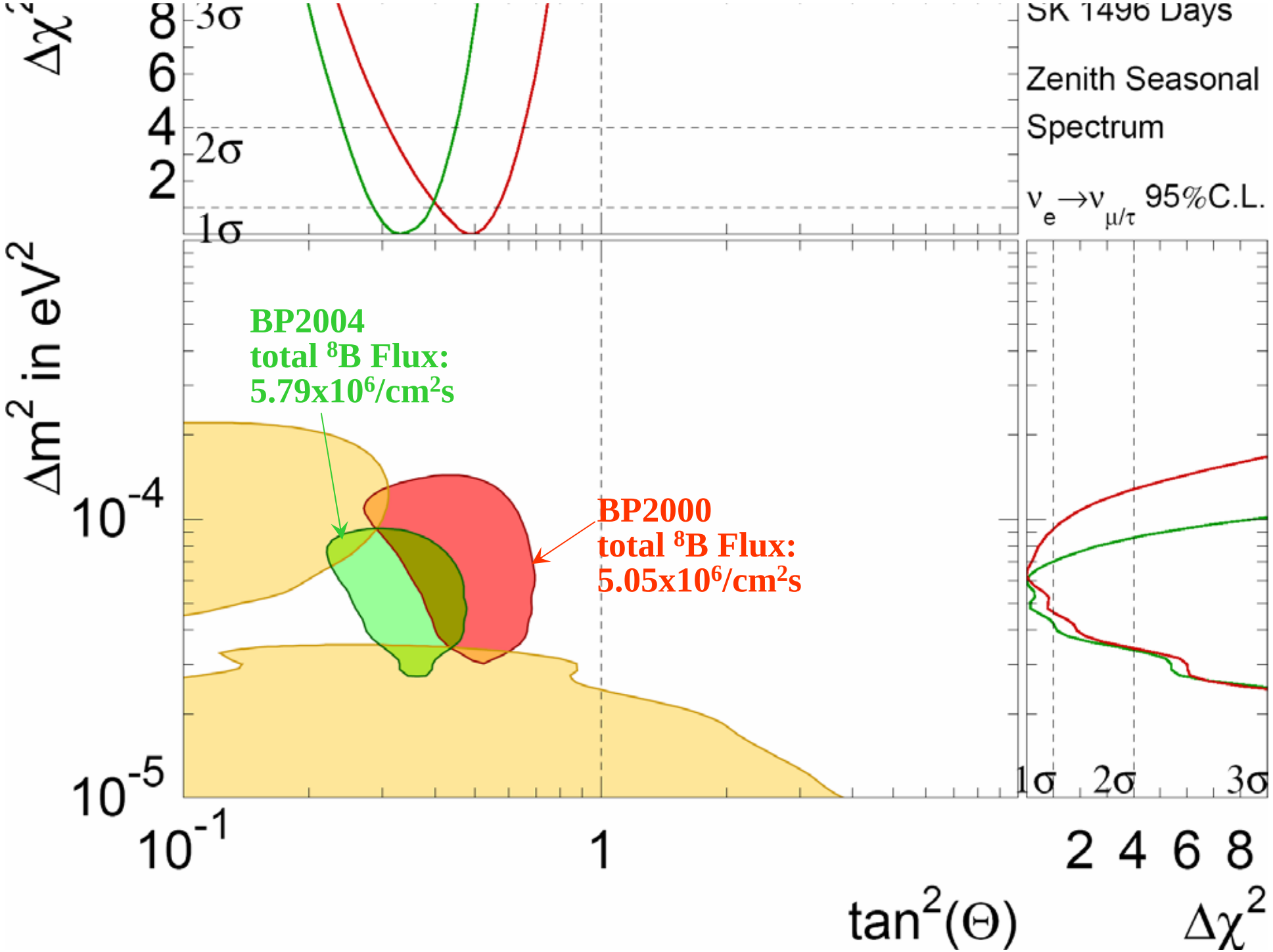
^{8}B spec. shape — **energy scale** — **energy resolution**

Function for energy correlated systematic errors


SK 1496 Days
Zenith Seasonal
Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
$\Delta\chi^2$
3σ
2σ
1σ
Δm^2 in eV^2
Flux independent
excluded region
$\tan^2(\Theta)$
$\Delta\chi^2$

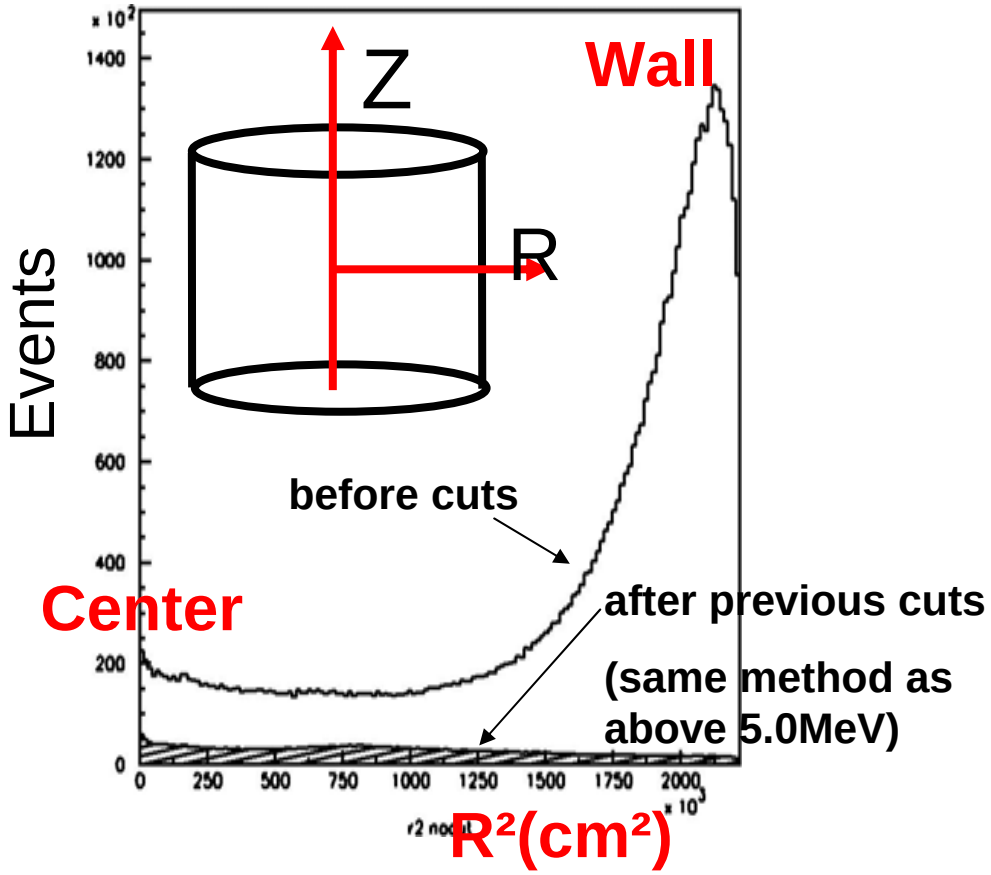

SK 1496 Days
Zenith Seasonal Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
Allowed region assuming fixed ^{8}B flux
BP2000 total ^{8}B Flux: $5.05 \times 10^6/cm^2s$
$\Delta\chi^2$
3σ
2σ
1σ
Δm^2 in eV^2
$\tan^2(\Theta)$
$\Delta\chi^2$

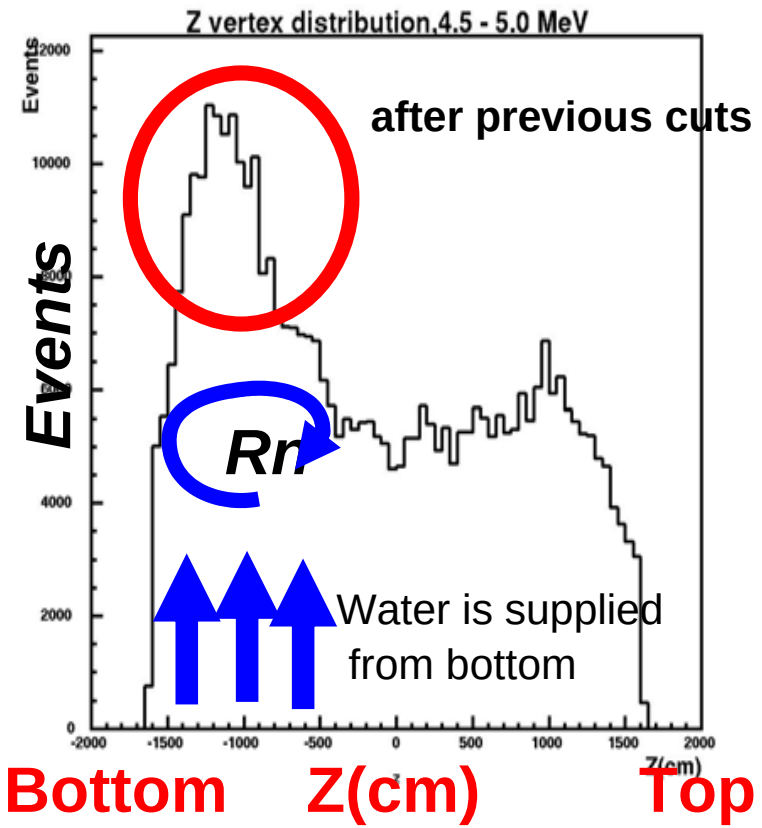

SK 1496 Days
Zenith Seasonal
Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
$\Delta\chi^2$
3σ
2σ
1σ
BP2000
total ^{8}B Flux:
5.05x10^6/cm^{2}s
BP2004
total ^{8}B Flux:
5.79x10^6/cm^{2}s
Δm^2 in eV^2
$\tan^2(\Theta)$
$\Delta\chi^2$


SK 1496 Days
Zenith Seasonal
Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
$\Delta\chi^2$
8
6
4
2
3σ
2σ
1σ
Δm^2 in eV^2
10^{-4}
10^{-5}
10^{-1}
1
$\tan^2(\Theta)$
BP2004
total ^{8}B Flux:
5.79x10^6/cm^{2}s
BP2000
total ^{8}B Flux:
5.05x10^6/cm^{2}s
1σ
2σ
3σ
2 4 6 8
$\Delta\chi^2$

Analysis of lower energy region in SK-I

Vertex position distribution of background (4.5 – 5.0 MeV)

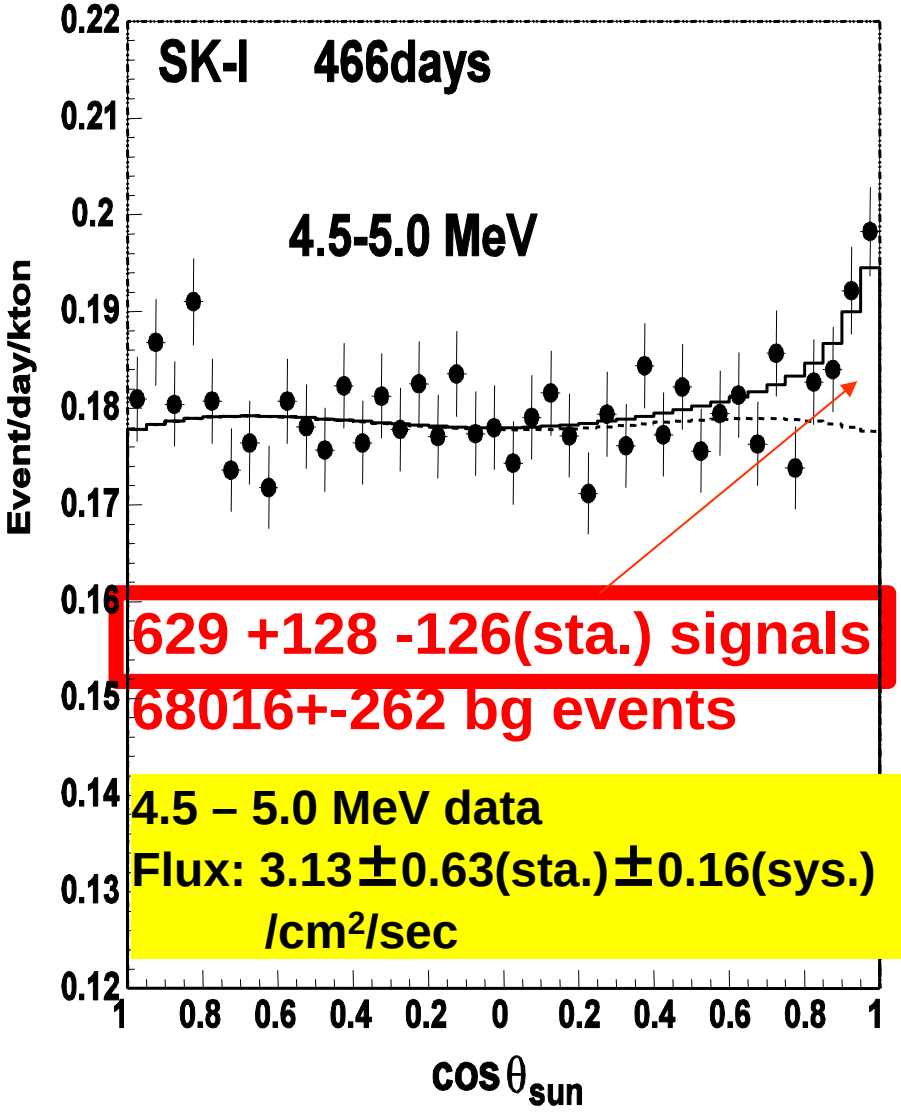




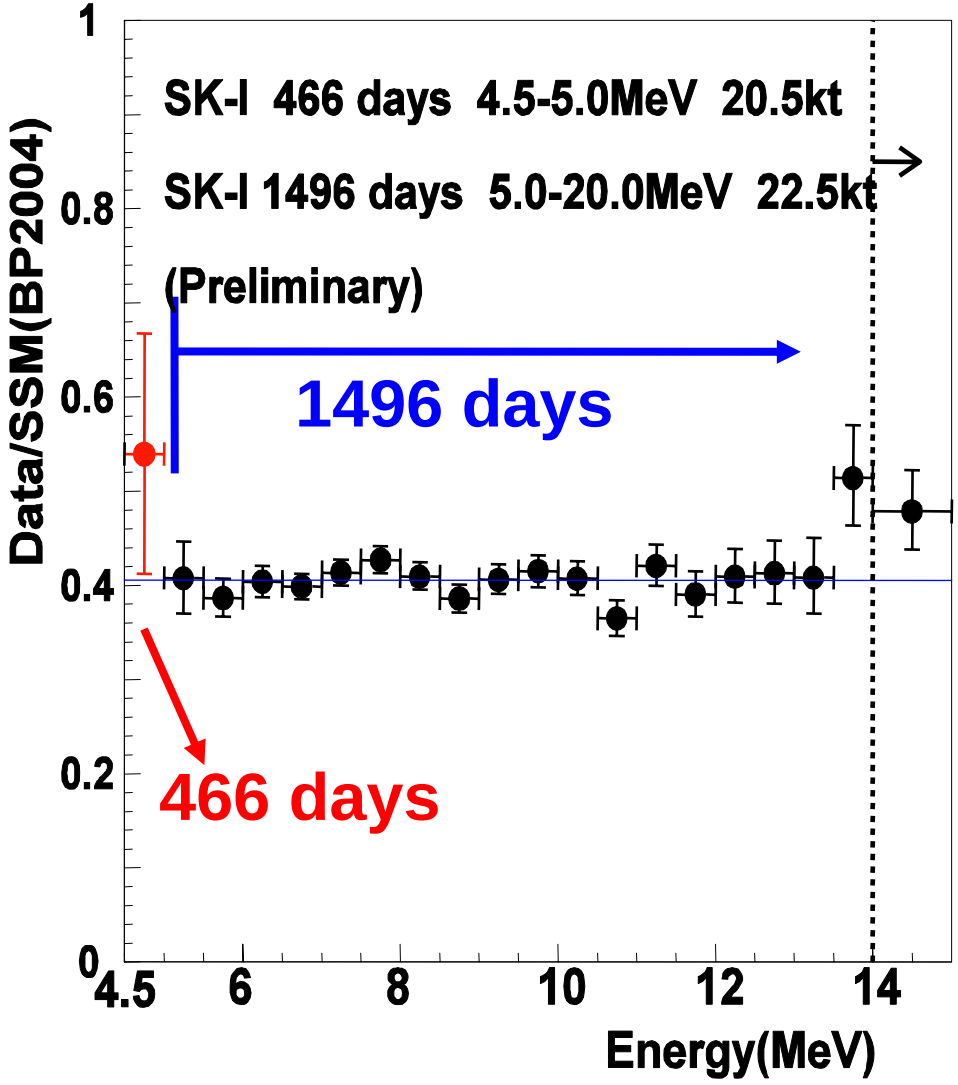
- Apply tighter cuts to reduce external background.
- Use improved vertex reconstruction program.
- Remove high radon periods.
- Select period when trigger eff. for 4.5-5.0MeV is >95%. (466days, Sep.1999-July 2001)

Analysis of lower energy region in SK-I

Direction to the sun



Solar neutrino energy spectrum



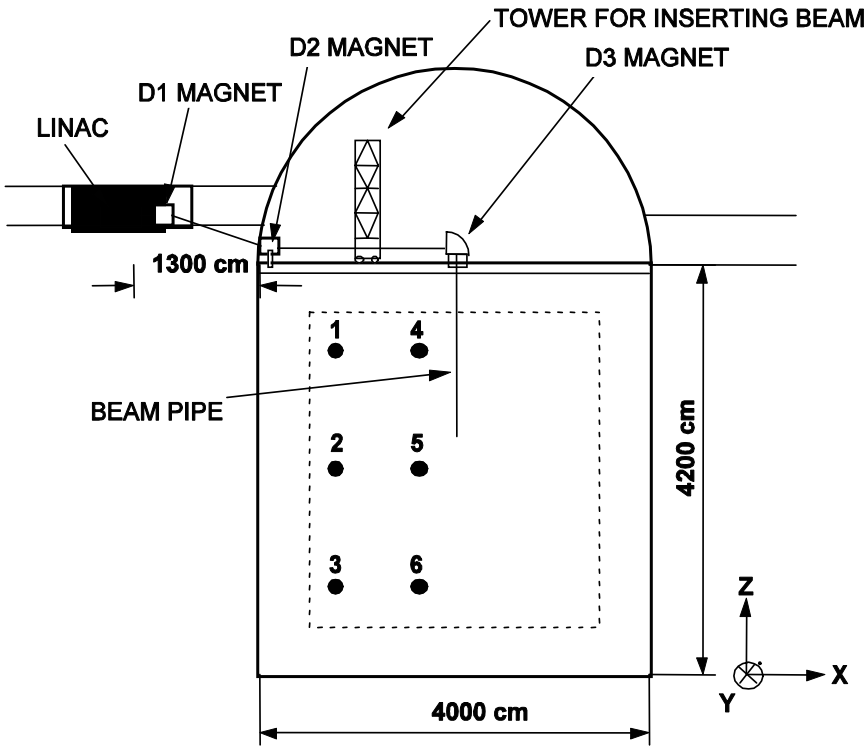
4.5-5.0 MeV data is consistent with previous results.

SK-II data

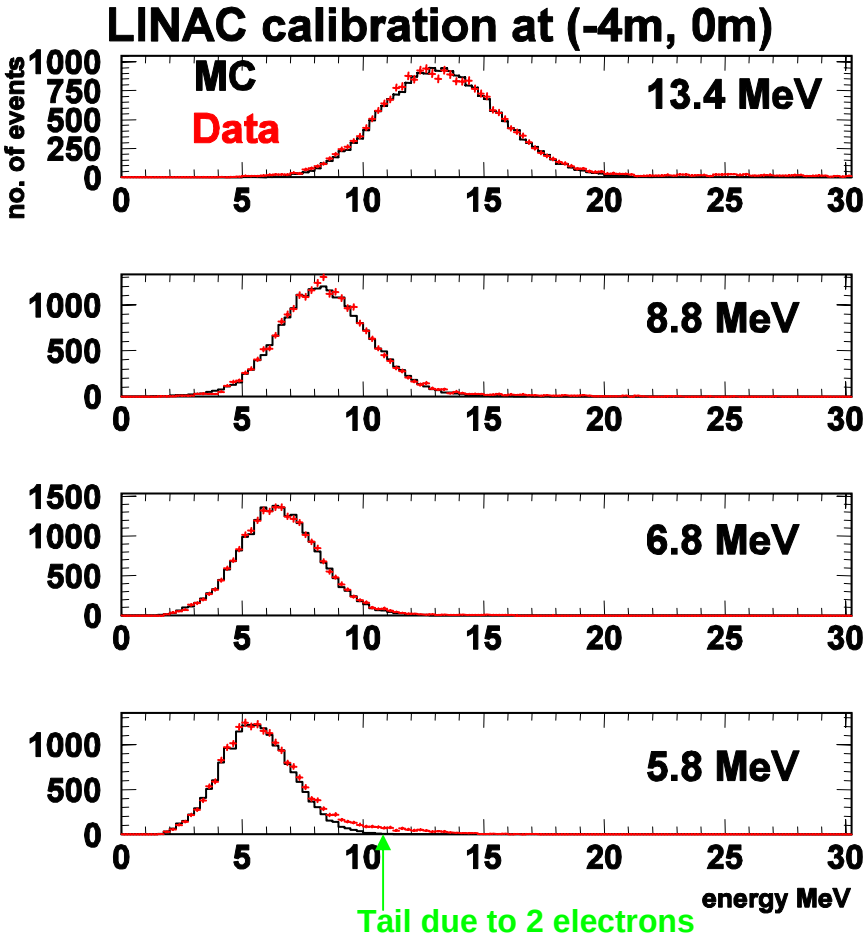
Detector calibration in SK-II

- PMT relative gain calibration by using Ni(n,γ)Ni source and an uniform light source (Xe-scintillation ball).
- Timing calibration by N_2-DYE laser ball.

LINAC calibration data were taken at 6 positions.

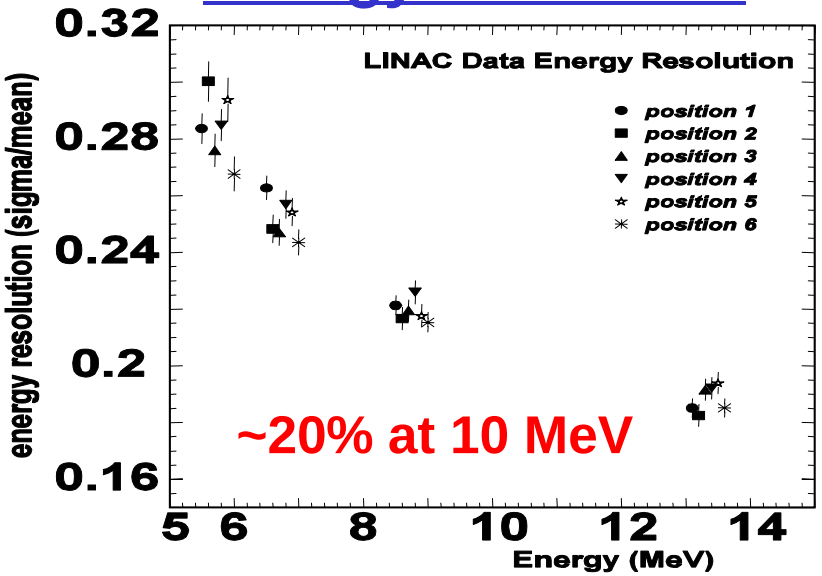


Energy distributions

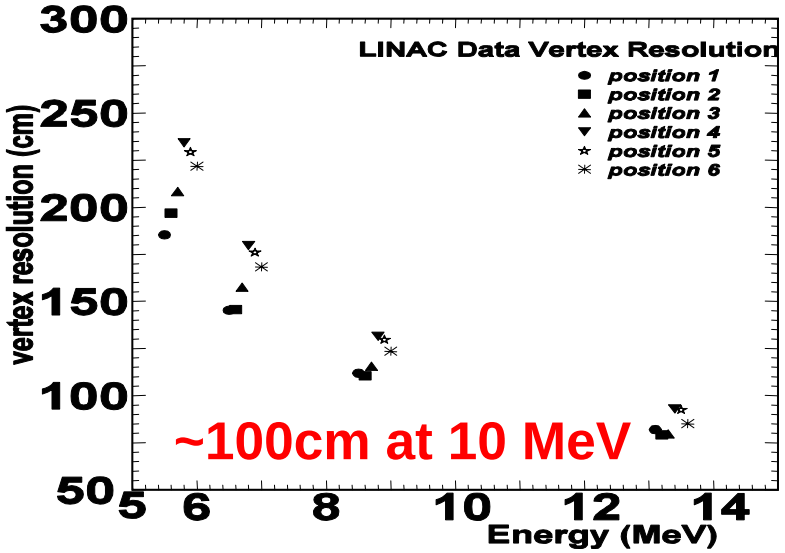


SK-II detector performance
(LINAC calibration)

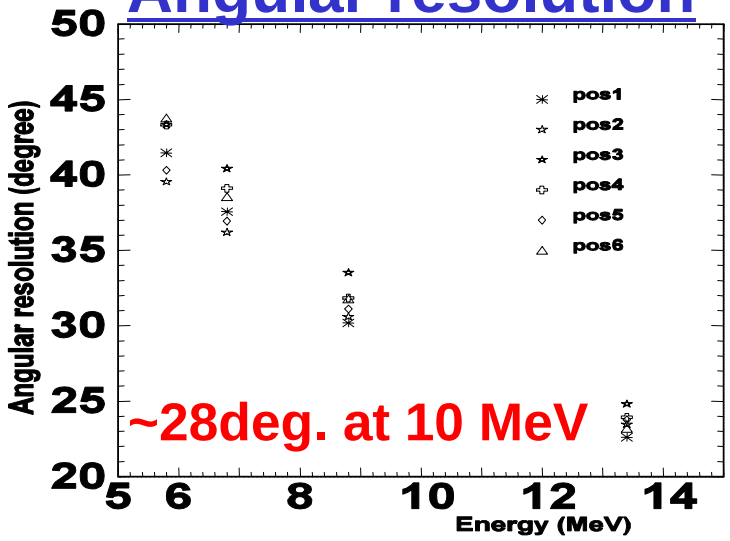
Energy resolution



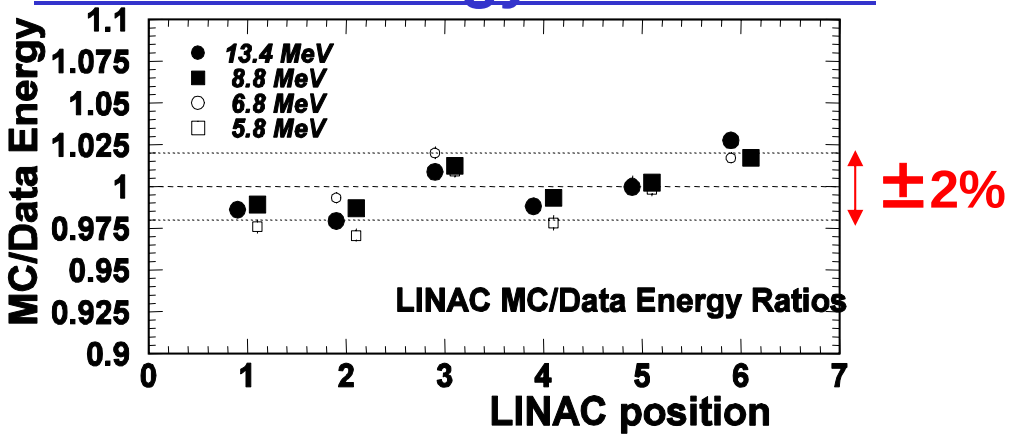
Vertex resolution



Angular resolution

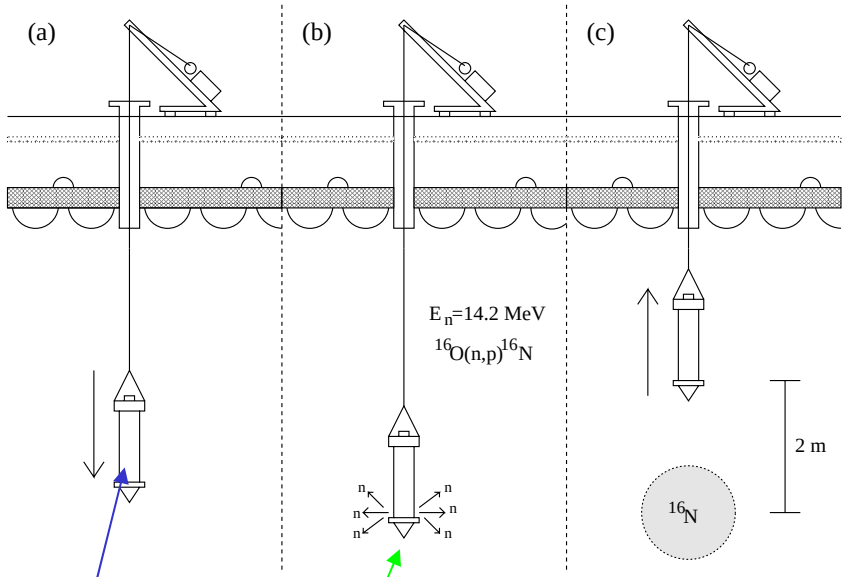


Absolute energy calibration



MC tuning is in progress.

^{16}N calibration



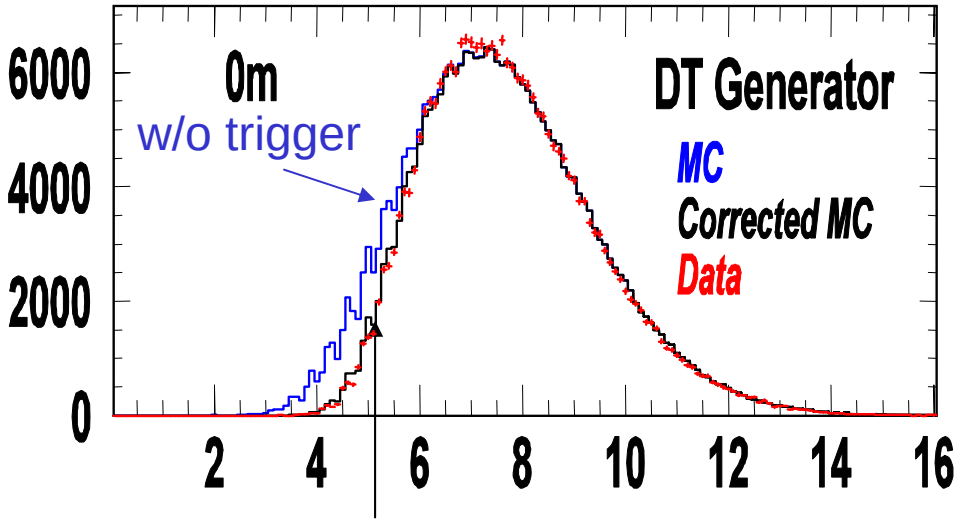
DT generator

D+T→He+n

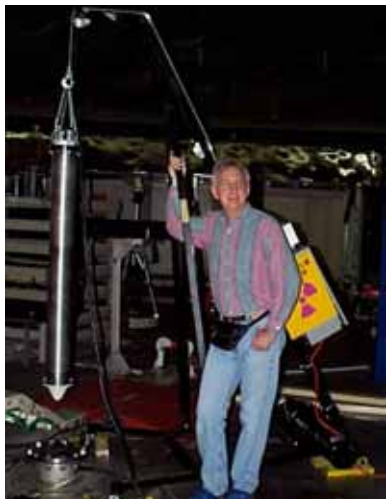
(14.2 MeV)

n+^{16}O→p+^{16}N

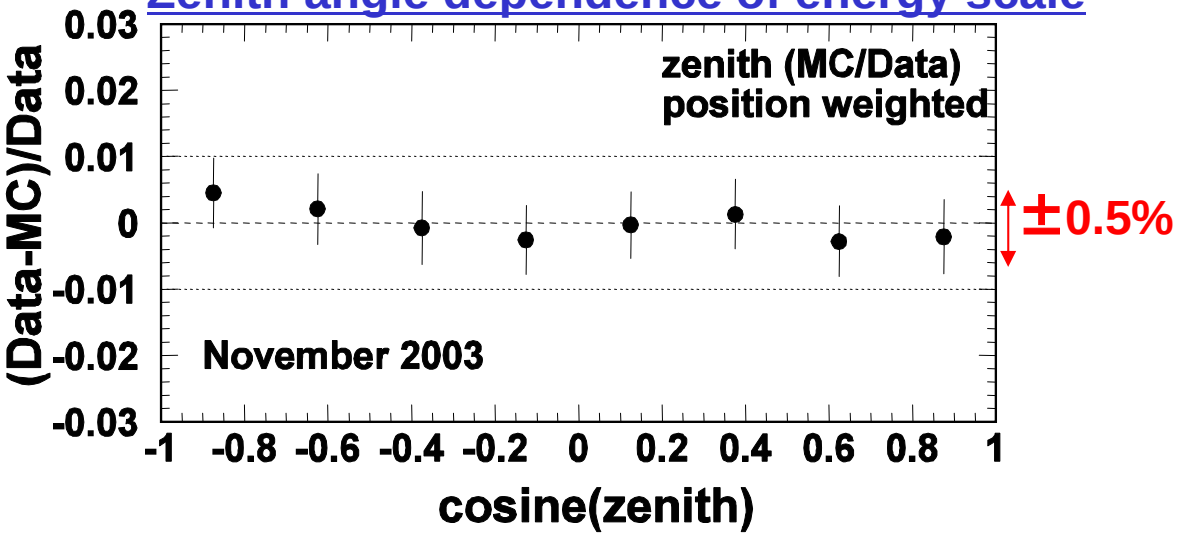
Energy spectrum



with trigger correction

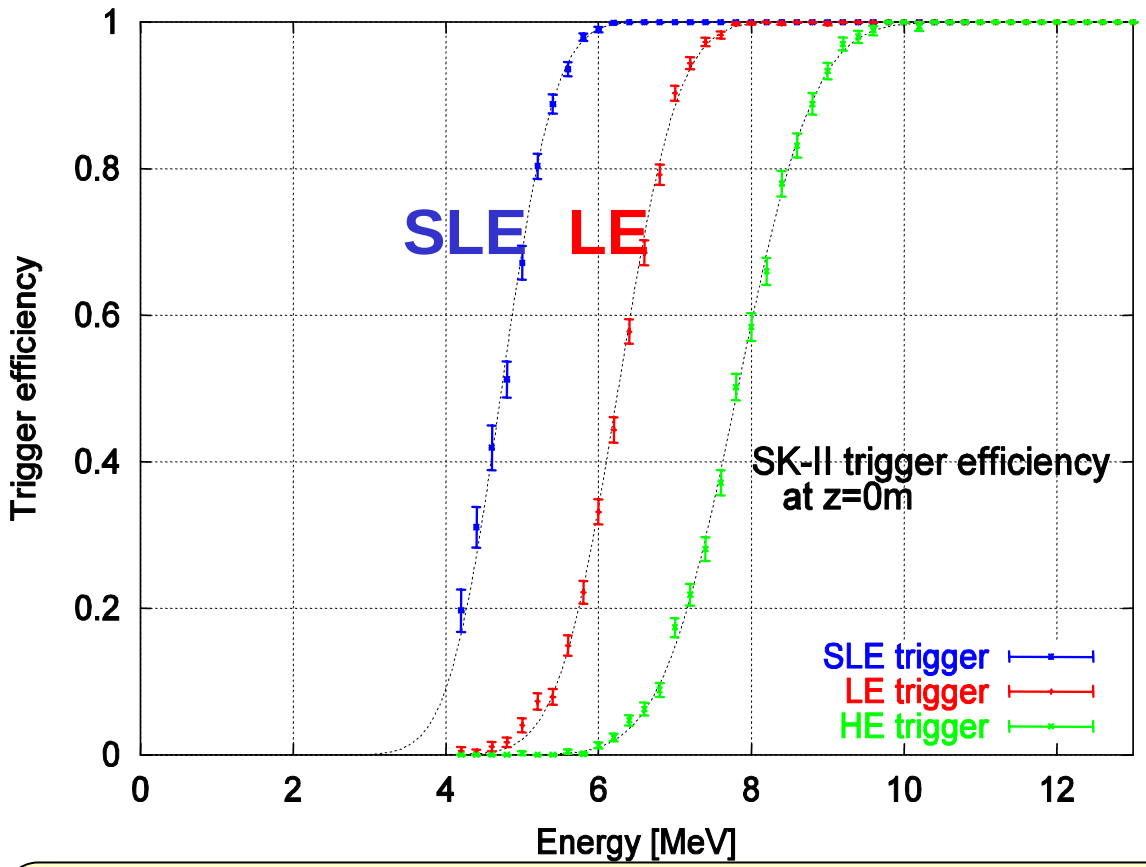


Zenith angle dependence of energy scale



SK-II Trigger

LE trigger: Number of hit PMTs within 200nsec: $N_{200ns} > 14$
SLE trigger: $N_{200ns} > 10$ (added after July 15, 2003)



Online vertex reconstruction and fiducial volume cut are applied to SLE events.

Trigger rate:

LE: ~70 Hz

SLE: ~1100 Hz

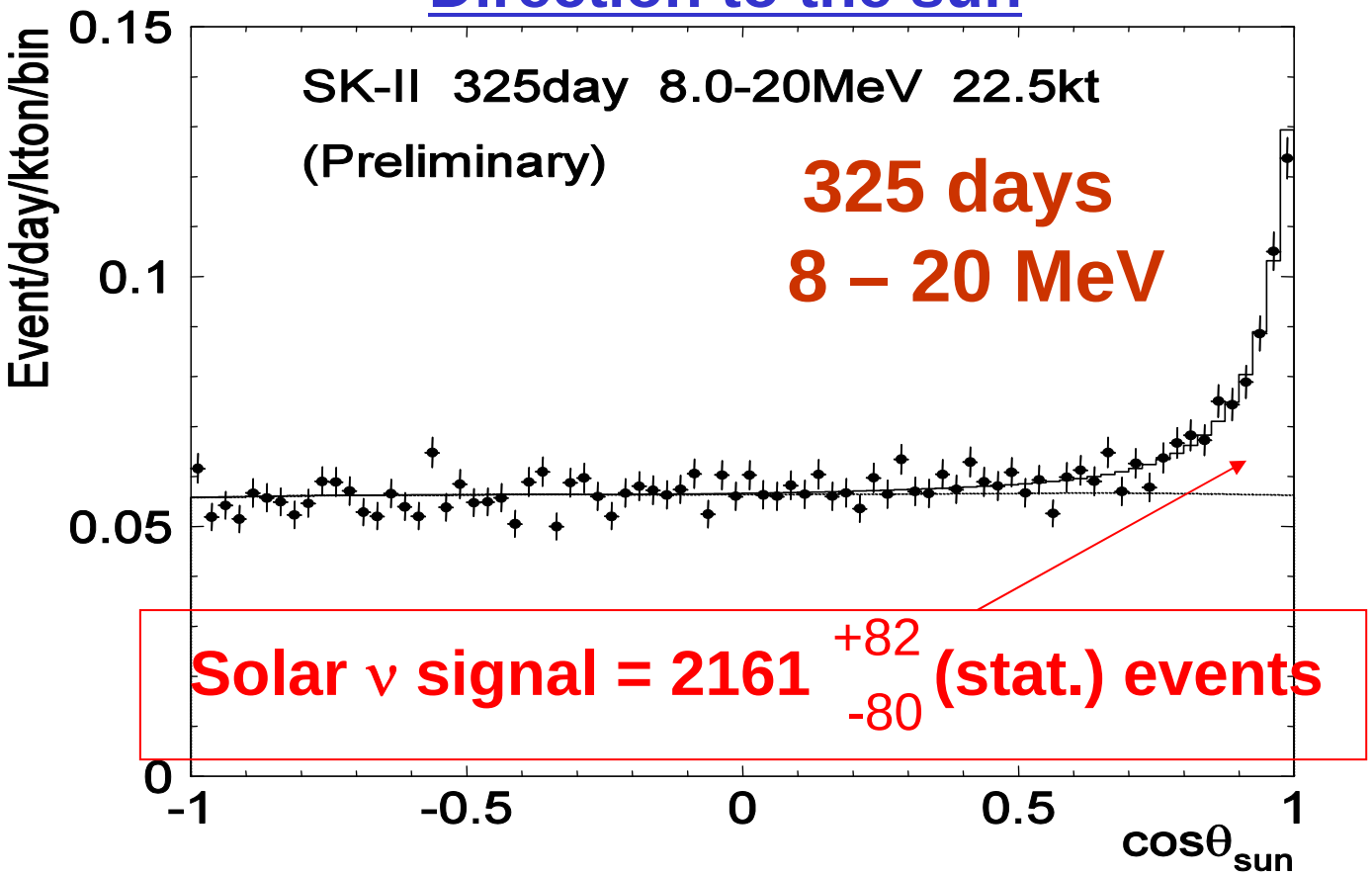
100% efficient for **E > 6.5 MeV for SLE trigger**

E > 8.0 MeV for LE trigger

SK-II preliminary results

Dec.24,2002 – March 25, 2004

Direction to the sun



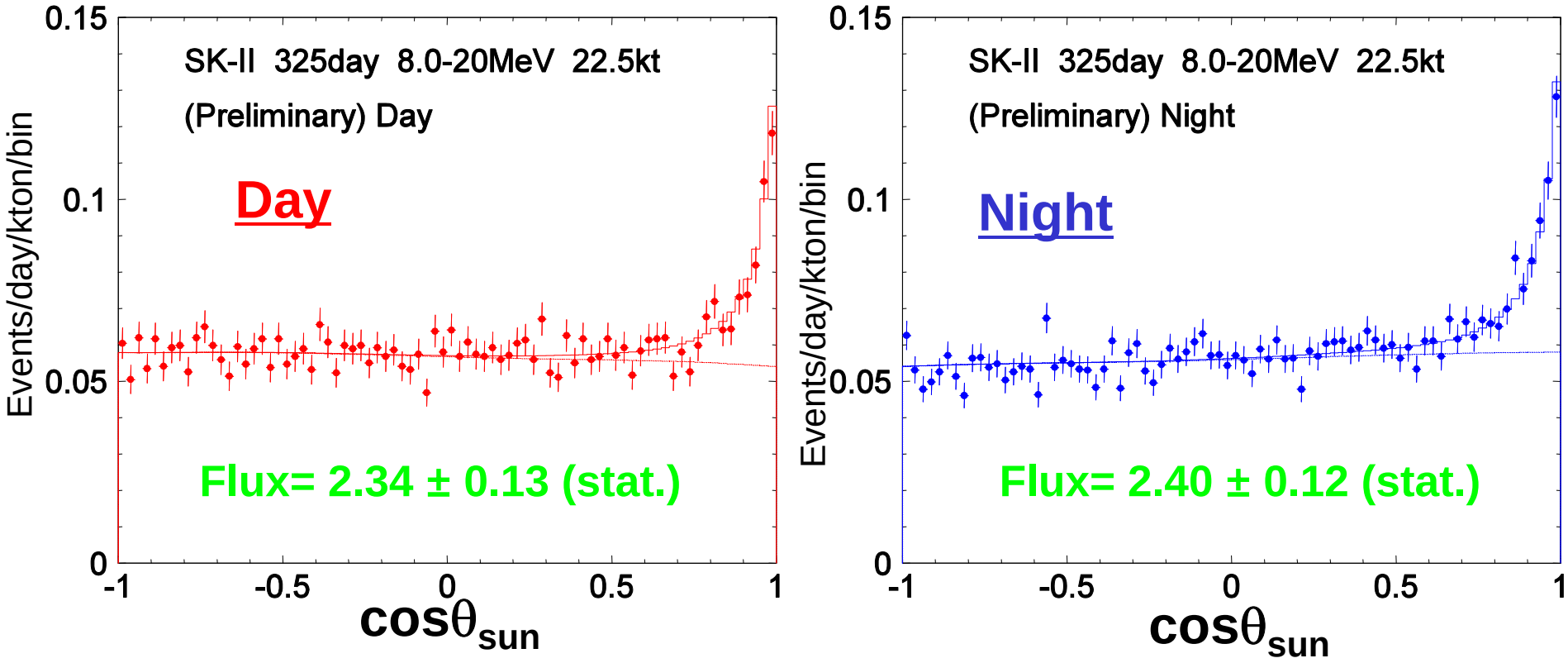
Flux= 2.38 ± 0.09 (stat.) ($\times 10^6/cm^2/s$)

(Systematic error under study)

(cf. SK-I result: 2.35 ± 0.02(stat.) ± 0.08(sys.))

SK-II: Day-Night difference

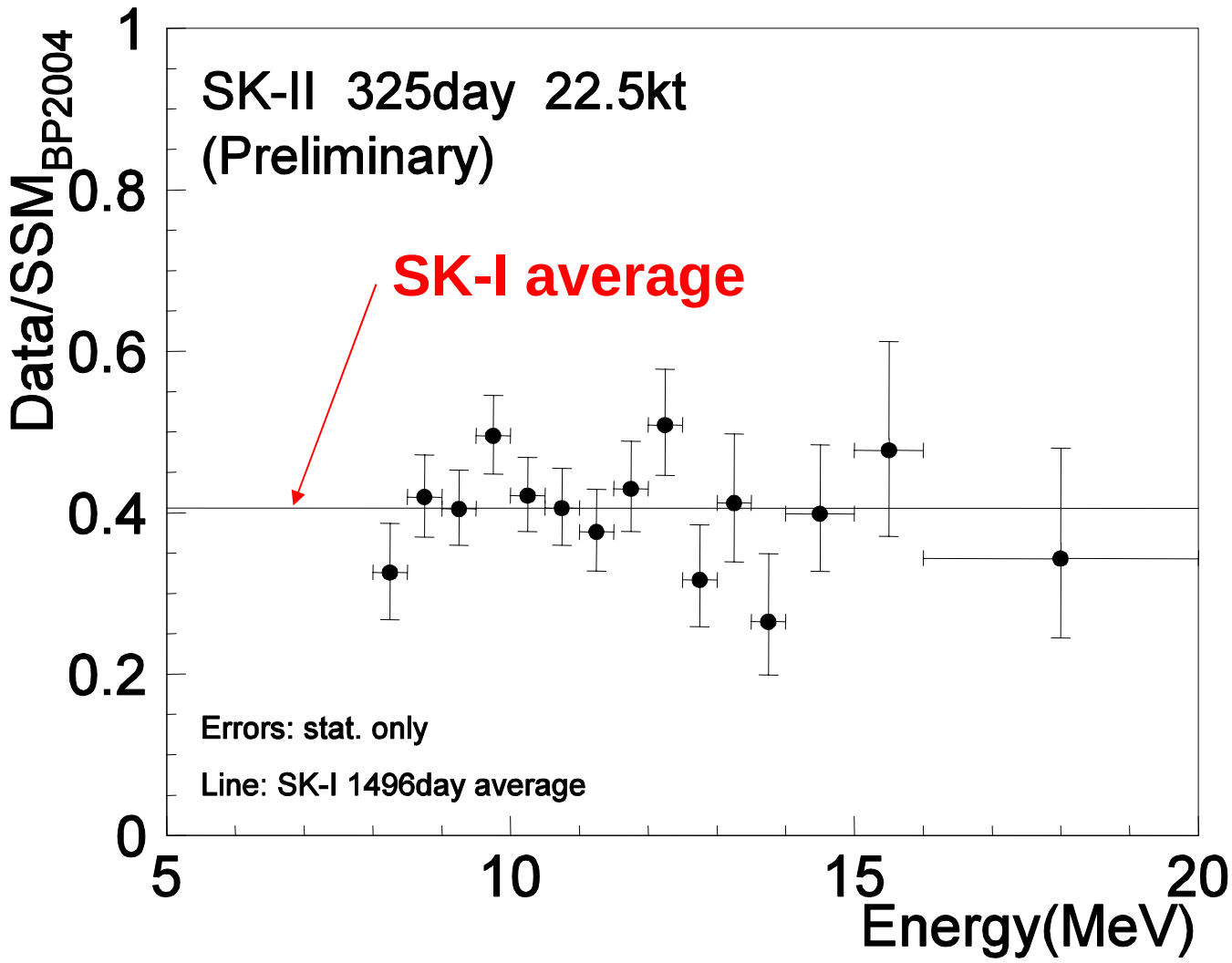
325 days (Dec.24,2002 – March 25, 2004)



$$A_{DN} = \frac{(D-N)}{(D+N)/2} = -0.025 \pm 0.075 \text{ (stat.)}$$

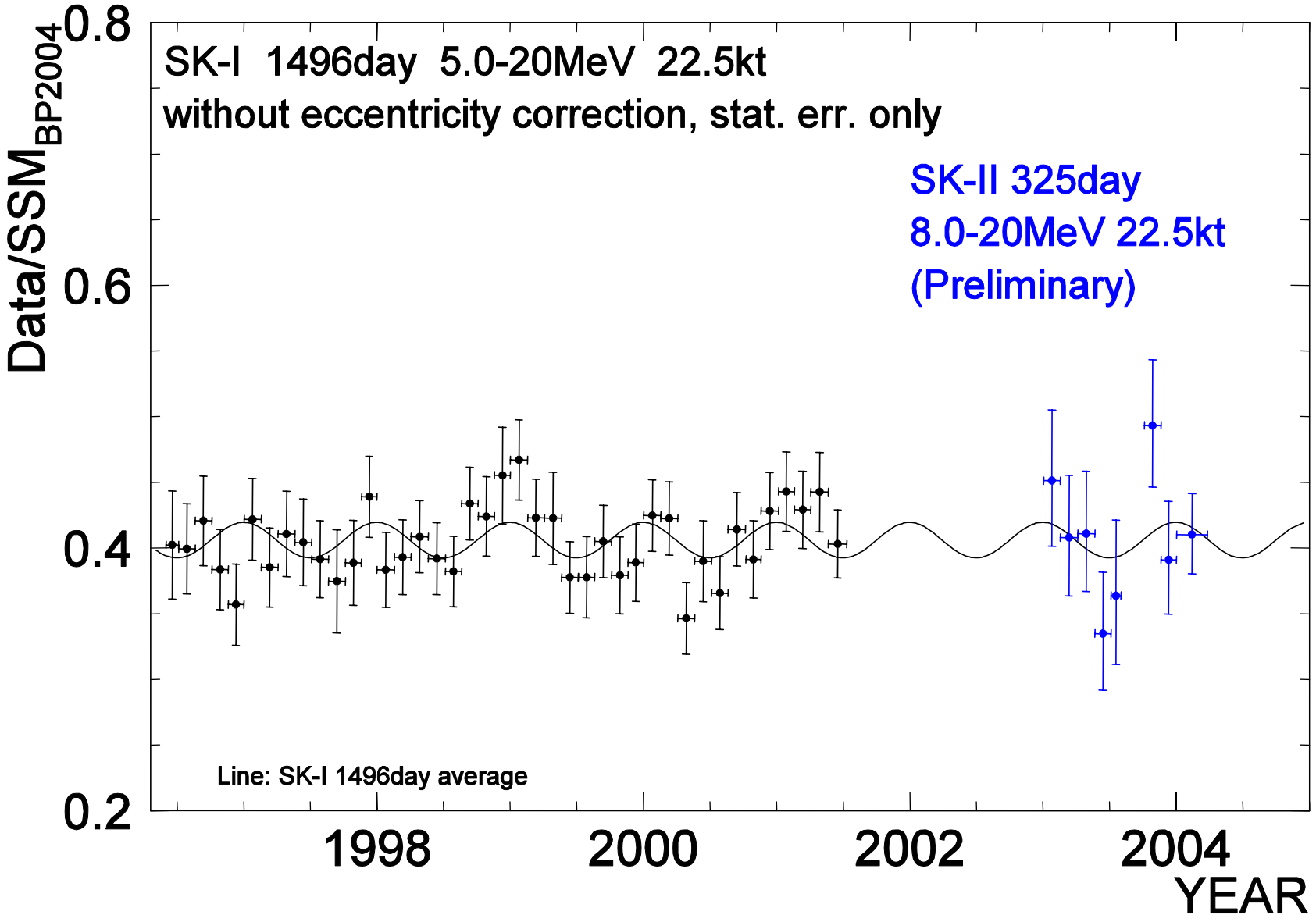
(Systematic error under study)

SK-II energy spectrum



Consistent with SK-I

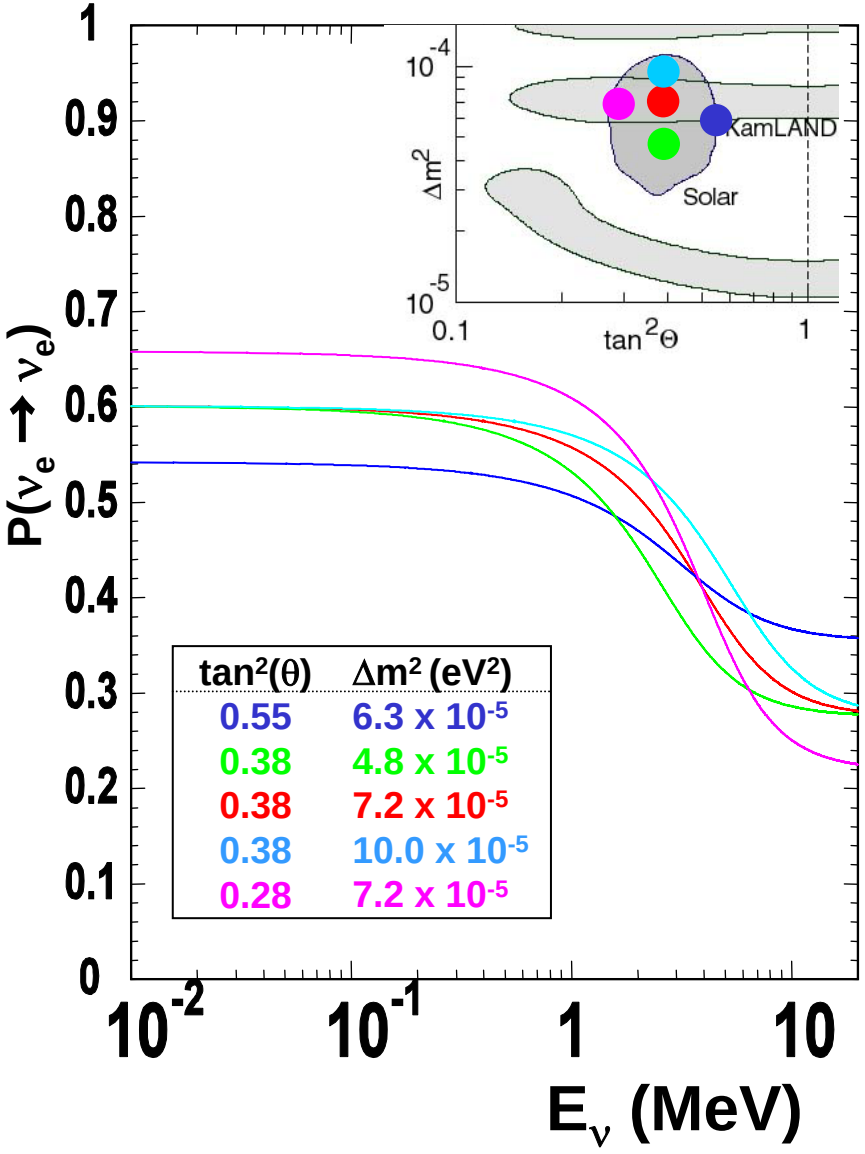
Time variation



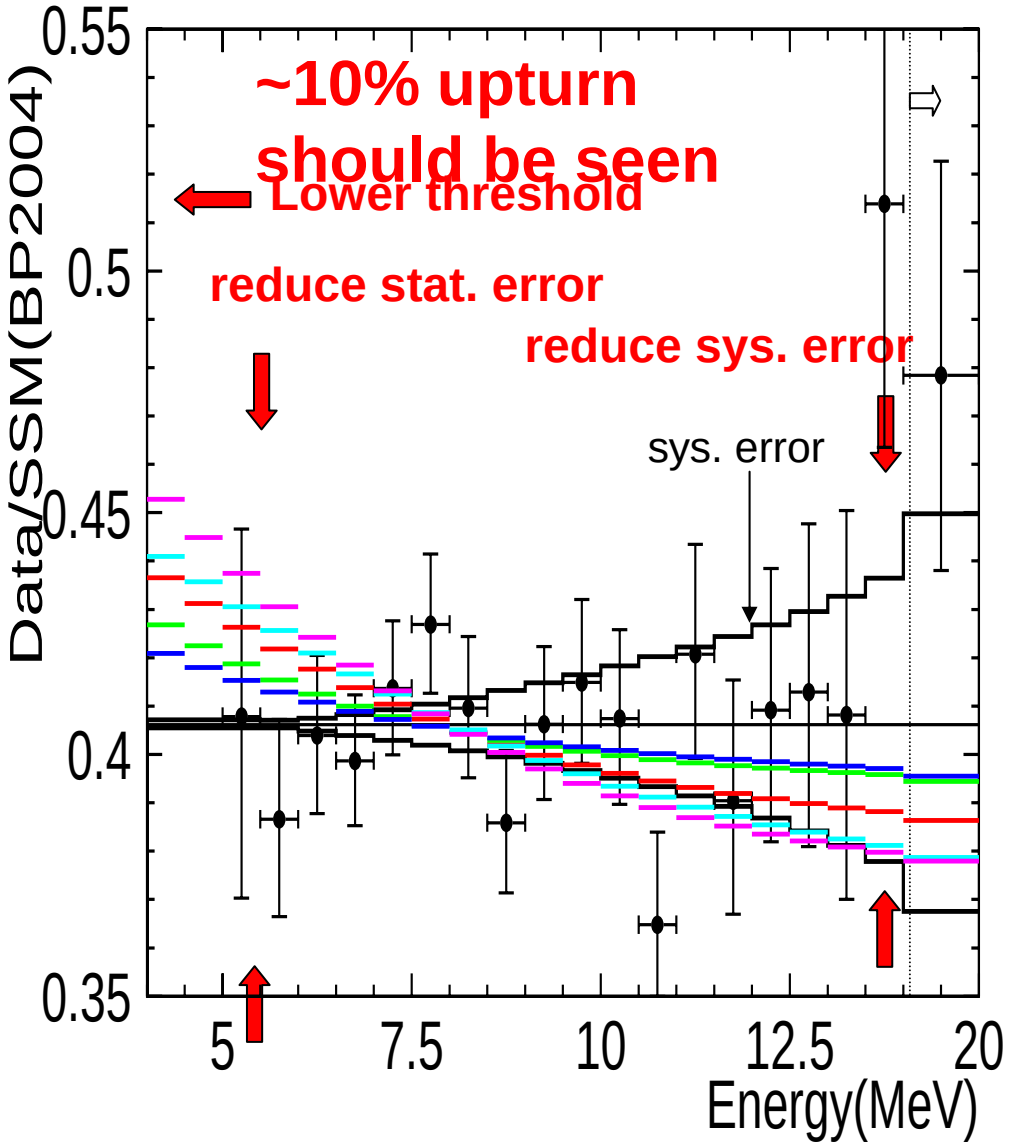
Future prospects towards SK-III

Possibility of detecting spectrum distortion

ν_e survival probability

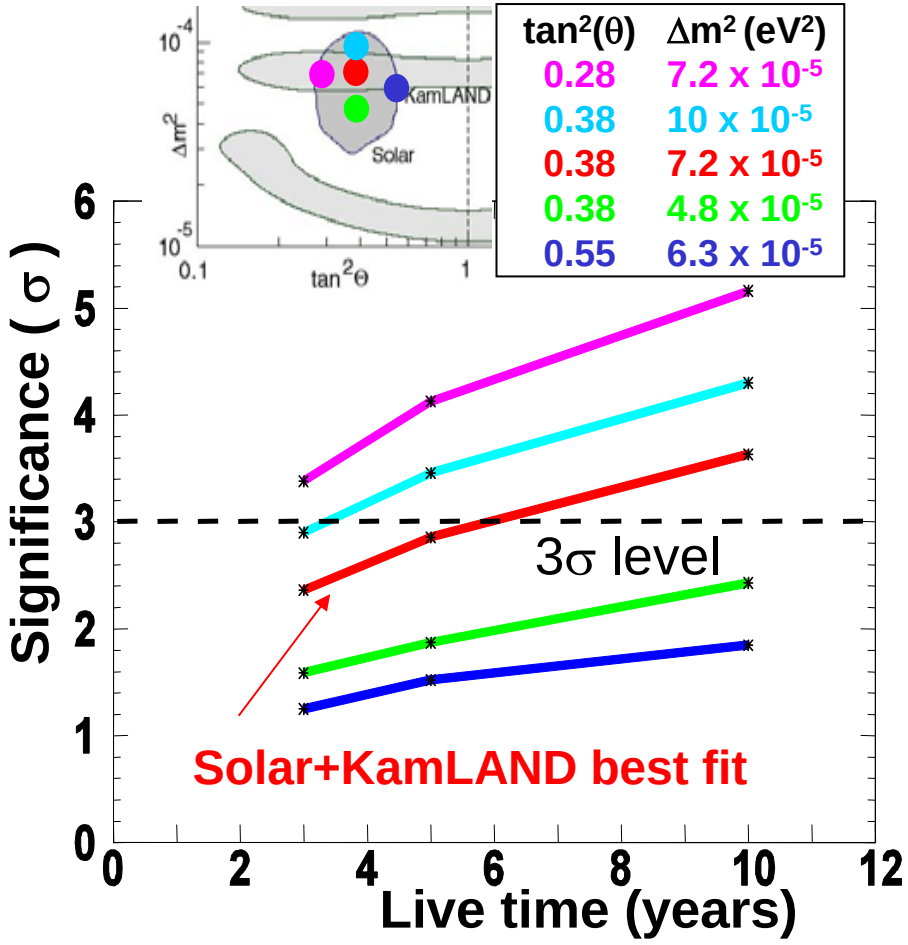


Recoil electron spectrum



Future prospects towards SK-III

Significance of spectrum distortion



$\tan^2(\theta)$	Δm^2 (eV^2)
0.28	7.2×10^{-5}
0.38	10×10^{-5}
0.38	7.2×10^{-5}
0.38	4.8×10^{-5}
0.55	6.3×10^{-5}

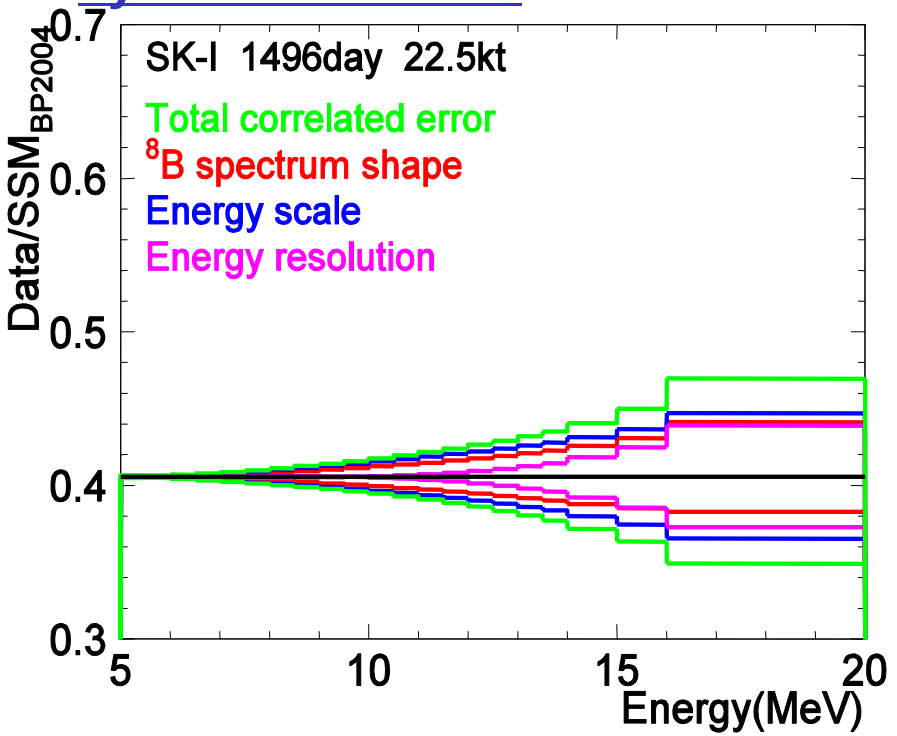
Assumptions:

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.

Conclusion

- High statistics solar neutrino data has been taken at Super-Kamiokade.
- Day/night asymmetry is obtained by unbinned method :

  A_{DN}= -1.8±1.6 +1.3/-1.2 %.
- Energy spectrum: SK prefers smaller Δm^2 and larger $\tan^2\theta$ compared with global best fit parameters.
- Assuming ^{8}B total flux of the SSM predictions, LMA solution is preferred.
- Solar neutrino signal in 4.5 – 5.0 MeV (total energy) bin was newly obtained.
- Preliminary results from SK-II are consistent with SK-I.
- Hope to see definite energy spectrum distortion in SK-III, if it should be there.