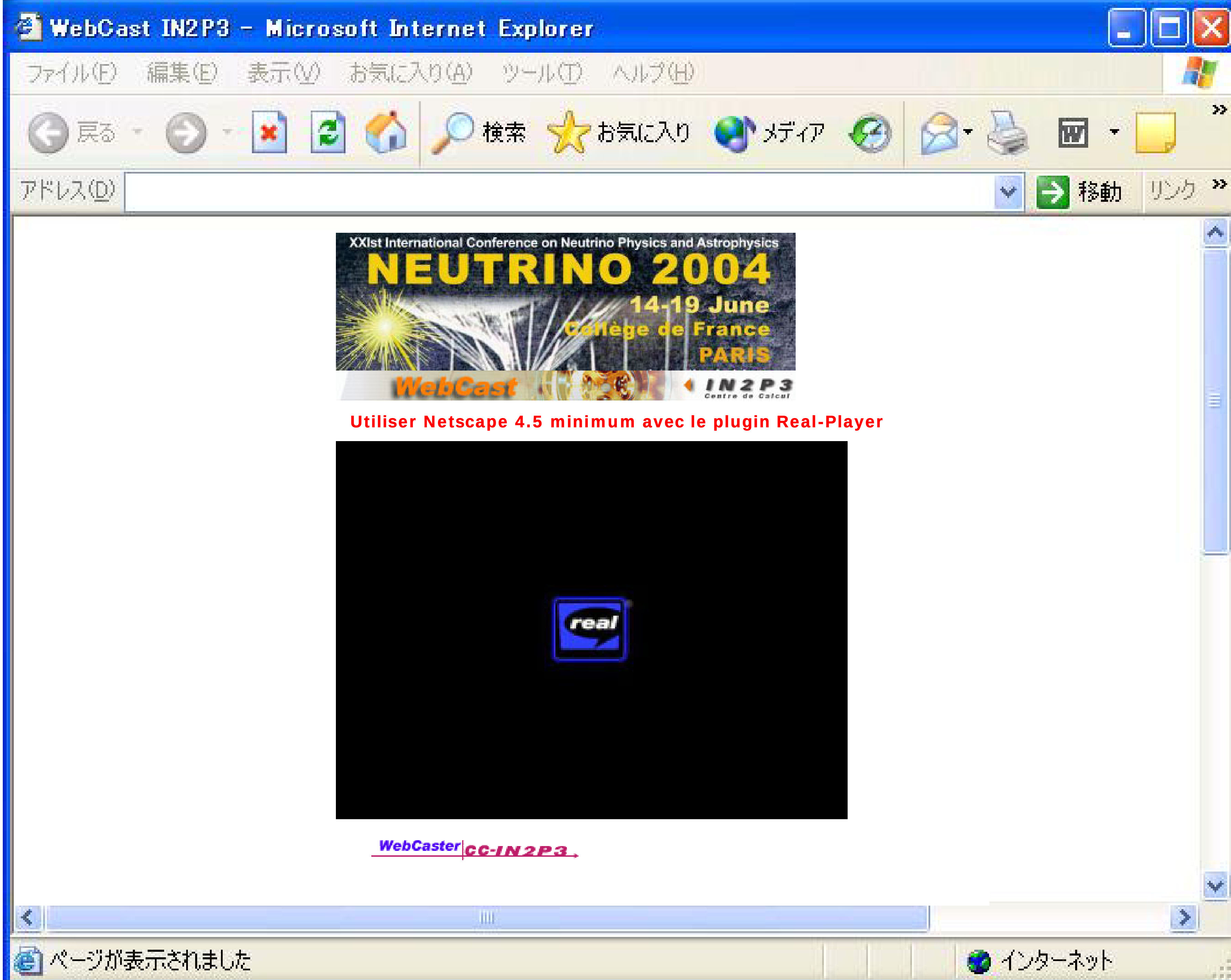
太陽ニュートリノの最新データ

第15回宇宙ニュートリノ研究会
2004年6月24日
小汐由介

- Super-Kamiokande
- SNO
- Future prospect


WebCast IN2P3 - Microsoft Internet Explorer
ファイル(F) 編集(E) 表示(V) お気に入り(A) ツール(T) ヘルプ(H)
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アドレス(D) 移動 リンク
XXIst International Conference on Neutrino Physics and Astrophysics
NEUTRINO 2004
14-19 June
Collège de France
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Utiliser Netscape 4.5 minimum avec le plugin Real-Player
real
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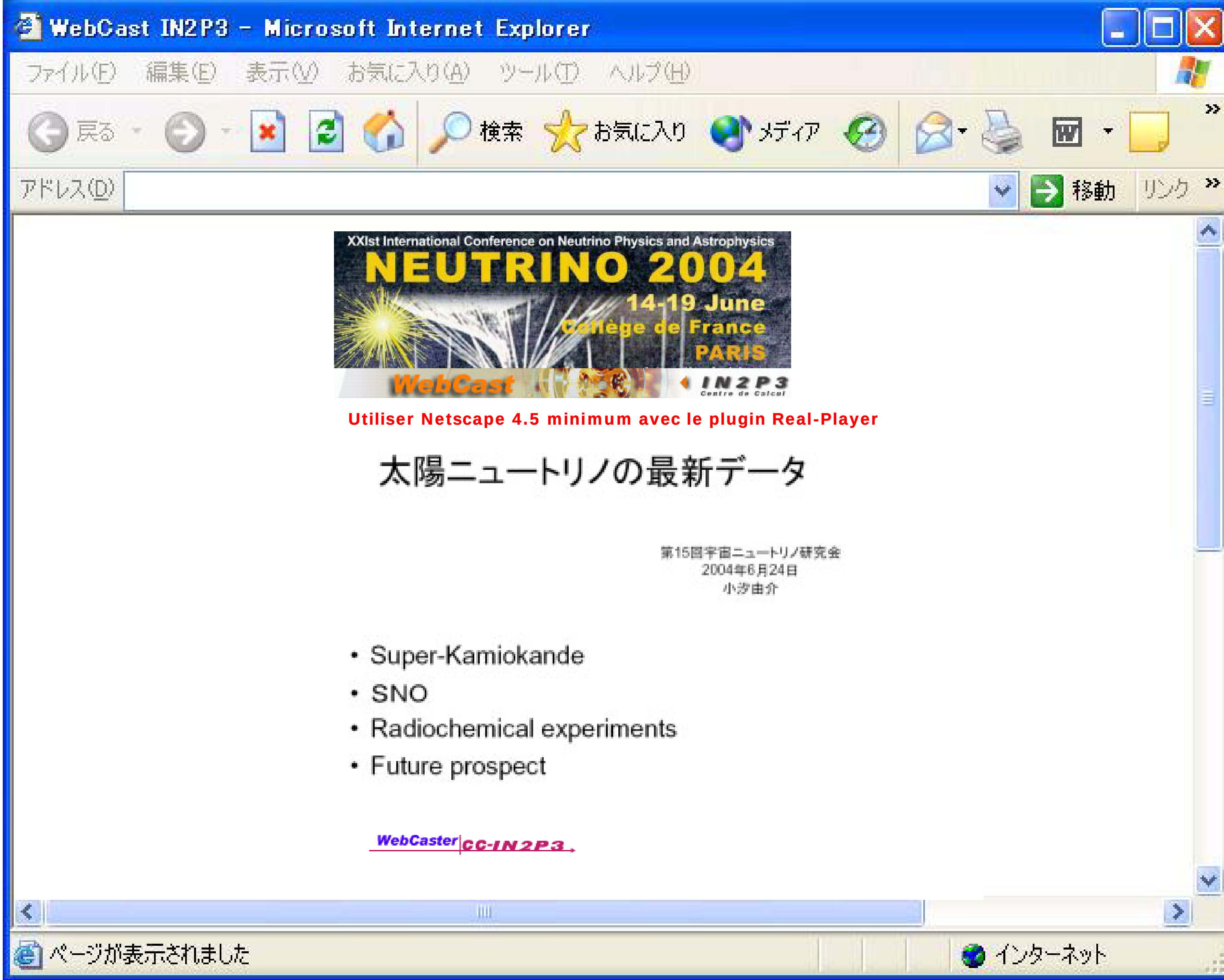
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Super-Kamiokande detector

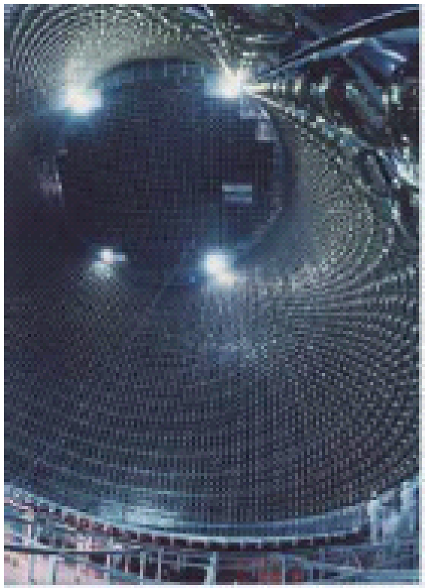
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007

SK-I

accident

SK-II

SK-III

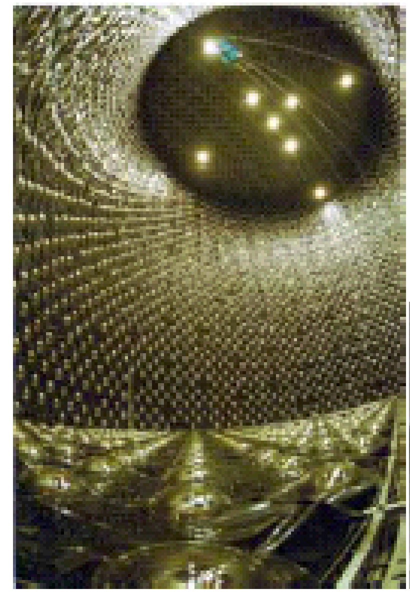


50kton total,

22kton fiducial volume

1000m underground

Water Cherenkov detector



SK full reconstruction (plan)

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

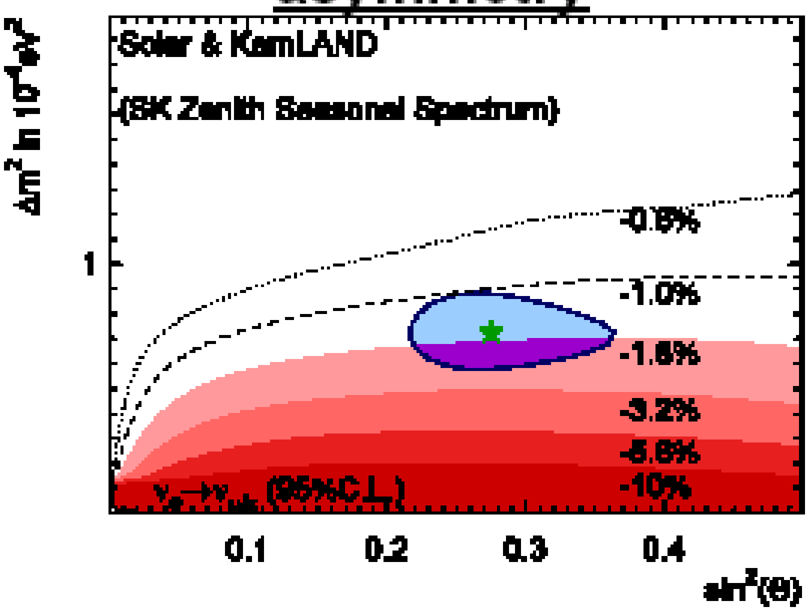
(*) Inner Detector

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

Solar neutrino measurement in SK

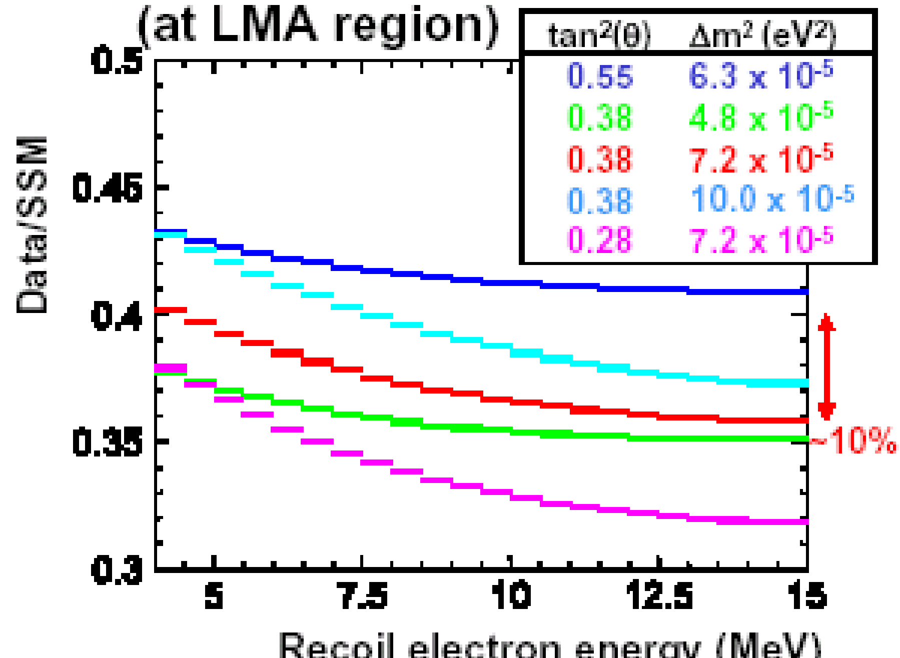
- ^{8}B neutrino measurement by $\nu + e^- \rightarrow \nu + e^-$
- Sensitive to ν_e, ν_μ, ν_τ $\sigma(\nu_{\mu(\tau)}+e^-) = \sim 0.15 \times \sigma(\nu_e+e^-)$
- High statistics ~15ev./day with E_e > 5MeV
- Real time measurement. Studies on time variations.
- Studies on energy spectrum.
- Precise energy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

Expected day/night asymmetry



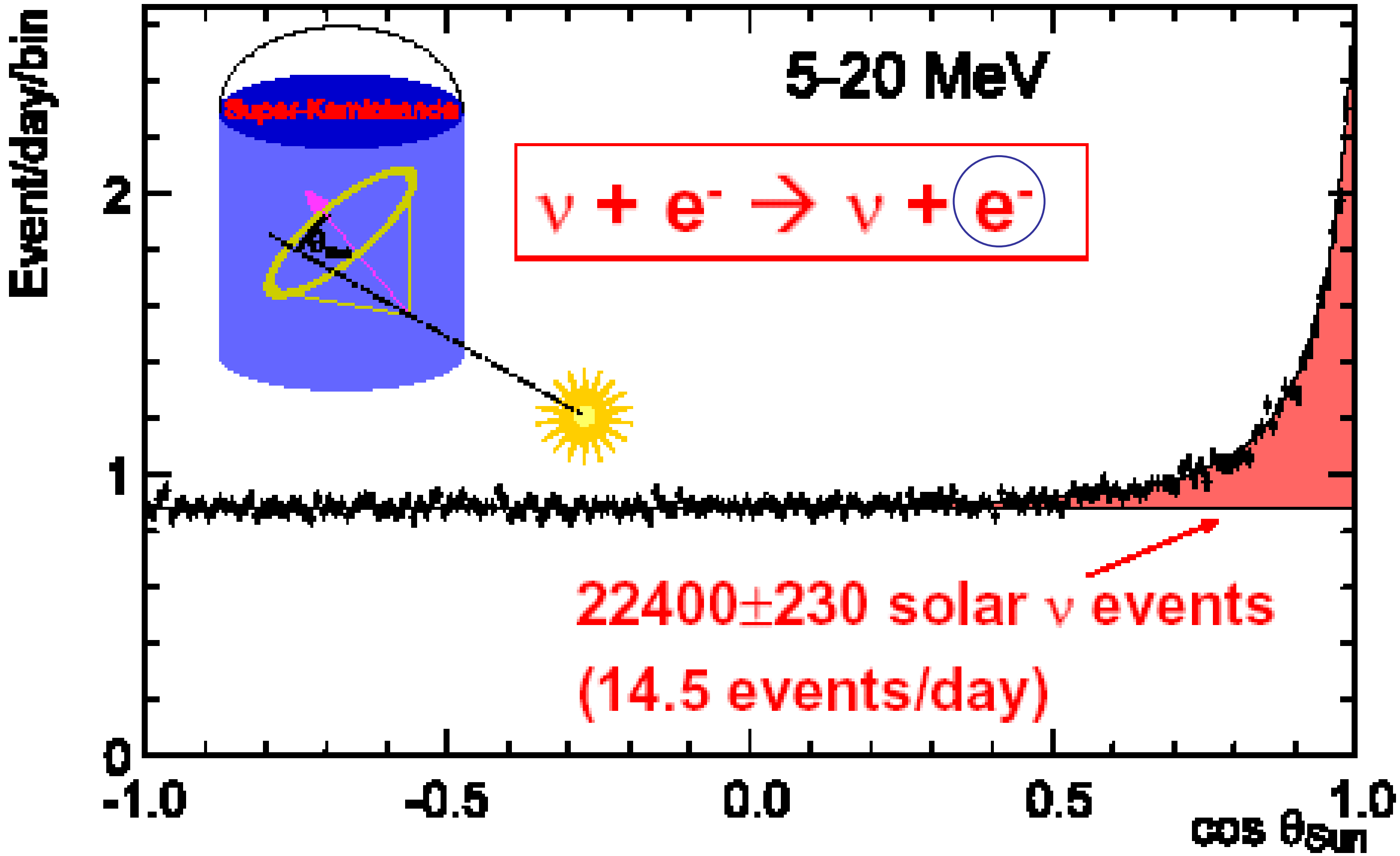
Expected spectrum distortion

(at LMA region)



Super-Kamiokande-I solar neutrino data

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

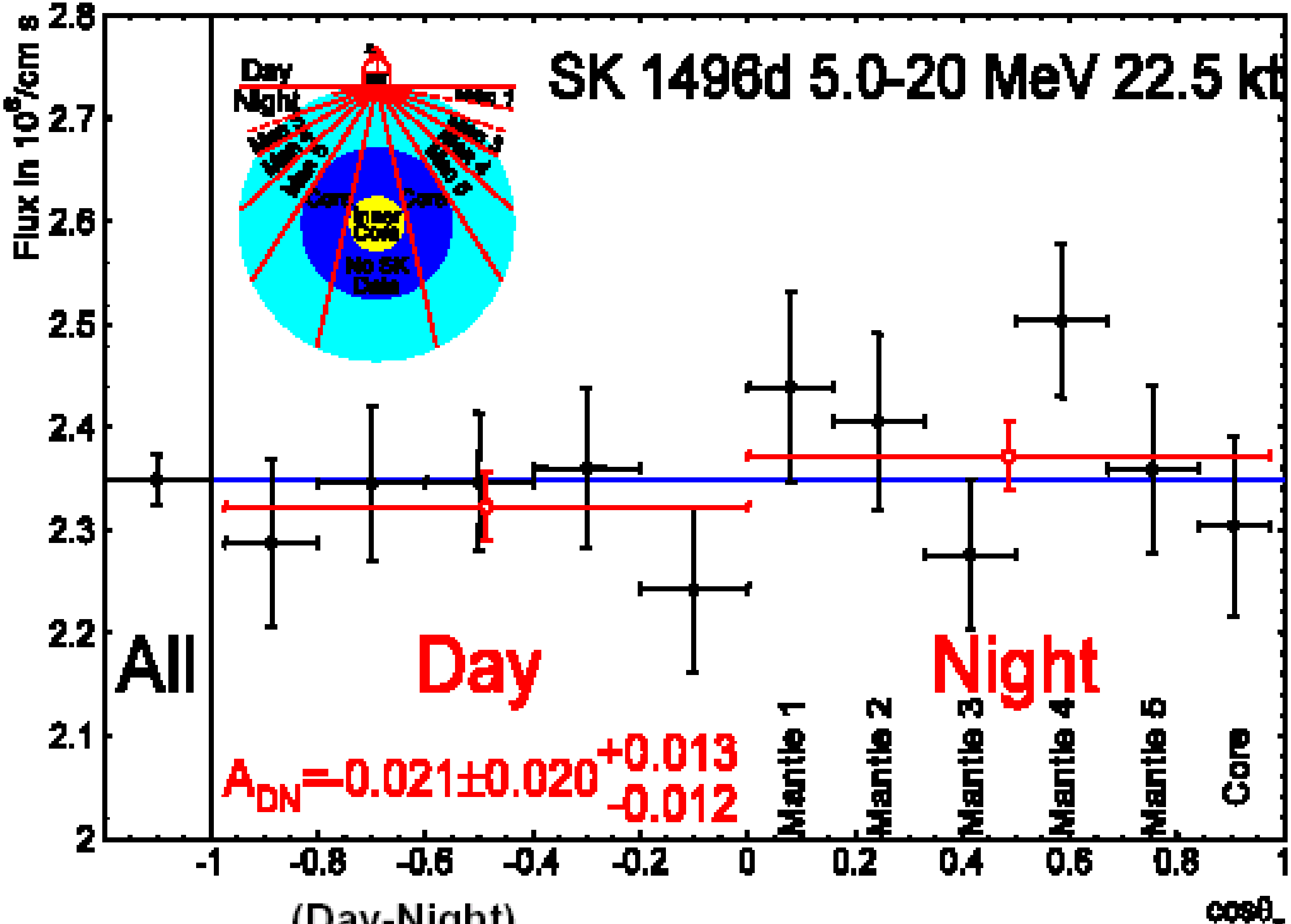


^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

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

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

SK-I day/night difference

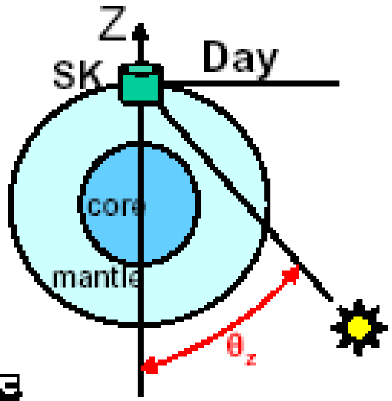


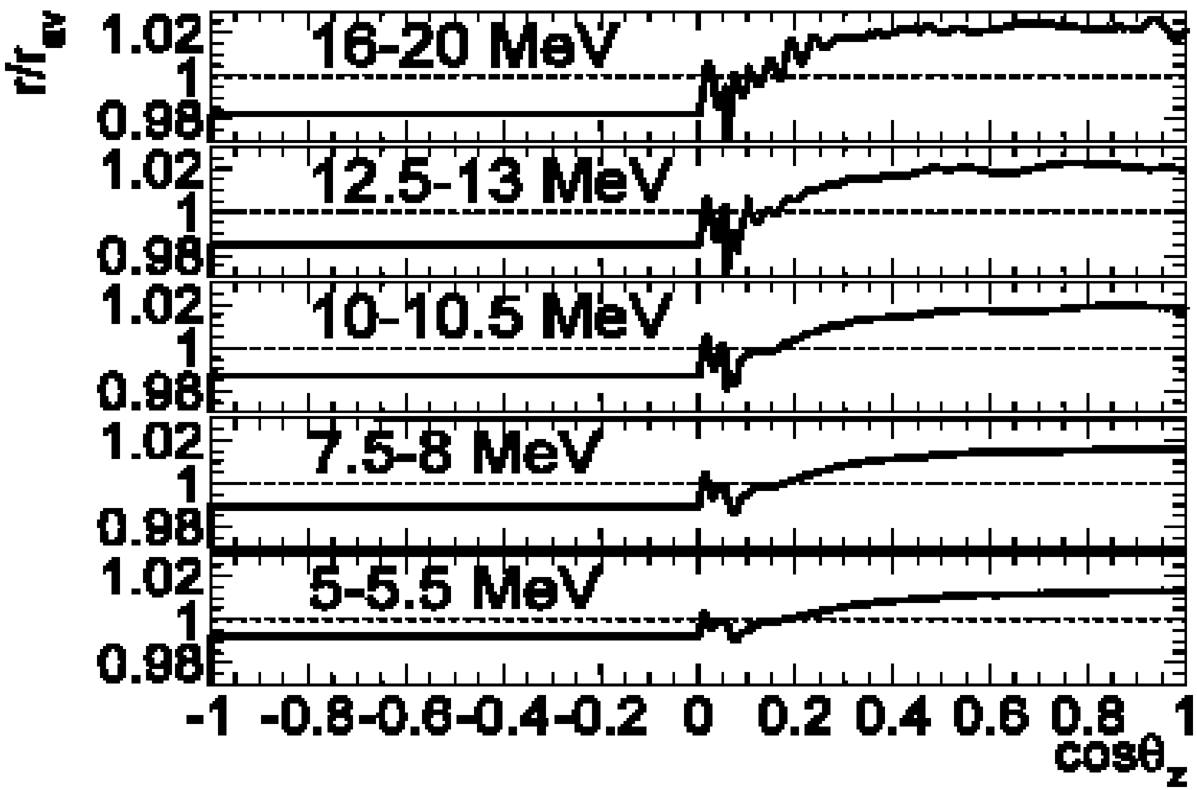
$$A_{DN} = \frac{(\text{Day-Night})}{(\text{Day+Night})/2}$$

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

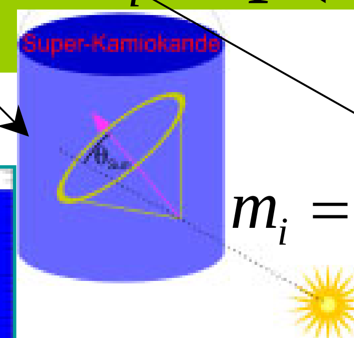
Likelihood for solar neutrino extraction

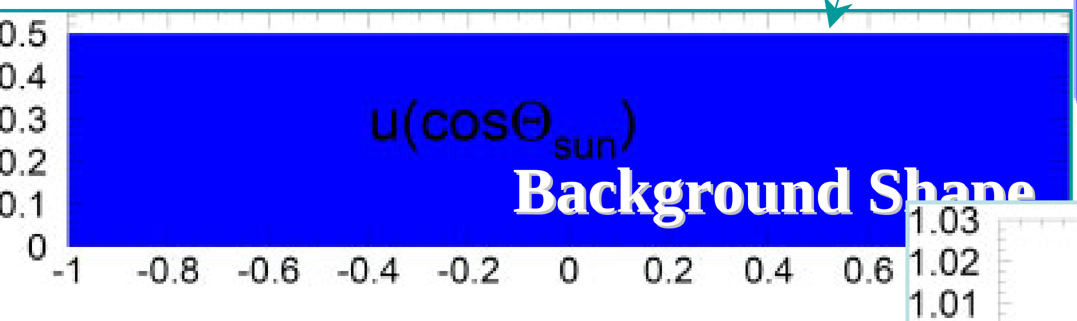
 # Backgrounds in each energy bins — **# Signal Events** — **Event Energy** — **Event "Time"**

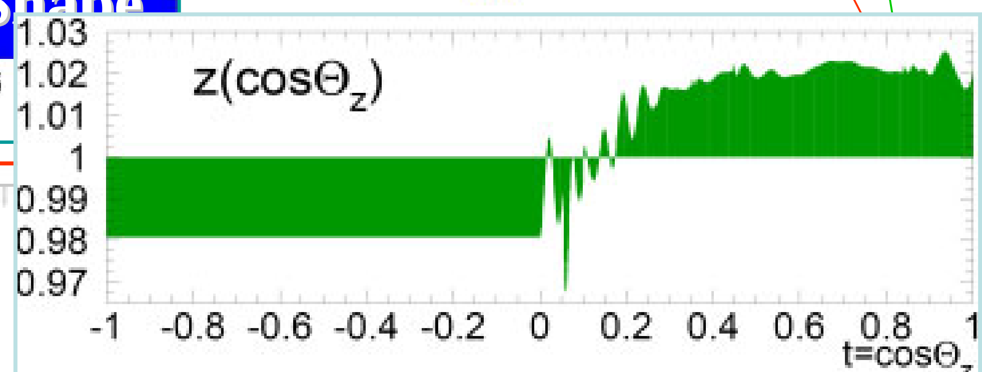
$$\mathbf{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(B_i \cdot u_i(c_\nu) + m_i S \cdot p(c_\nu, E_\nu) \qquad \right)$$

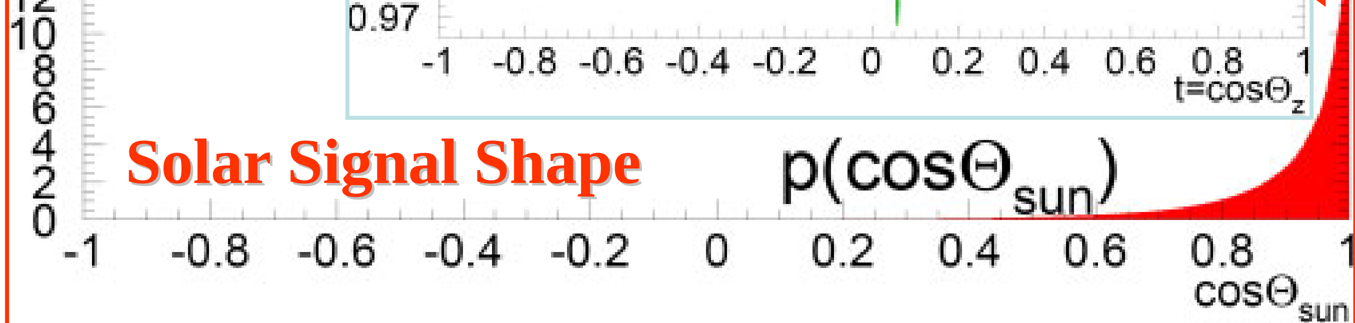
21 Energy bins

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

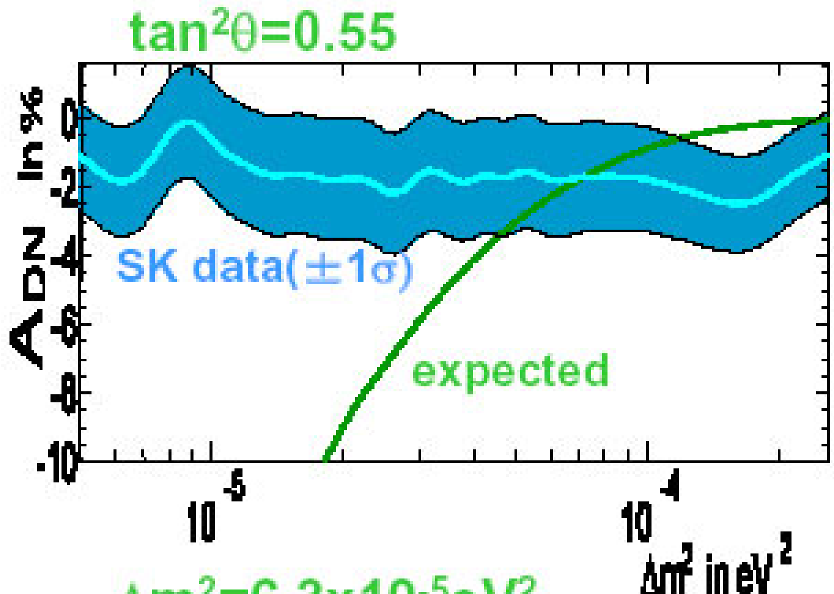


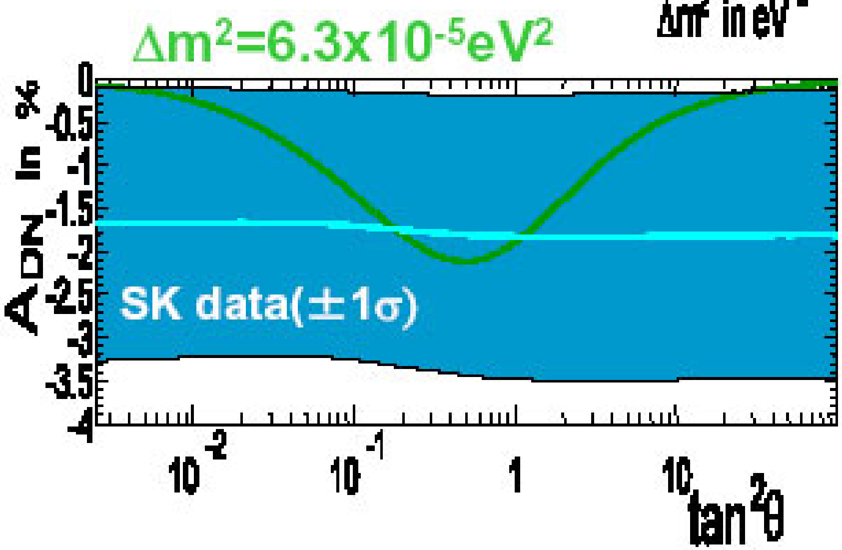






Day/night asymmetry





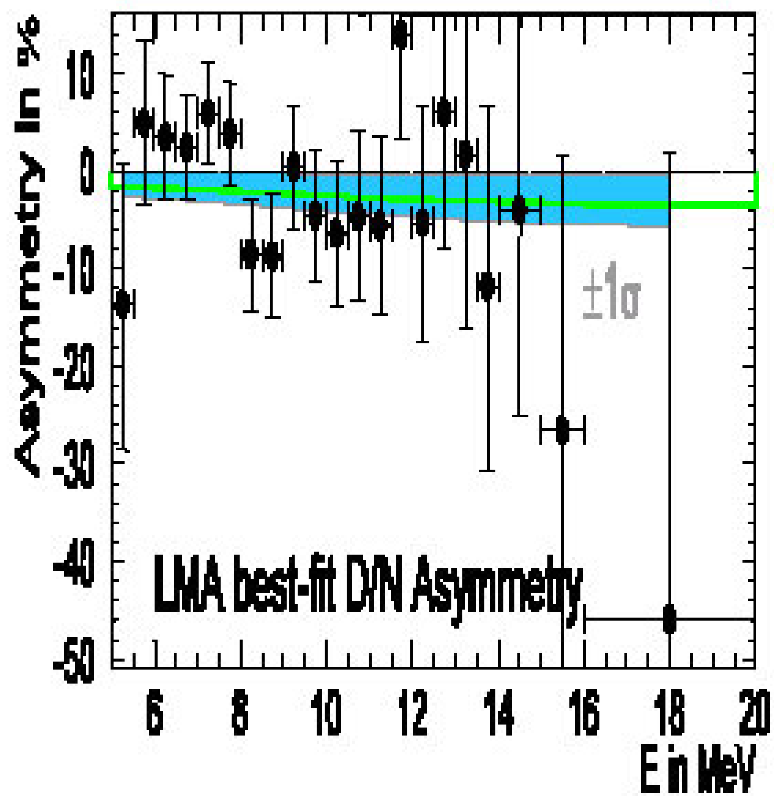
LMA best fit

(Assuming BP2000 flux and error)

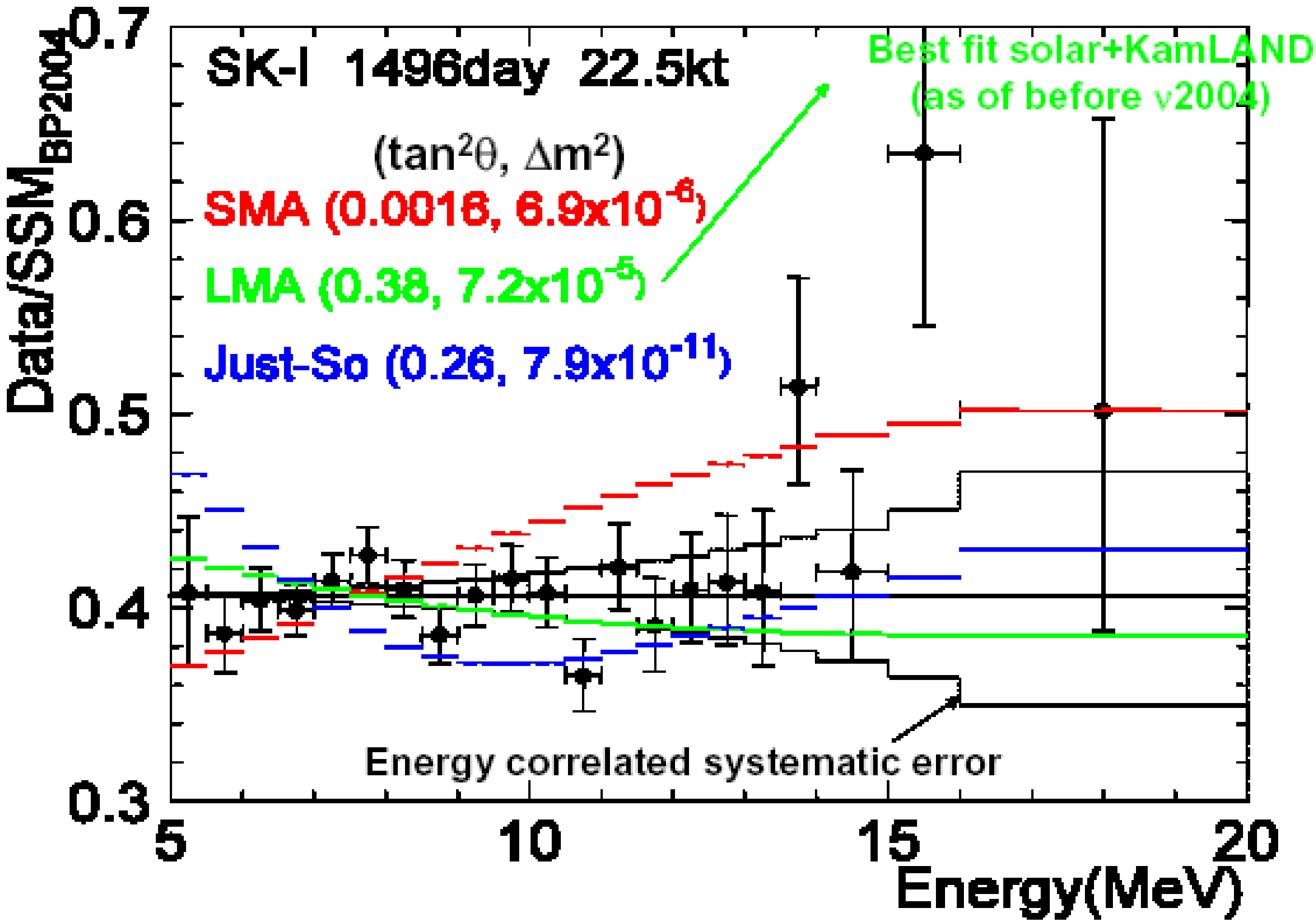
$\Delta m^2 = 6.3 \times 10^{-5} eV^2$

$\tan^2\theta = 0.55$

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



Energy spectrum of SK-I



Oscillation analysis

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

Spectrum

Energy correlated systematic error

Time variation

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

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

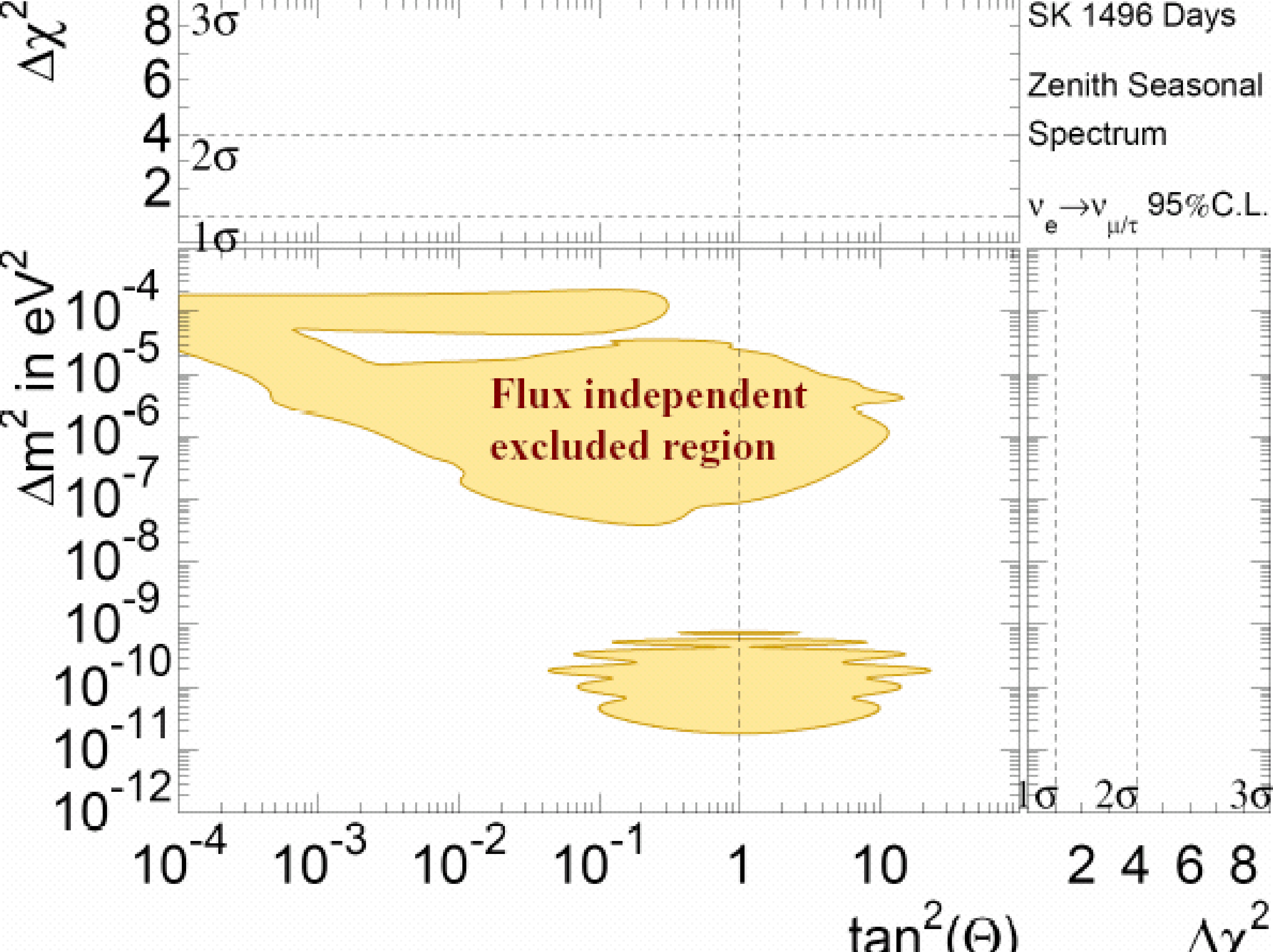
$$f_i\left(\delta_{\mathrm{B}}, \delta_S, \delta_R\right) = f_i^B\left(\delta_{\mathrm{B}}\right) \times f_i^S\left(\delta_S\right) \times f_i^R\left(\delta_R\right)$$

^{8}B spec. shape

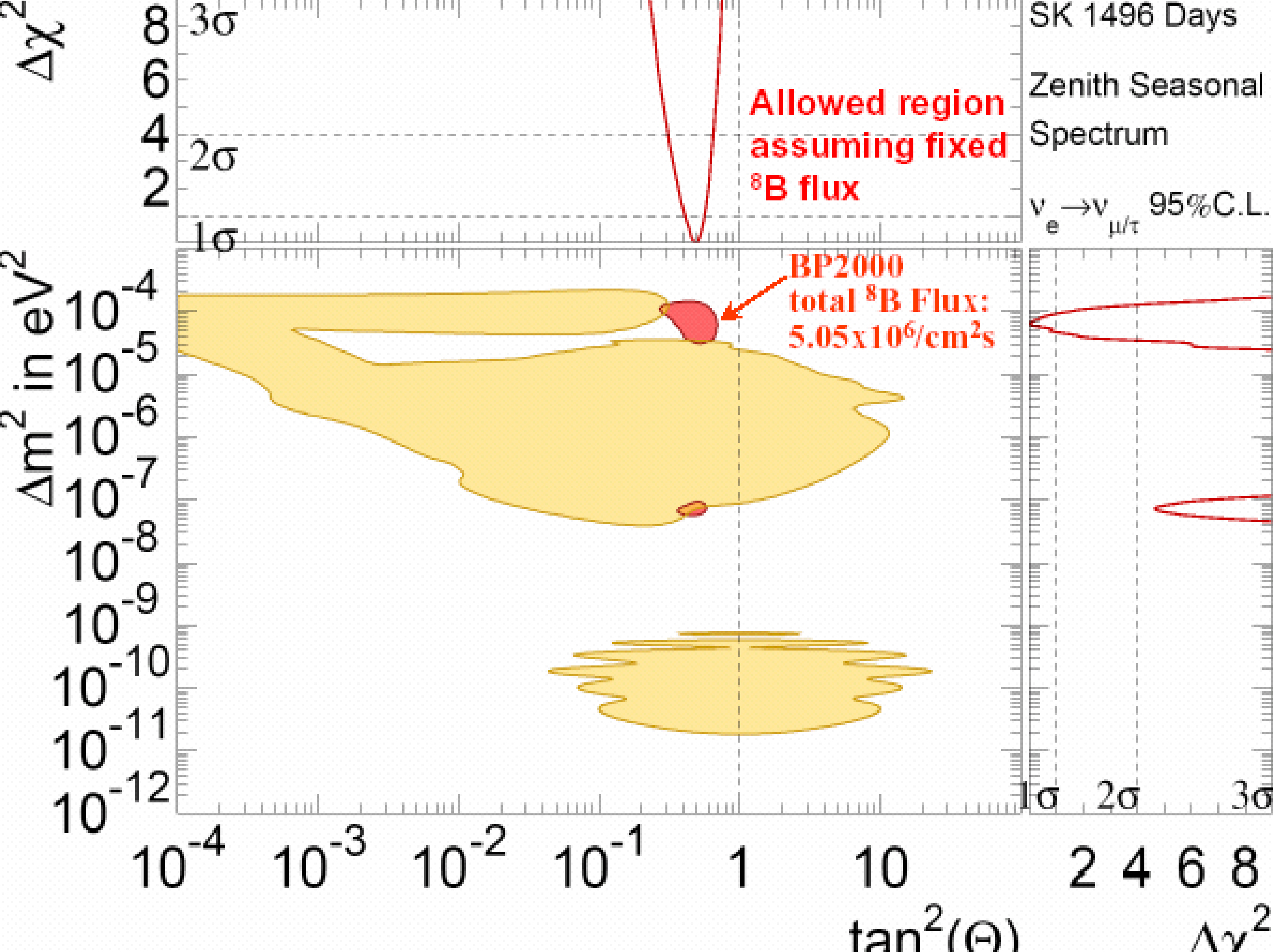
energy scale

energy resolution

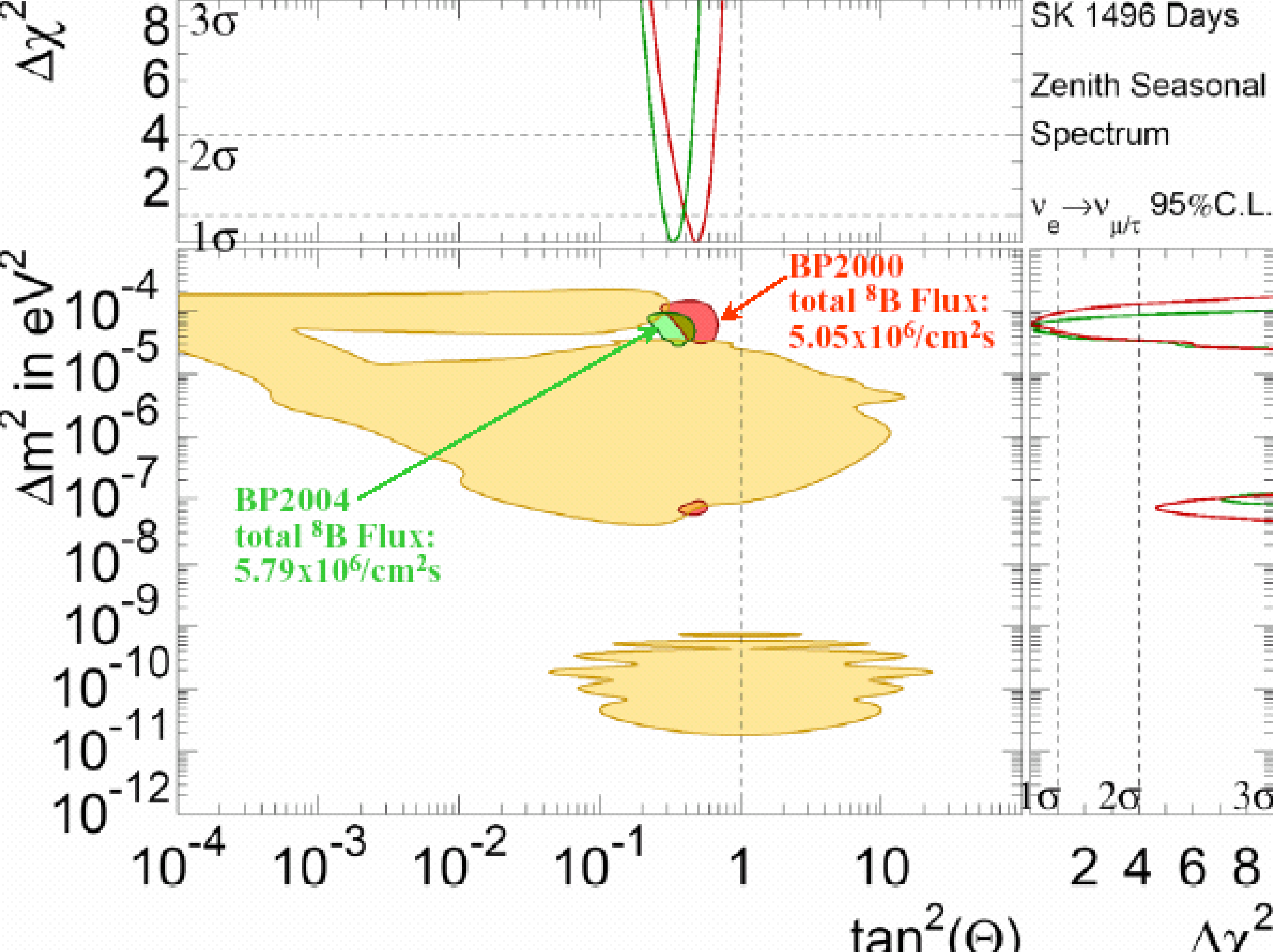
Function for energy correlated systematic errors



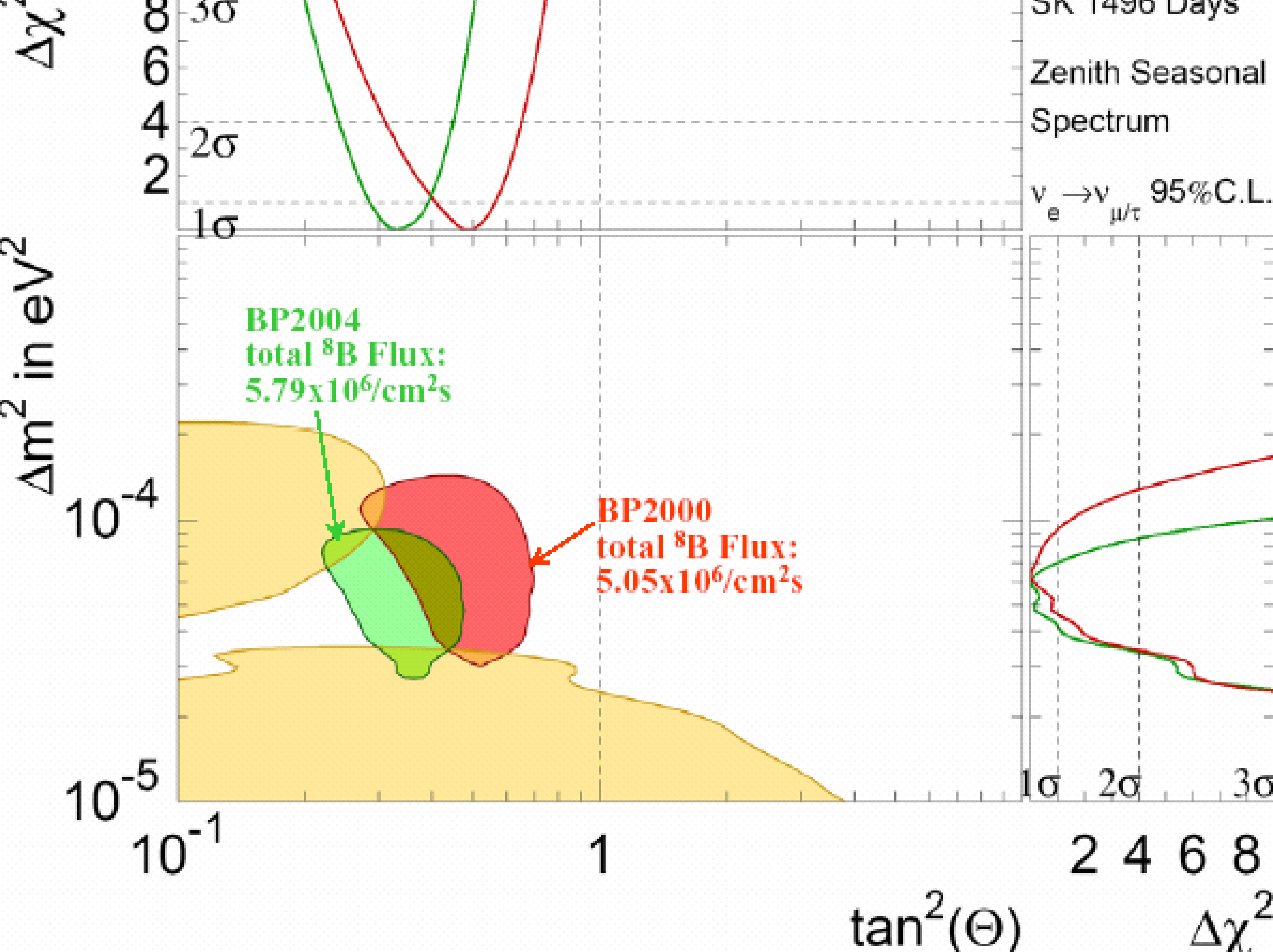
SK 1496 Days
Zenith Seasonal
Spectrum
$\nu_e \rightarrow \nu_{\mu/\tau}$ 95%C.L.
Flux independent
excluded region
$\Delta\chi^2$
Δm^2 in eV^2
$\tan^2(\Theta)$
3σ
2σ
1σ



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



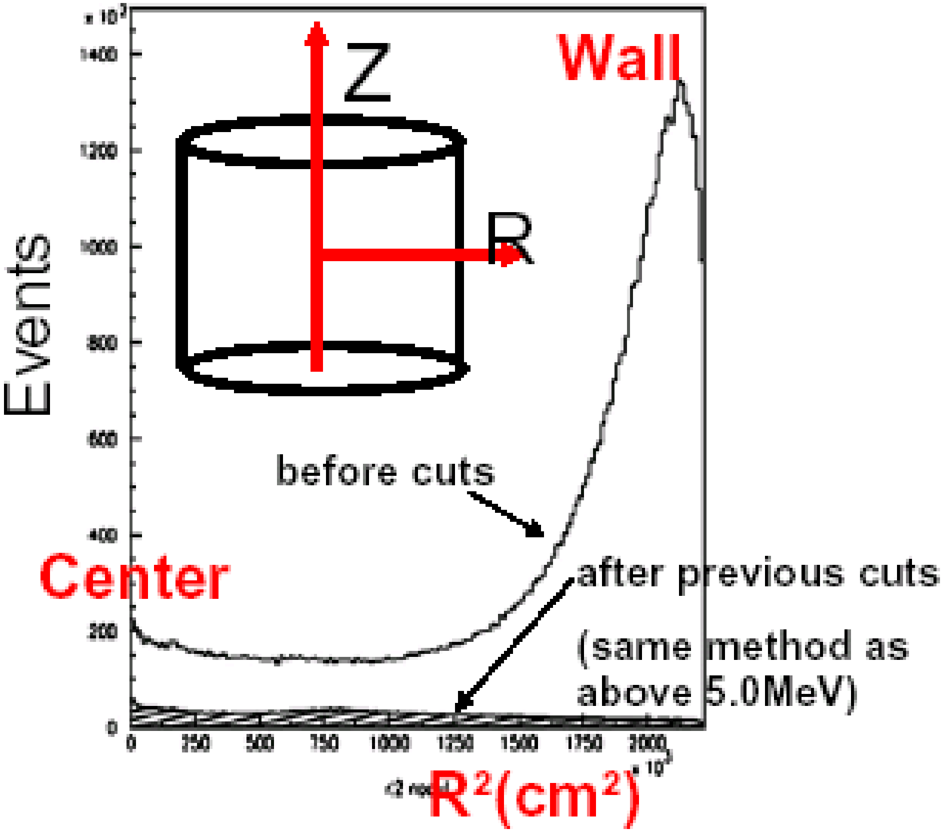
SK 1496 Days
Zenith Seasonal
Spectrum
$\nu_e \to \nu_{\mu/\tau}$ 95%C.L.
BP2000
total ^{8}B Flux:
5.05×10^6/cm^{2}s
BP2004
total ^{8}B Flux:
5.79×10^6/cm^{2}s
$\Delta\chi^2$
Δm^2 in eV^2
$\tan^2(\Theta)$
1σ
2σ
3σ

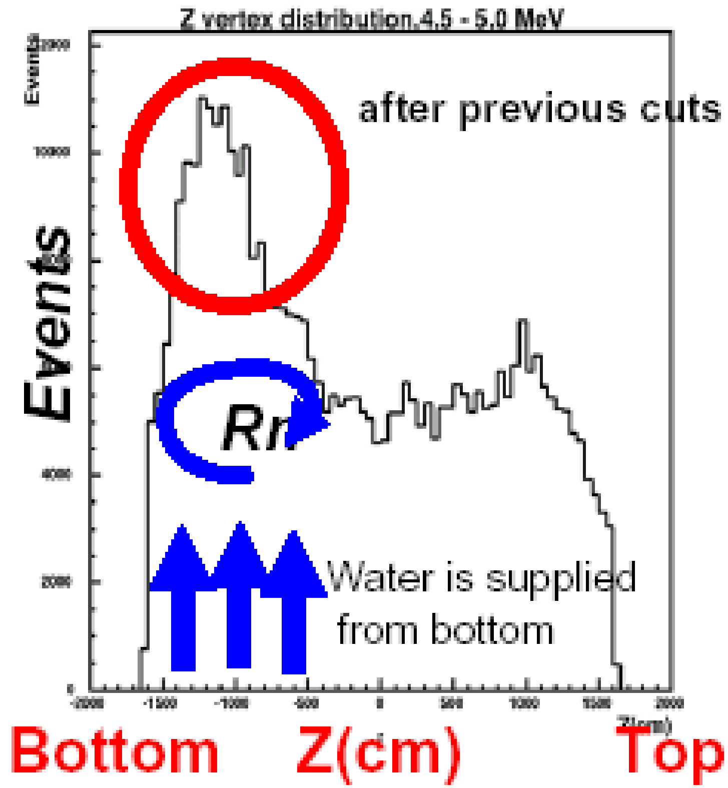


SK 1496 Days
Zenith Seasonal
Spectrum
νe→νμ/τ 95%C.L.
BP2004
total 8B Flux:
5.79x10^6/cm^2s
BP2000
total 8B Flux:
5.05x10^6/cm^2s
Δm² in eV²
tan²(Θ)
Δχ²
1σ
2σ
3σ

Analysis of lower energy region in SK-I

Vertex position distribution of background (4.5 – 5.0 MeV)

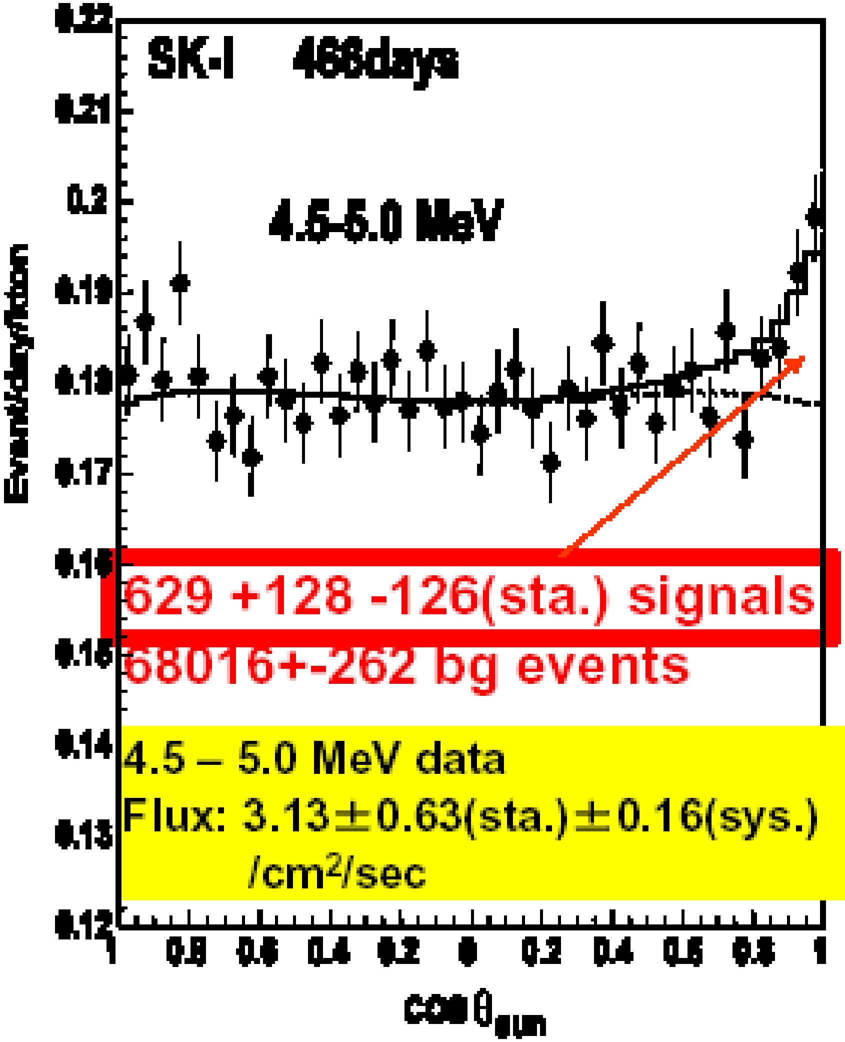




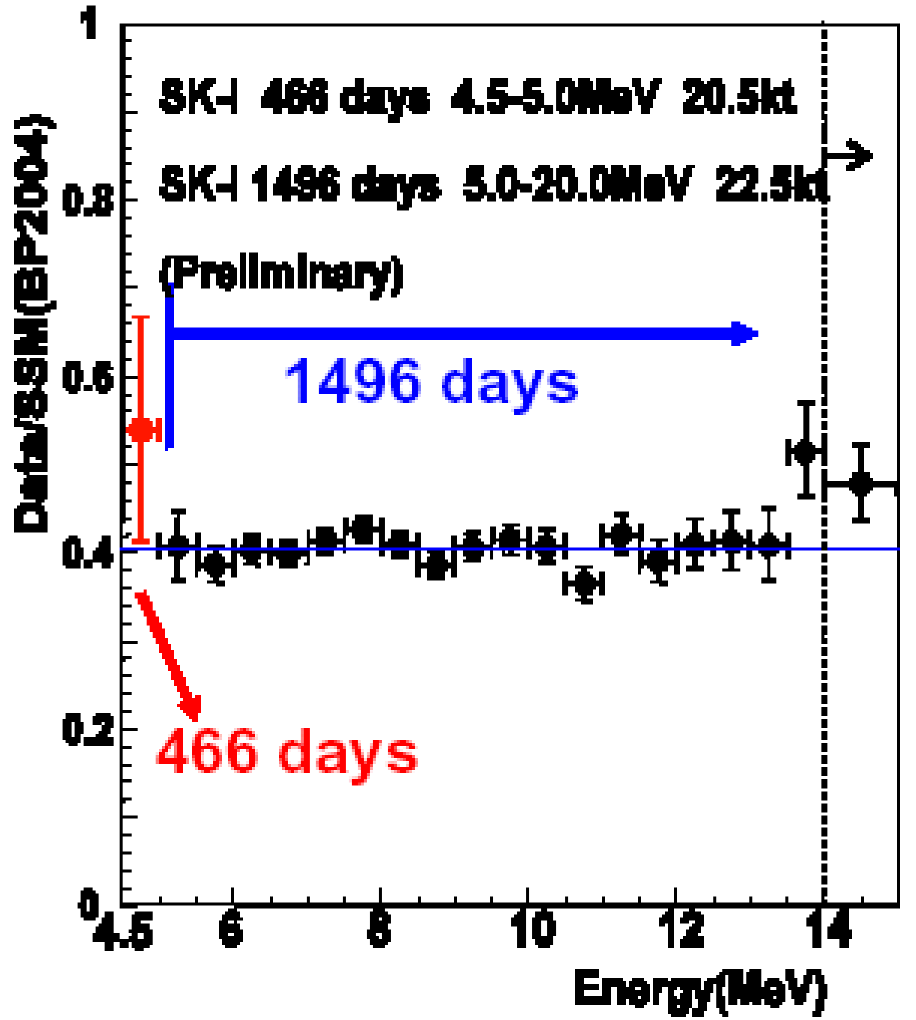
- Apply tighter cuts to reduce external background.
- Use improved vertex reconstruction program.
- Remove high radon periods.
- Select period when trigger eff. for 4.5-5.0MeV is >95%. (466days, Sep.1999-July 2001)

Analysis of lower energy region in SK-I

Direction to the sun



Solar neutrino energy spectrum

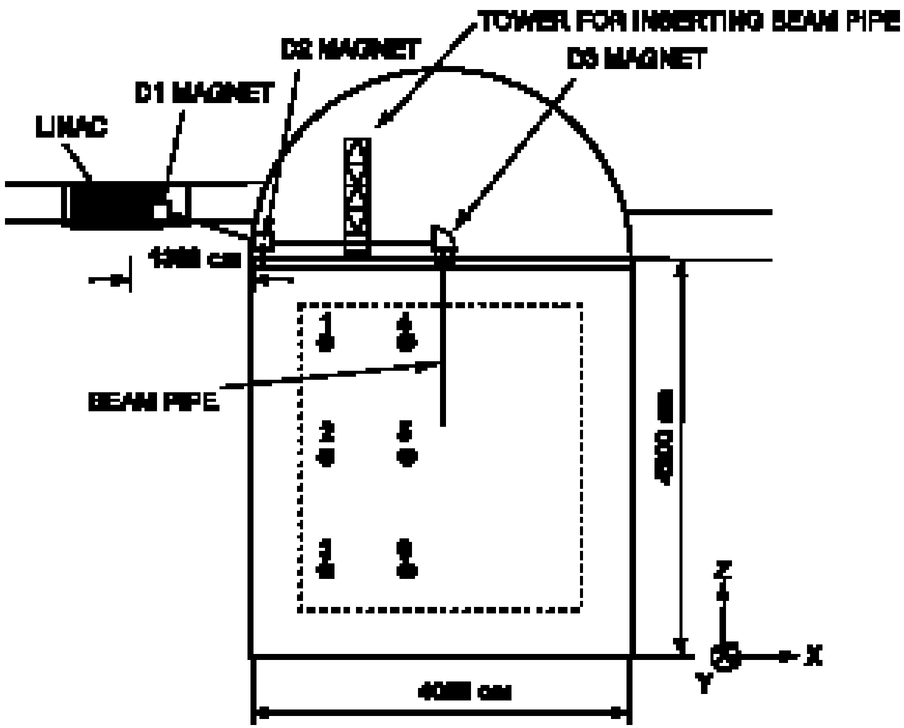


4.5-5.0 MeV data is consistent with previous results.

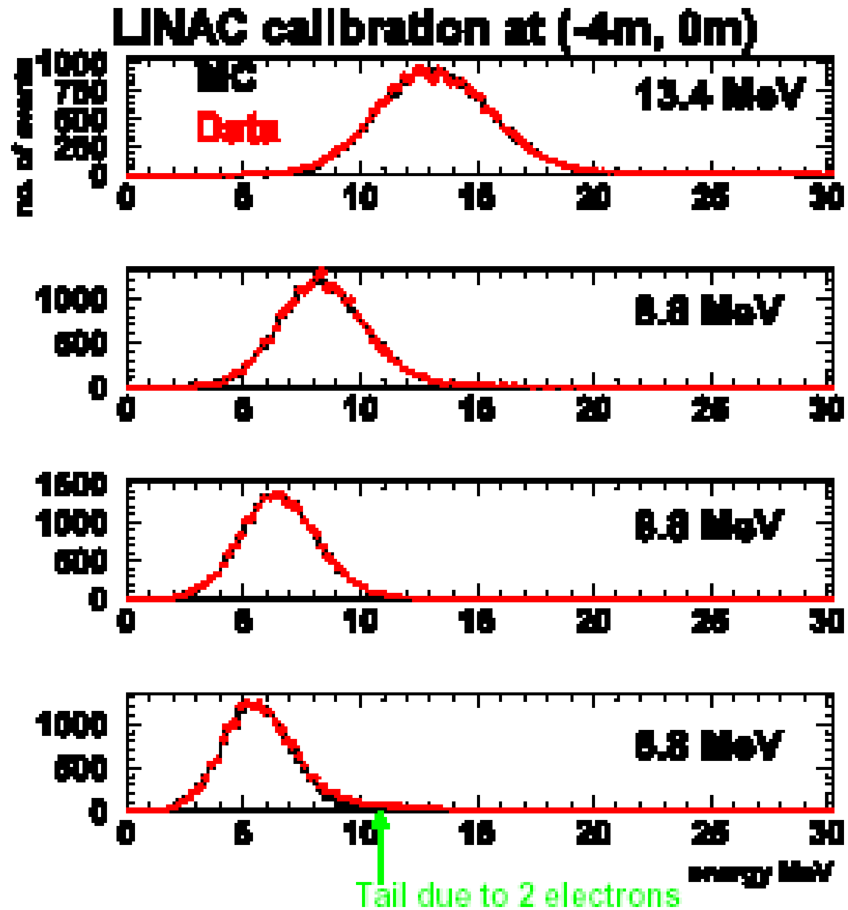
Detector calibration in SK-II

- 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.



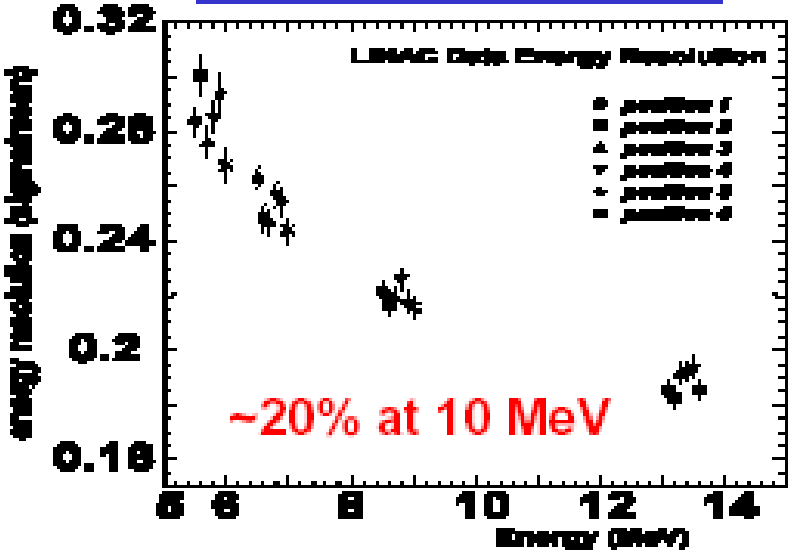
Energy distributions



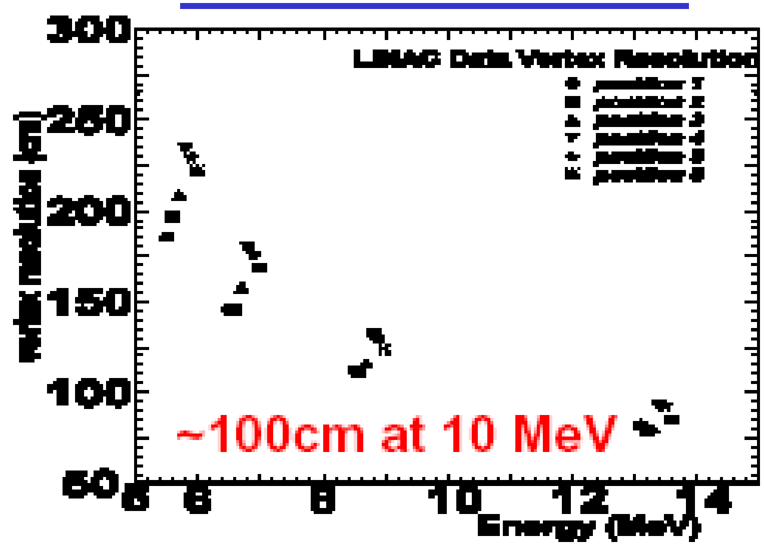
SK-II detector performance

(LINAC calibration)

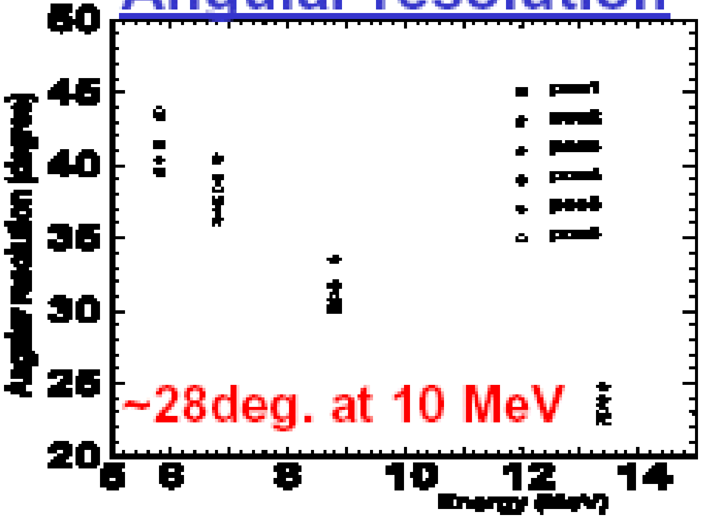
Energy resolution



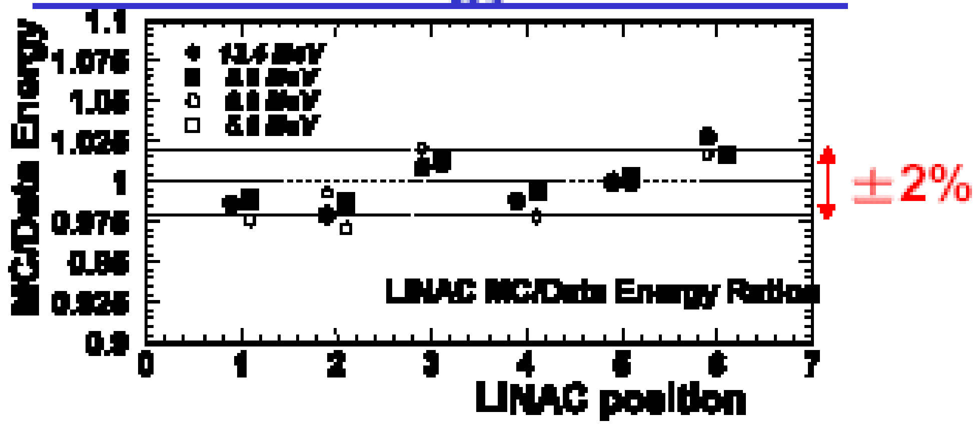
Vertex resolution



Angular resolution

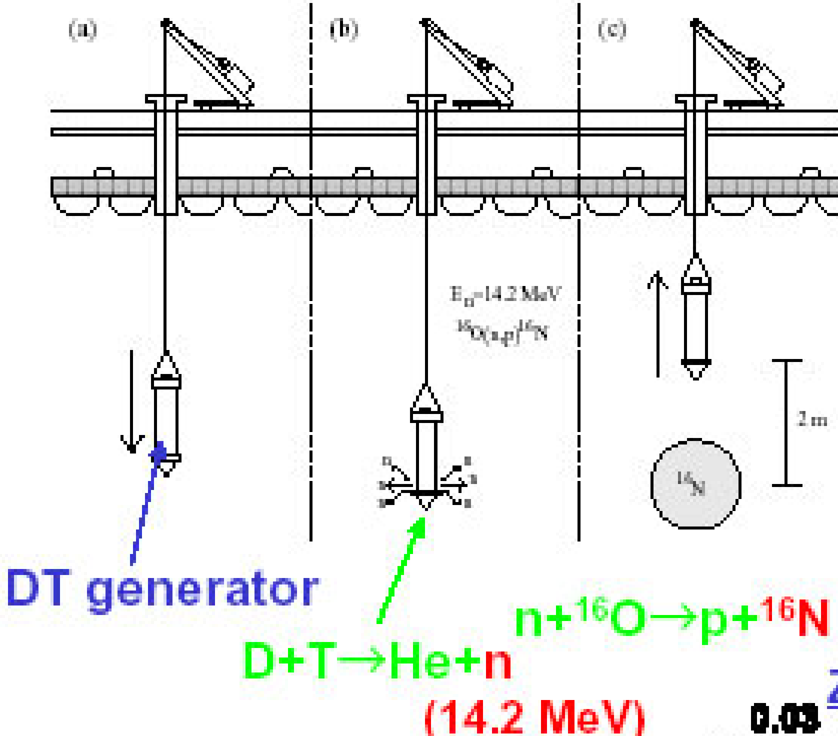


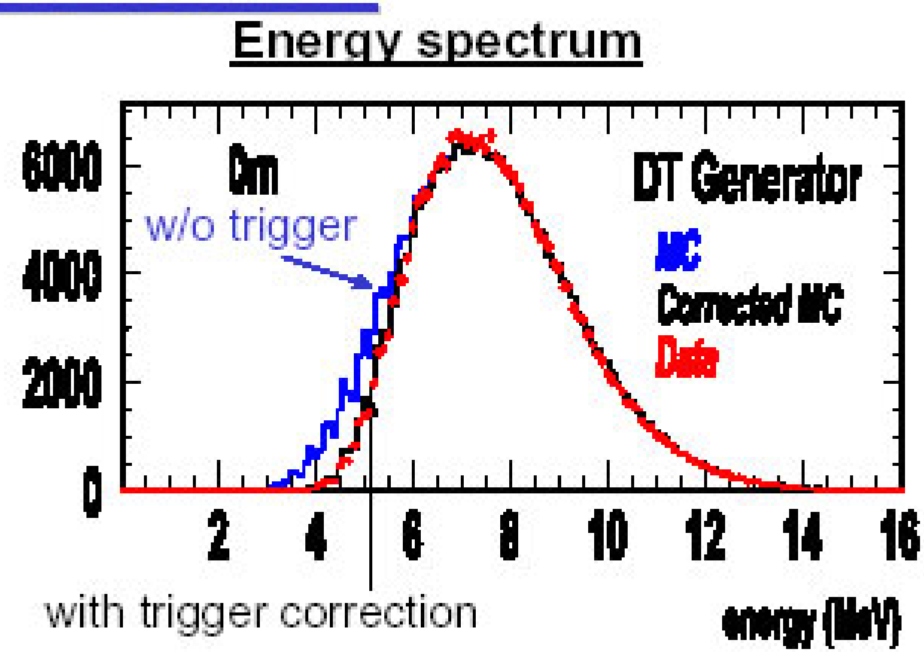
Absolute energy calibration

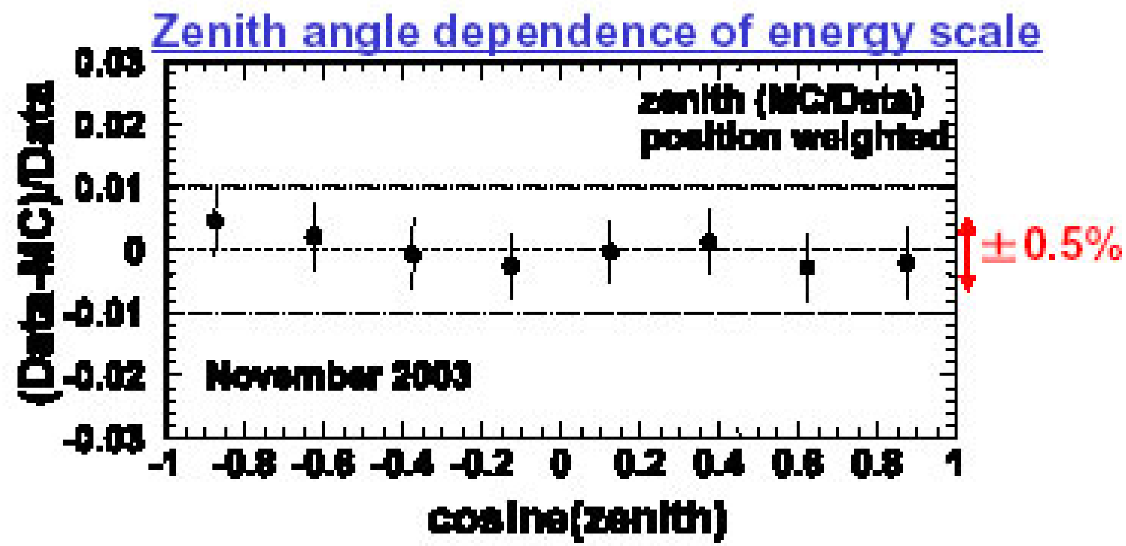


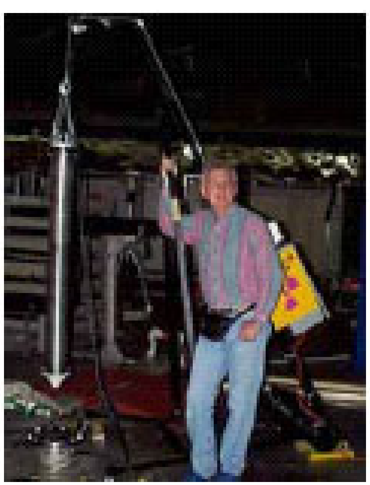
MC tuning is in progress.

^{16}N calibration



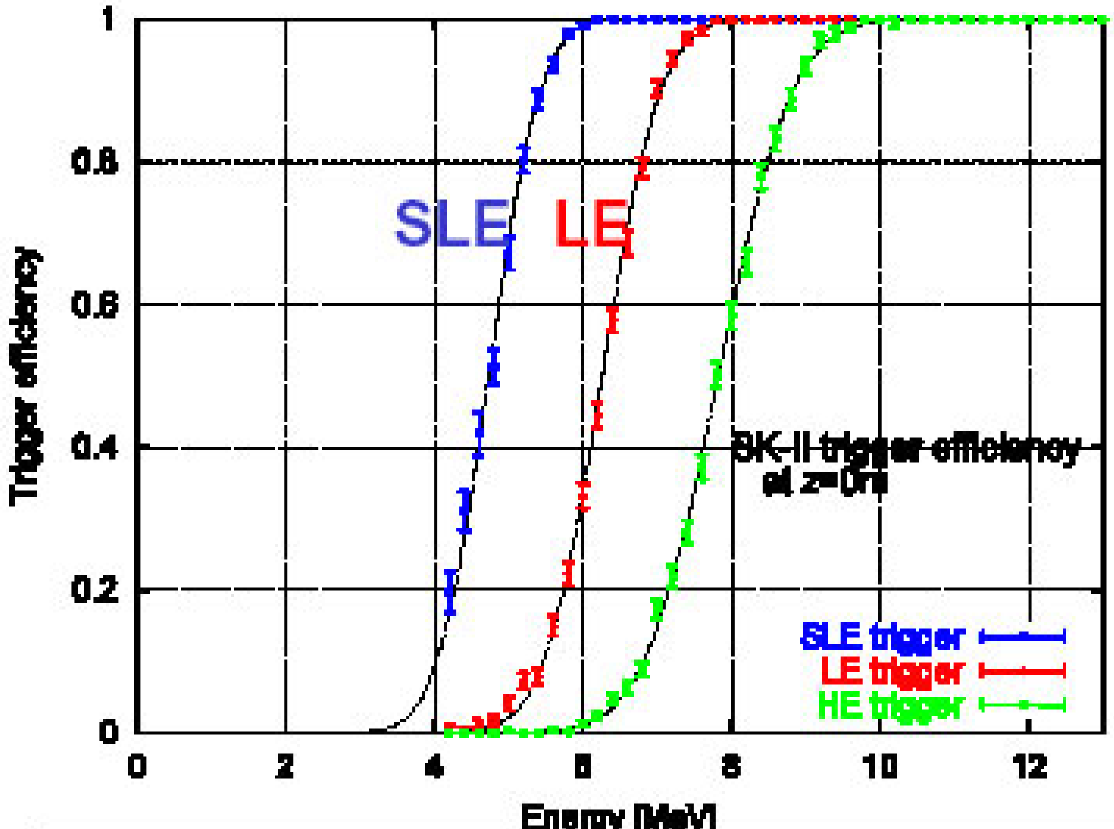






SK-II Trigger

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

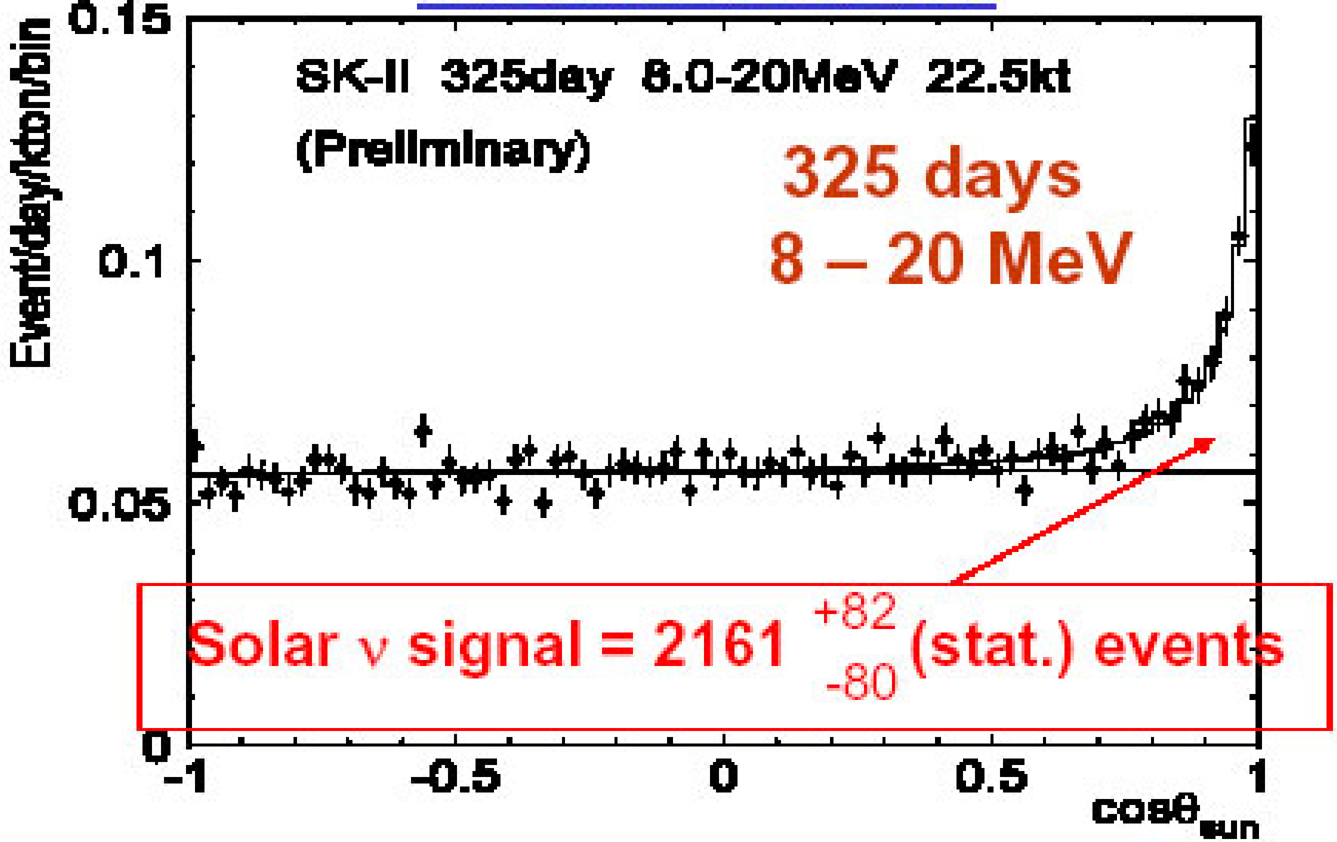
100% efficient for E > 6.5 MeV for SLE trigger

E > 8.0 MeV for LE trigger

SK-II preliminary results

Dec.24,2002 – March 25, 2004

Direction to the sun



Solar ν signal = 2161 $^{+82}_{-80}$ (stat.) events

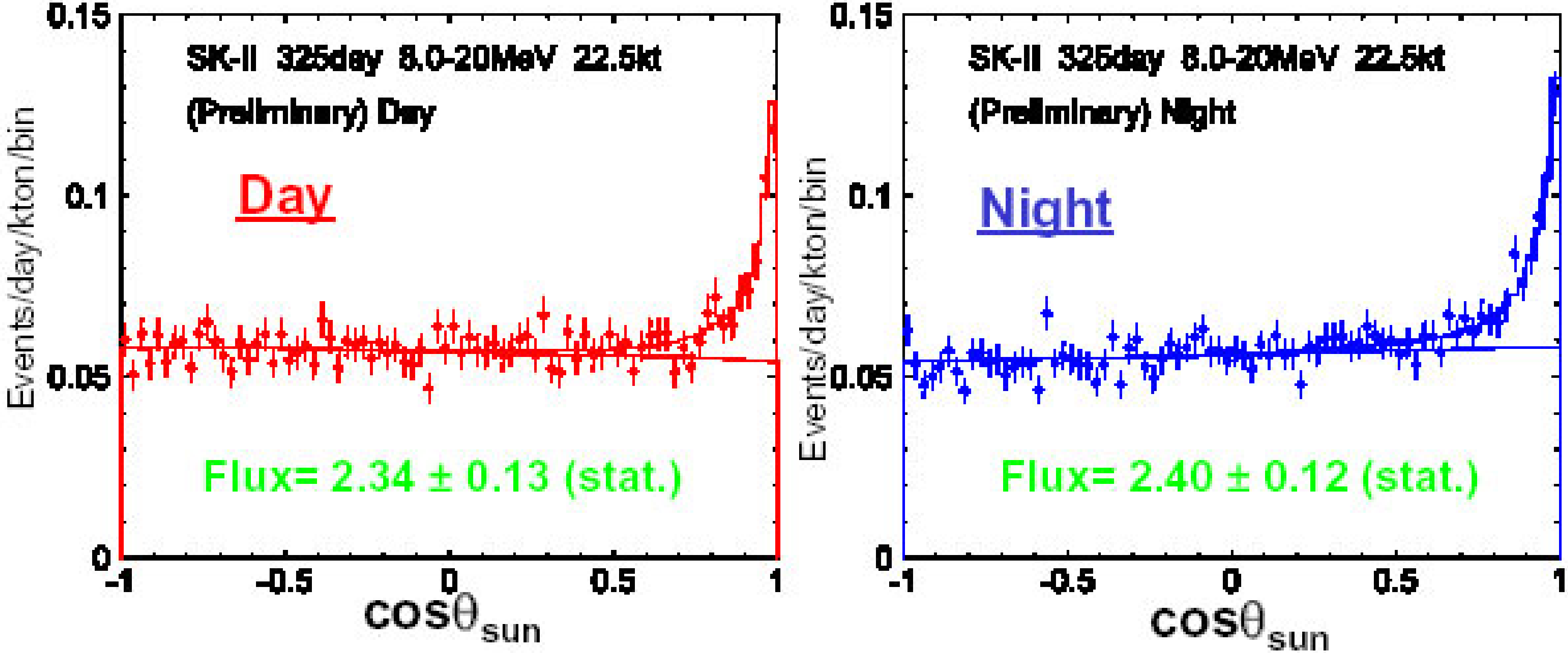
Flux= 2.38 ± 0.09 (stat.) ($\times 10^6/cm^2/s$)

(Systematic error under study)

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

SK-II: Day-Night difference

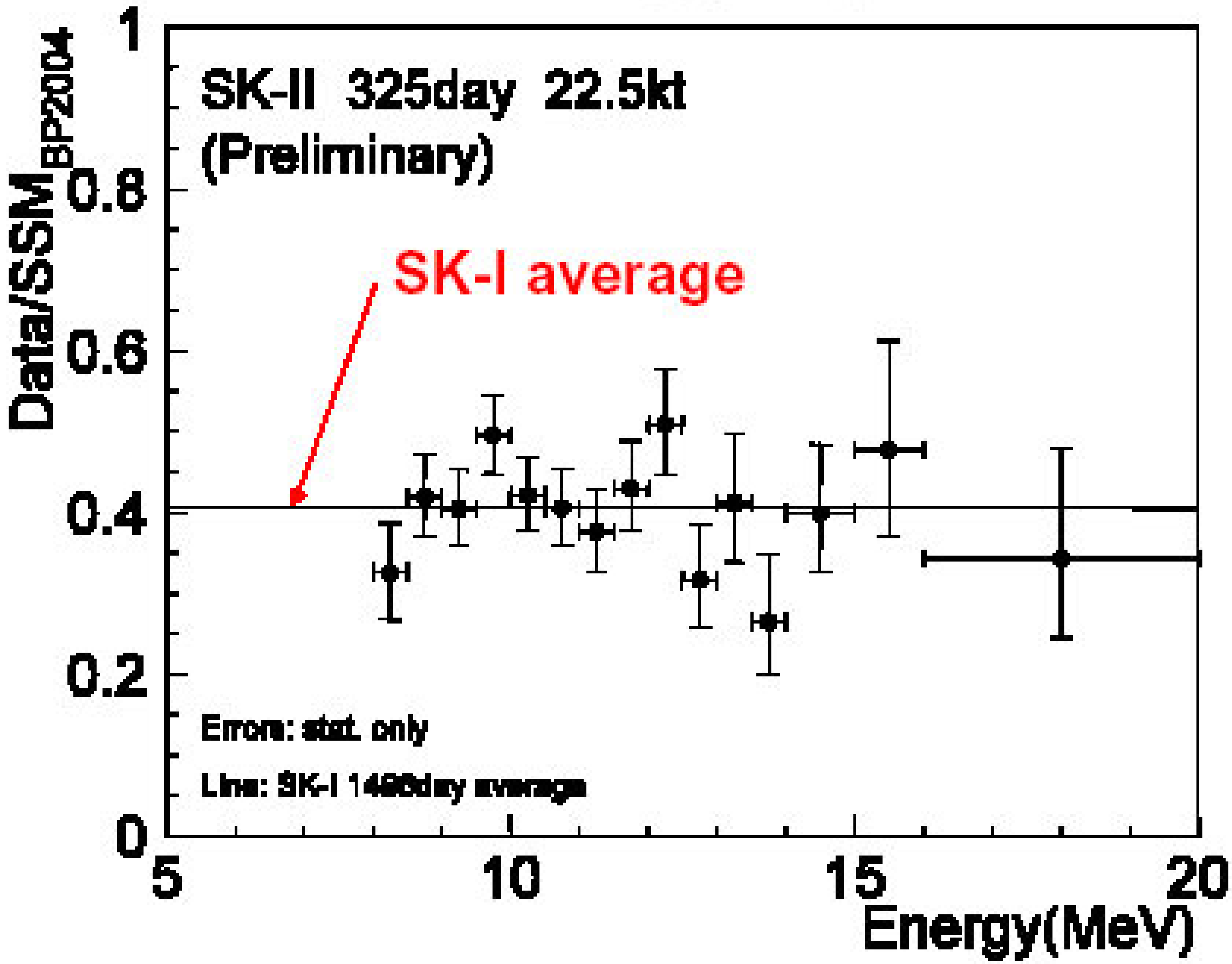
325 days (Dec.24,2002 – March 25, 2004)



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

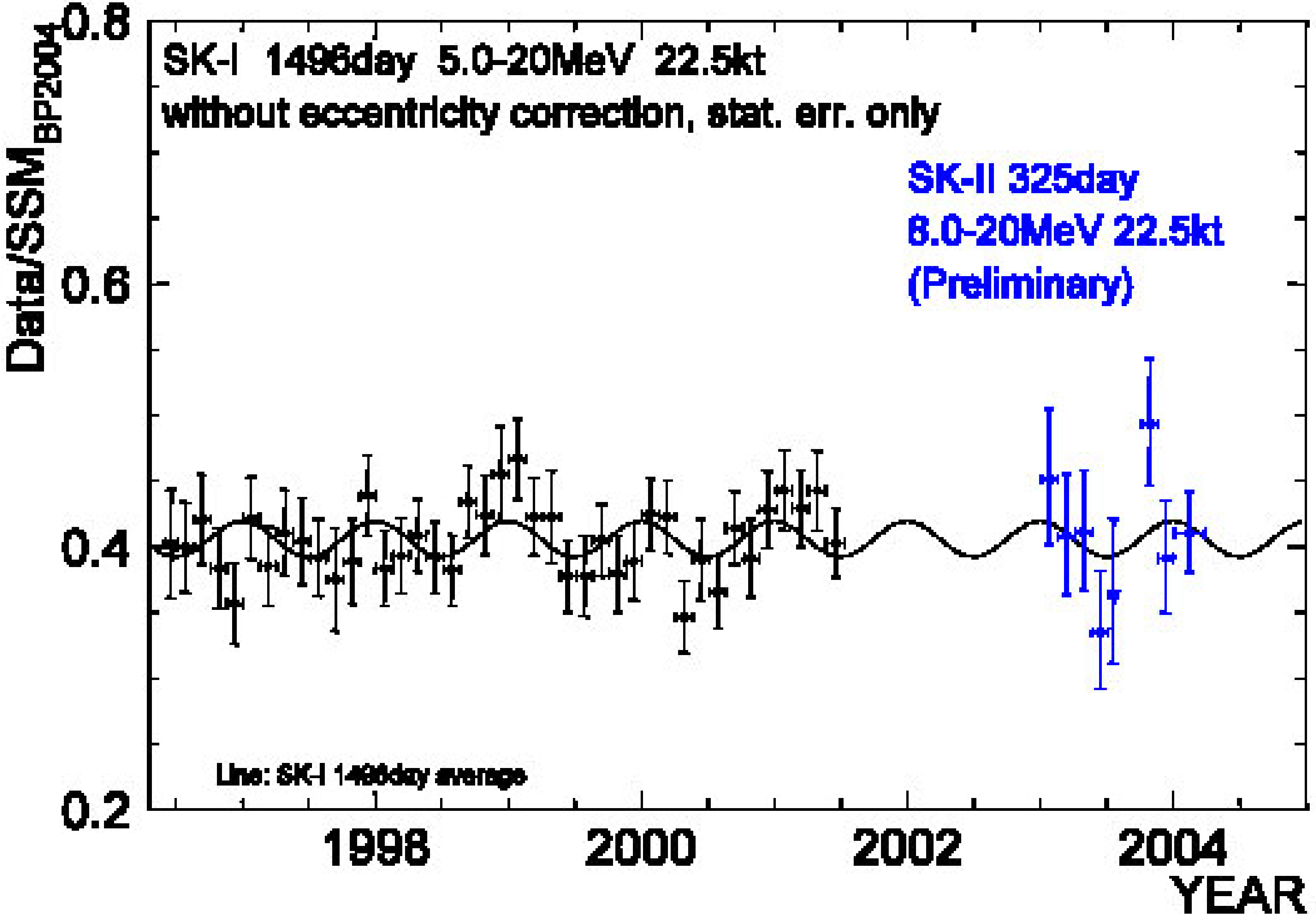
(Systematic error under study)

SK-II energy spectrum

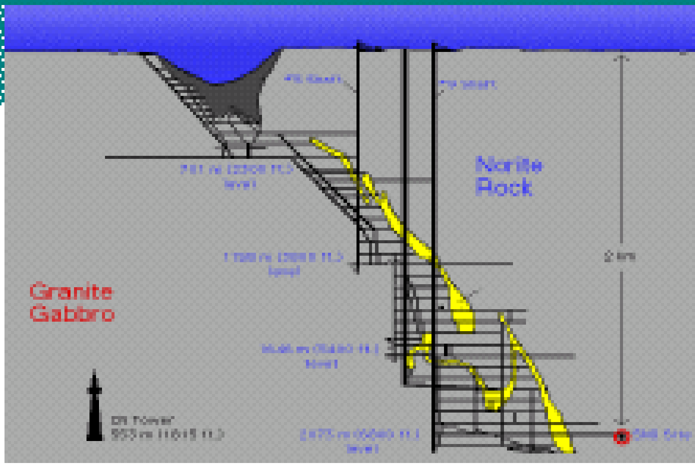


Consistent with SK-I

Time variation



Sudbury Neutrino Observatory



1000 tonnes D_2O

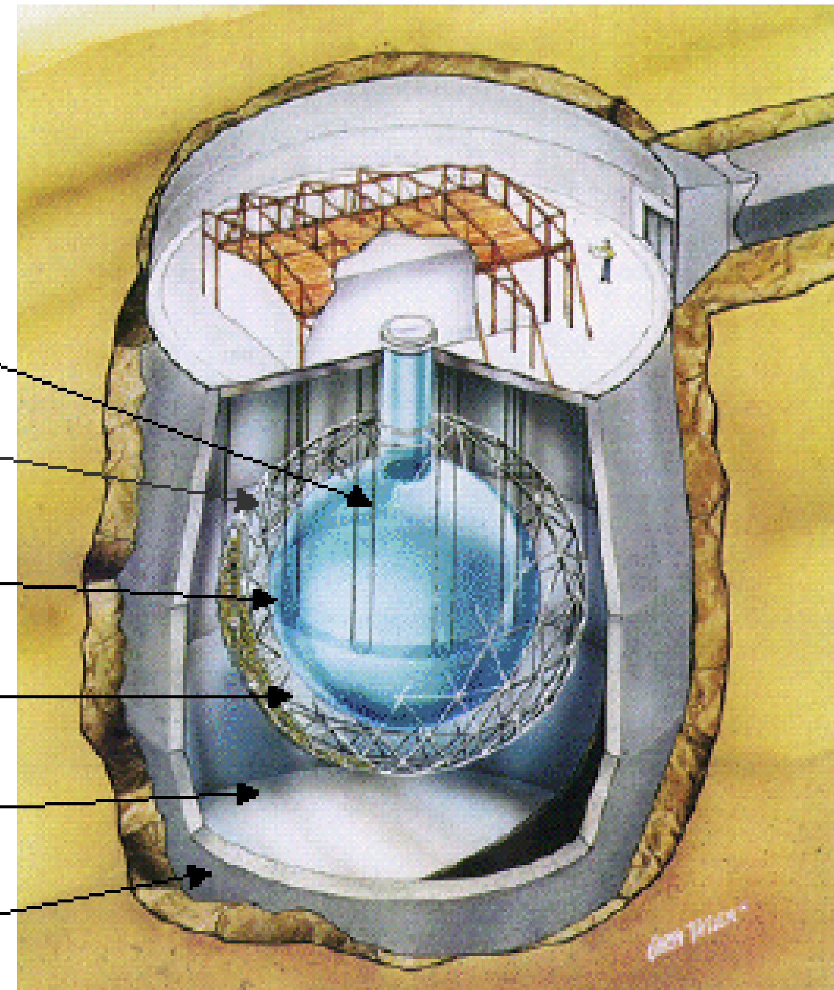
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal



Sudbury Neutrino Observatory

CC $\nu_e + d \Rightarrow p + p + e^-$

- Gives ν_e energy spectrum well
- Weak direction sensitivity $\propto$ 1-1/3cos(θ)
- ν_e only.

NC $\nu_x + d \Rightarrow p + n + \nu_x$

- Measure total ^8B ν flux from the sun.
- Equal cross section for all ν types

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

- Low Statistics
- Mainly sensitive to ν_e, some
- sensitivity to ν_μ and ν_τ
- Strong direction sensitivity

Key physics signatures

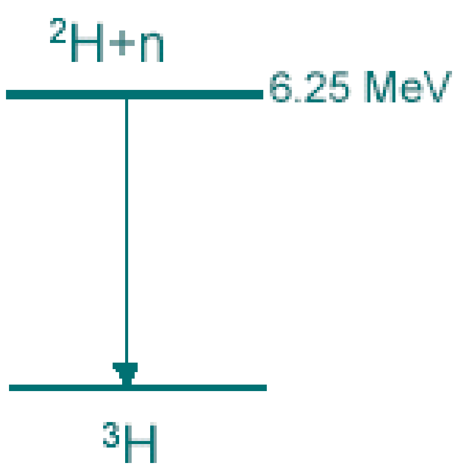
$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

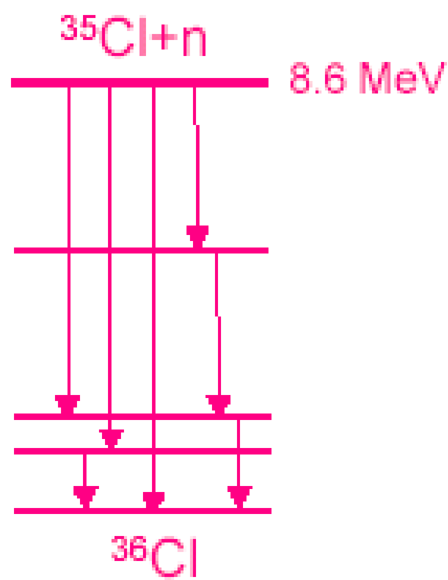
$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

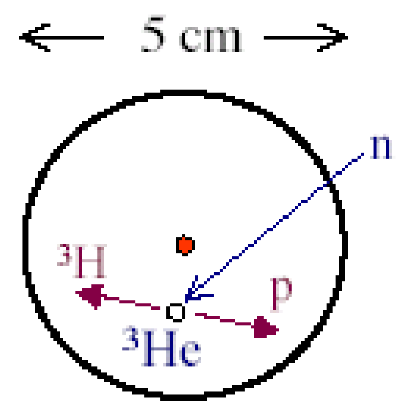
Φ_{day} vs Φ_{night}

SNO - 3 neutron detection methods

Phase I (D_2O)	Phase II (salt)	Phase III (^3He)
Nov. 99 - May 01	July 01 - Sep. 03	Summer 04 - Dec. 06
n captures on $^2H(n, \gamma)^3H$	2 t NaCl. n captures on $^{35}Cl(n, \gamma)^{36}Cl$	40 proportional counters $^3He(n, p)^3H$
σ = 0.0005 b	σ = 44 b	σ = 5330 b
Observe 6.25 MeV γ	Observe multiple γ's	Observe p and ^3H
PMT array readout	PMT array readout	PC independent readout
Good CC	Enhanced NC	Event by Event Det.







$n + {}^3He \rightarrow p + {}^3H$

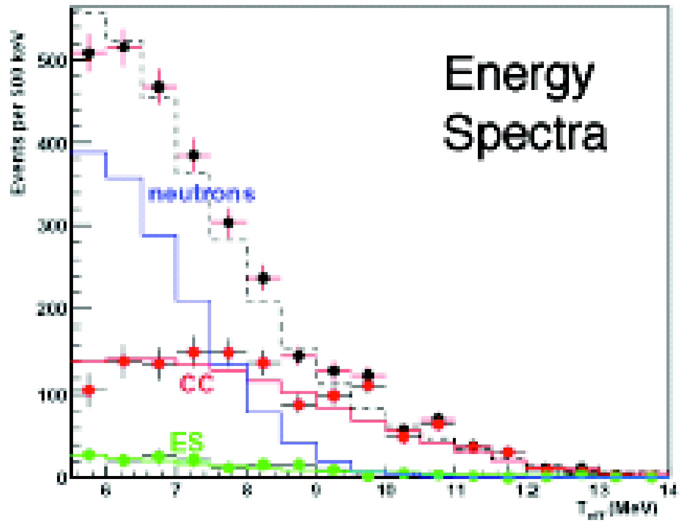
Event Distributions (PRL 92, 181301, 2004)

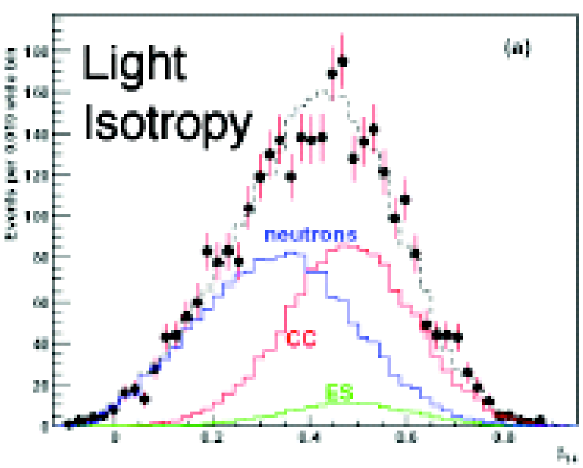
Salt Phase

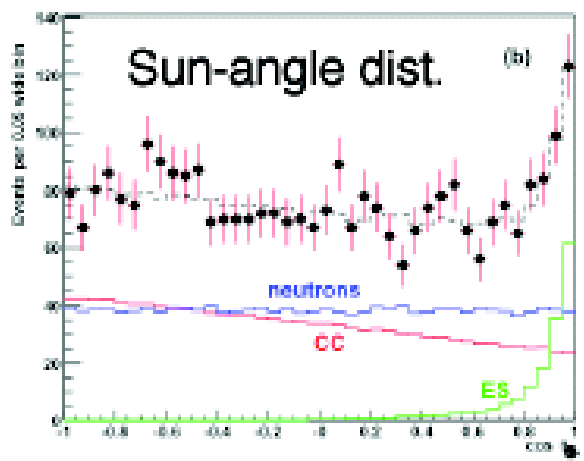
$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.306 \pm 0.026\ (\text{stat}) \pm 0.024\ (\text{syst})$$

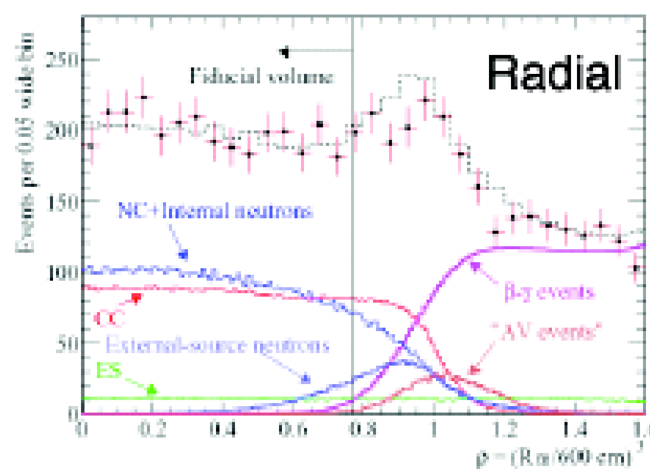
#EVENTS

CC	$1339.6^{+63.8}_{-61.5}$
ES	$170.3^{+23.9}_{-20.1}$
NC	$1344.2^{+69.8}_{-69.0}$





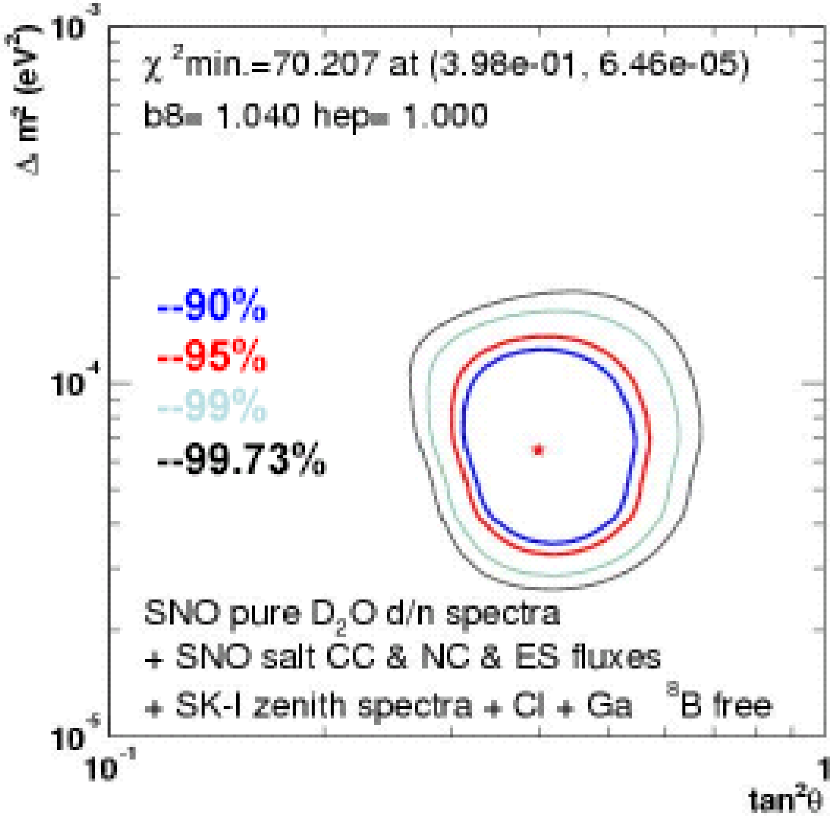


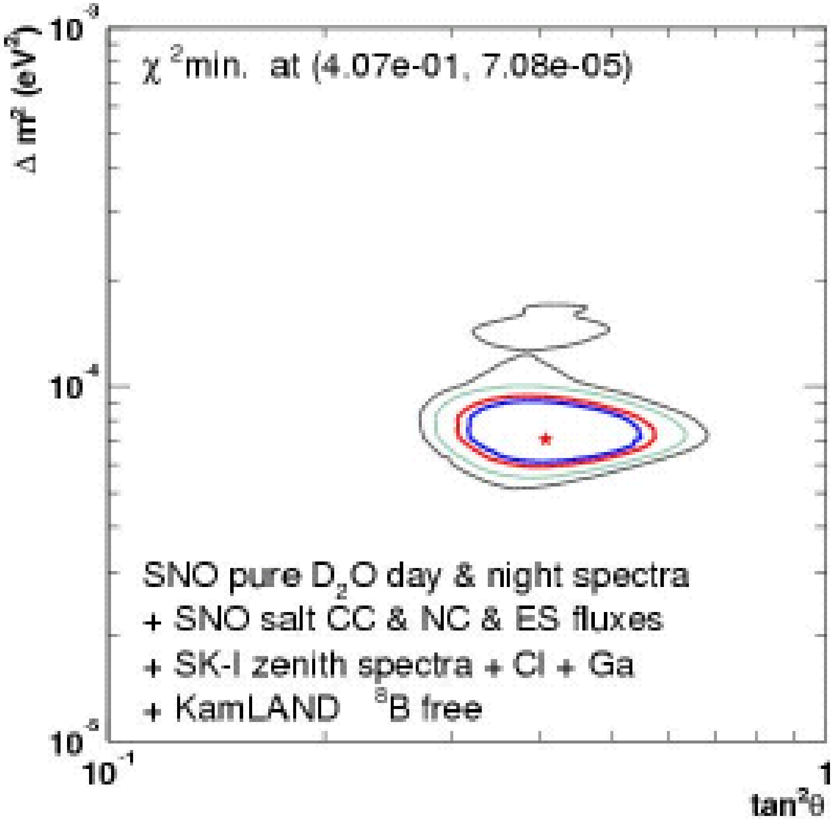


SNO First Salt Result [PRL 92, 181301, 2004]

Salt Phase

$$\phi(^8B)_{meas} = (0.88 \pm 0.04\ (exp) \pm 0.23\ (th))\ \phi(^8B)_{SSM}$$



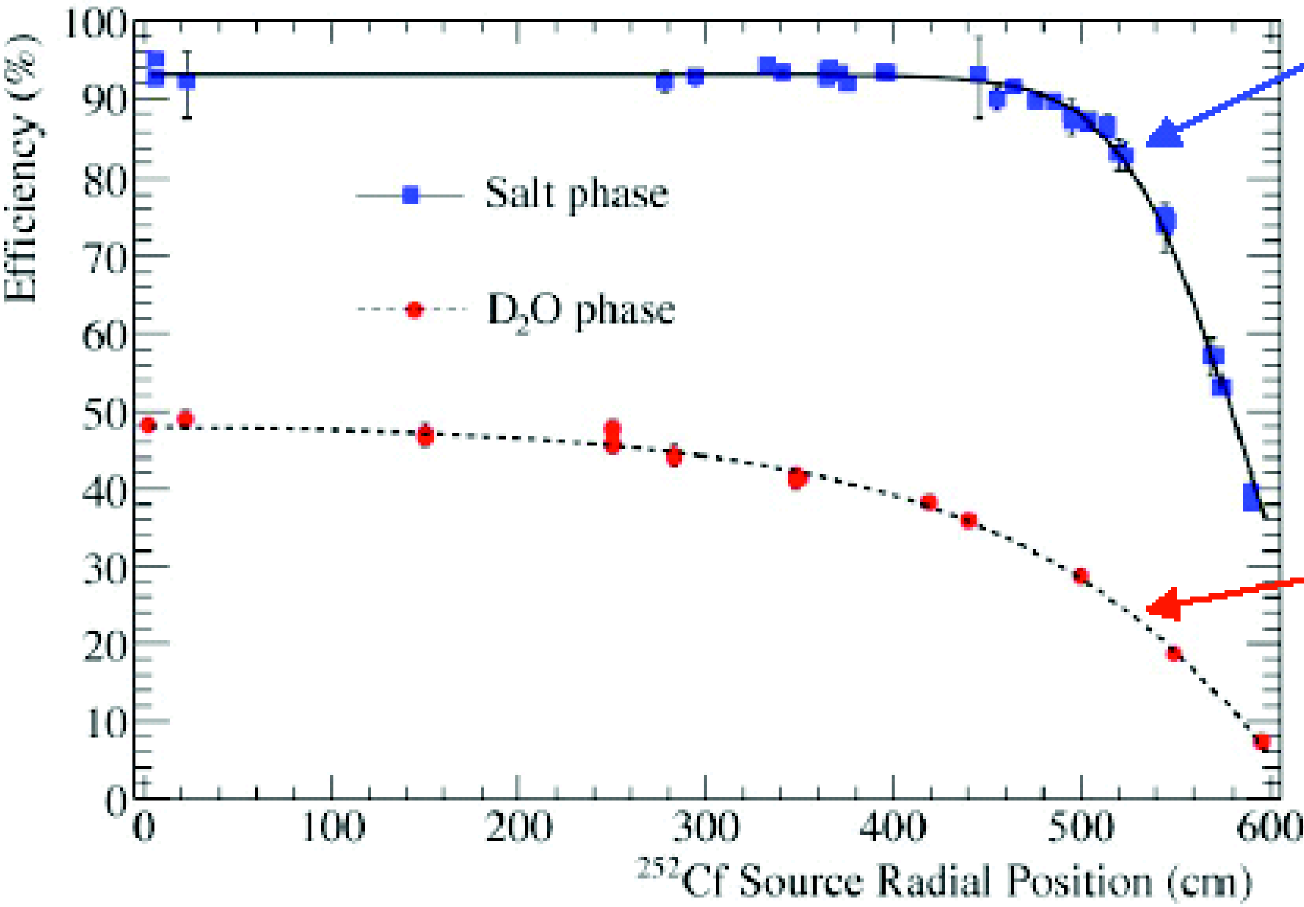


Disfavors maximal mixing at a level equivalent to 5.4 σ.

LMA I only at > 99% CL

Neutron Capture Efficiency in SNO

Salt Phase



$^{35}Cl(n,\gamma)^{36}Cl$

Net Average Efficiency 39.9%

$T_e \geq 5.5$ MeV and $R_\gamma \leq 550$ cm

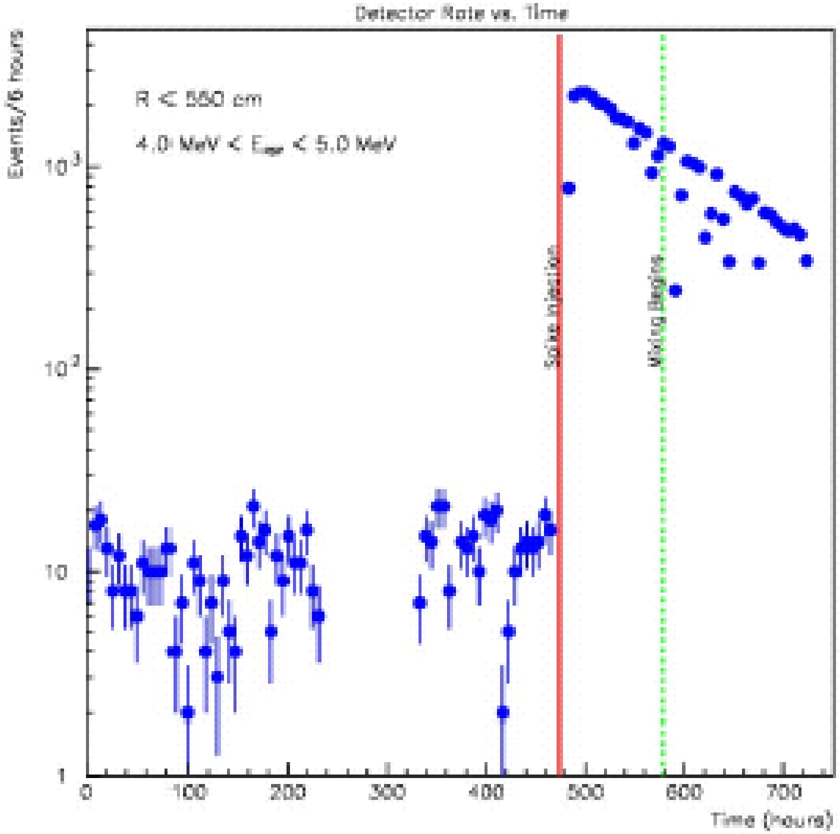
$^{2}H(n,\gamma)^{3}H$

Net Average Efficiency 14.4%

$T_e \geq 5.0$ MeV and $R_\gamma \leq 550$ cm

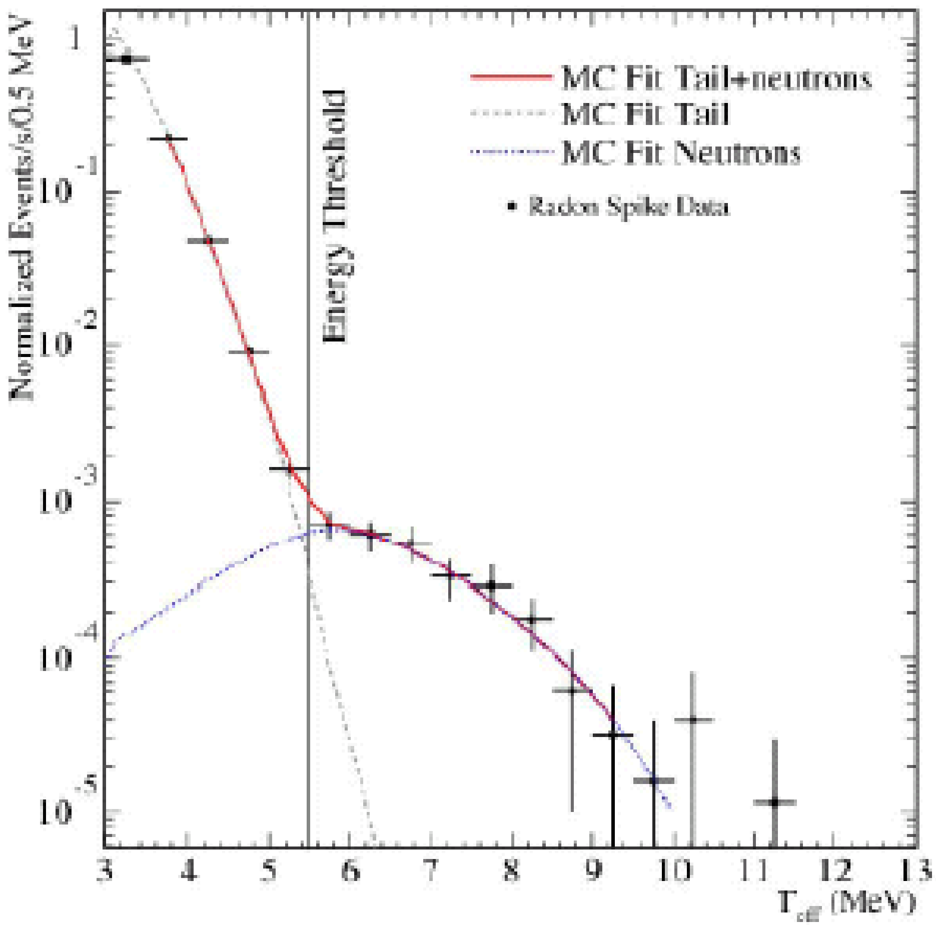
Calibrated Radon "Spike" Studies

81 Bq of ^{222}Rn slowly mixed in heavy water.



Calibrated Radon "Spike" Studies

81 Bq of ^{222}Rn slowly mixed in heavy water.



^{3}He Proportional Counters ("NC Detectors")

Detection Principle

$$^2H + \nu_x \rightarrow p + n + \nu_x - 2.22 \text{ MeV} \quad \text{(NC)}$$

$$^3He + n \rightarrow p + {}^3H + 0.76 \text{ MeV}$$

40 Strings on 1-m grid

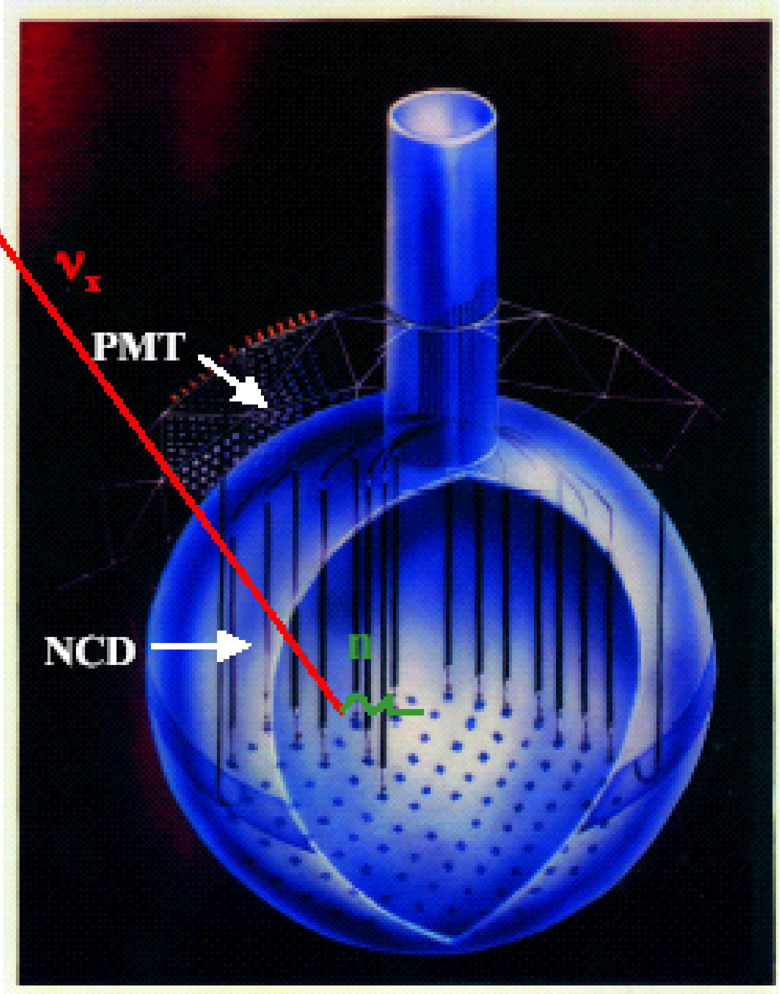
398 m total active length

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

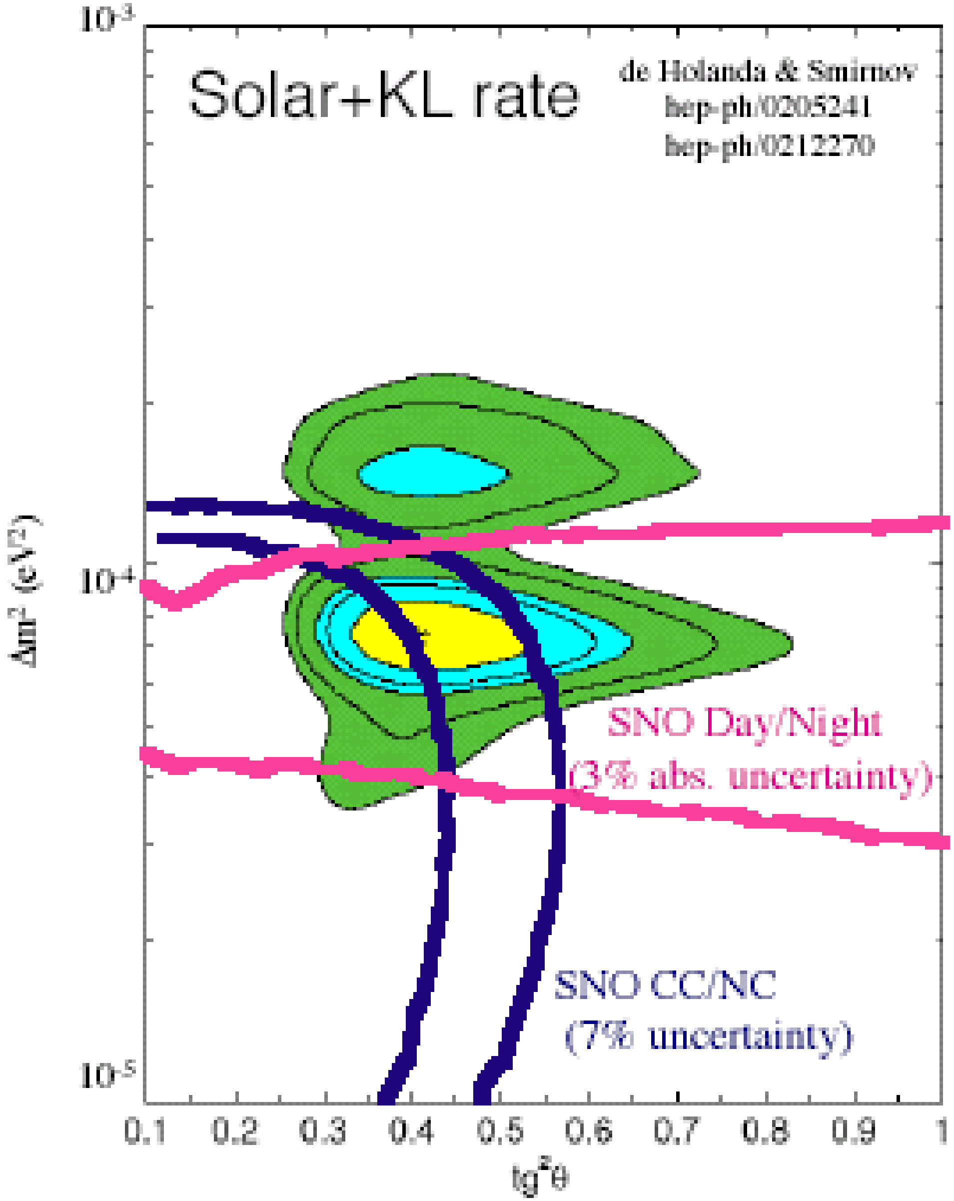
^{3}He array removes neutrons from CC, calibrates remainder. CC spectral shape.

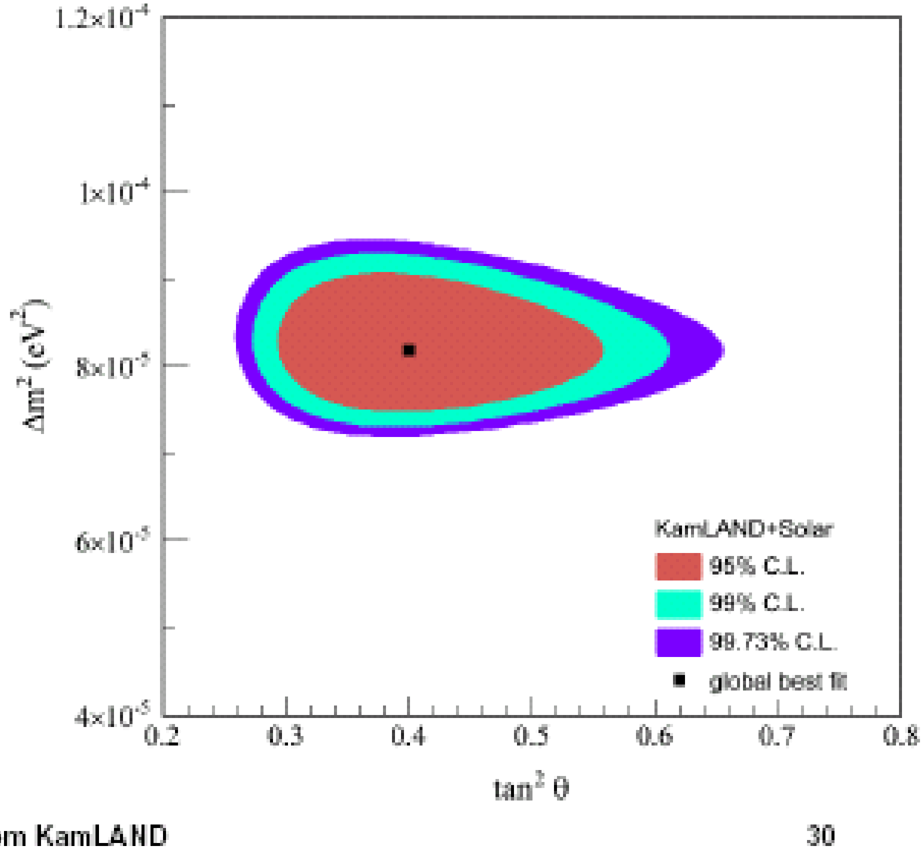


Precision ν measurements with SNO

3rd Phase

- Improved (~2x precision) SNO NC/CC measurement would yield an improved θ_{12} value
- Similar improvement of SNO Day/Night asymmetry would help with Δm_{12}
- Consistency tests
- In 3 ν mixing, also helps constrain θ_{13}
  (Maltoni et al. hep-ph/0309130)





KamLAND!

$$\Delta m_{12}^2 = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$

What's next for solar neutrino?

⇨ Find "smoking gun" to determine the parameter in solar neutrino experiments.

Aim of the future solar neutrino experiments

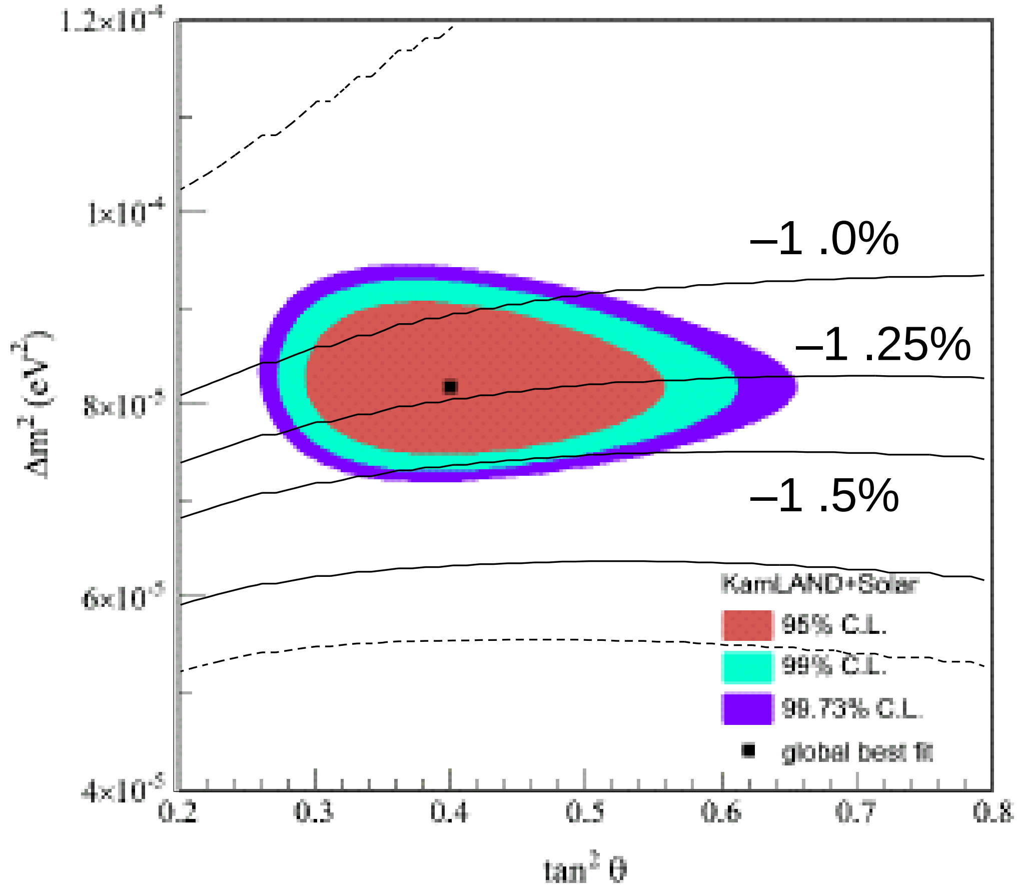
- Confirmation of LMA

  & find small sub-leading effects

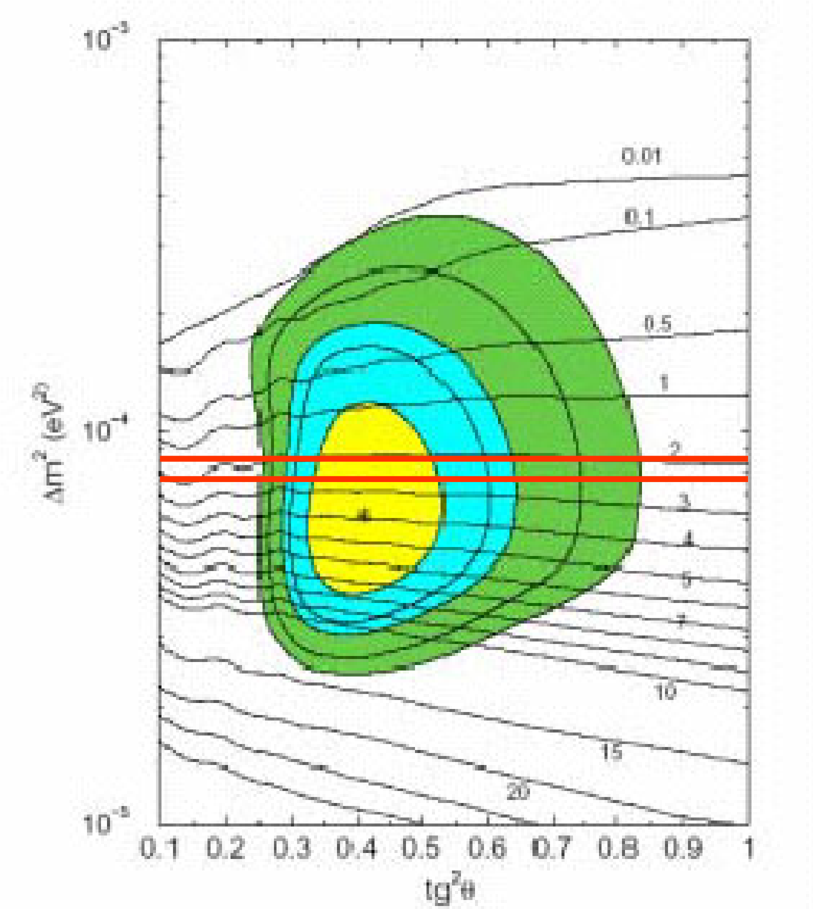
  - ^{8}B: low energy upturn & Day/Night effect
  - Matter Vacuum transition
    - Precise spectrum measurements in low energy
      - Cl – problem?
  - Sterile neutrinos?
    - Best by pp neutrinos
  - Other sub-leading effects
    - Test of CPT (Solar + KamLAND), ...
- Precise determination of θ_{12} and Δm_{12}
    - ^{8}B (large WC)
    - pp-neutrino, ^{7}Be(CC+ES)
- Astrophysics
  - Test of SSM (energy creation, photon luminosity) and….
  - Study the interior of the sun and….

Day/Night asymmetry

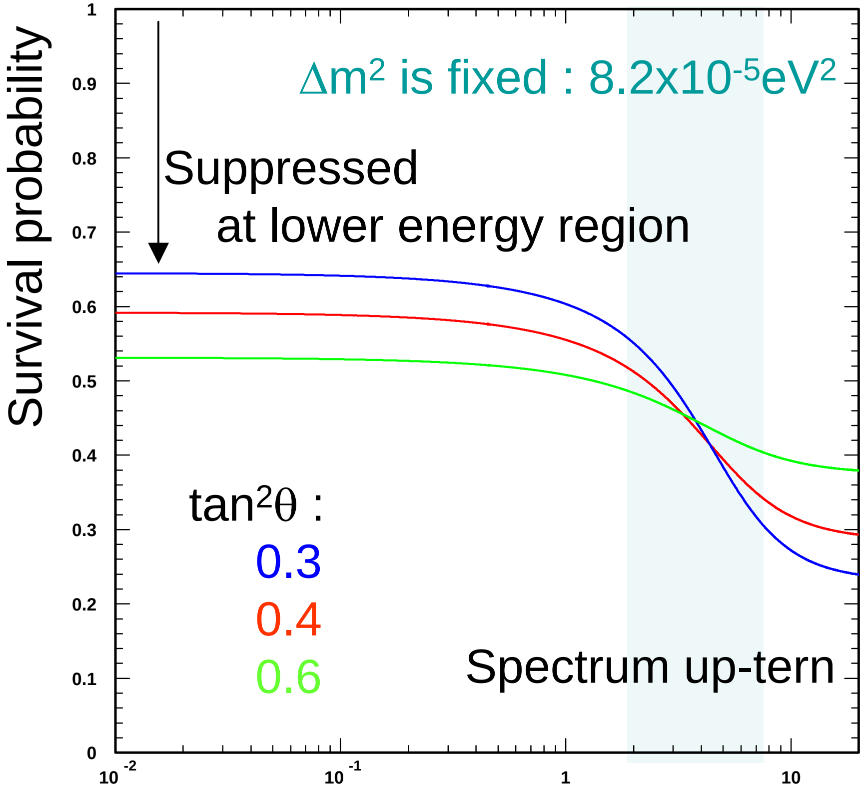
SK

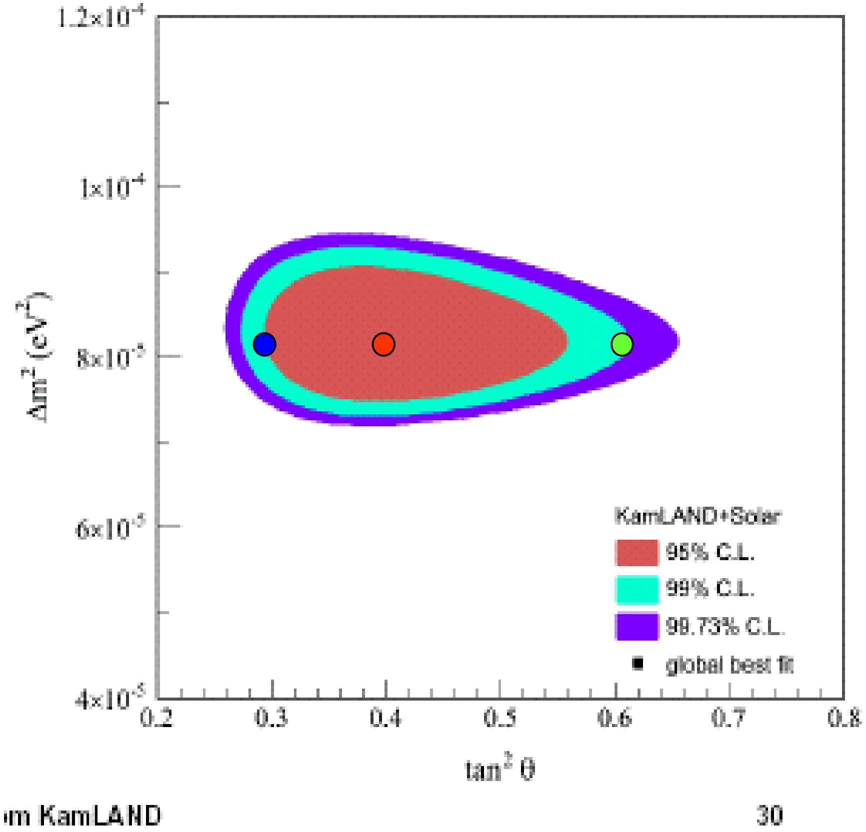


SNO



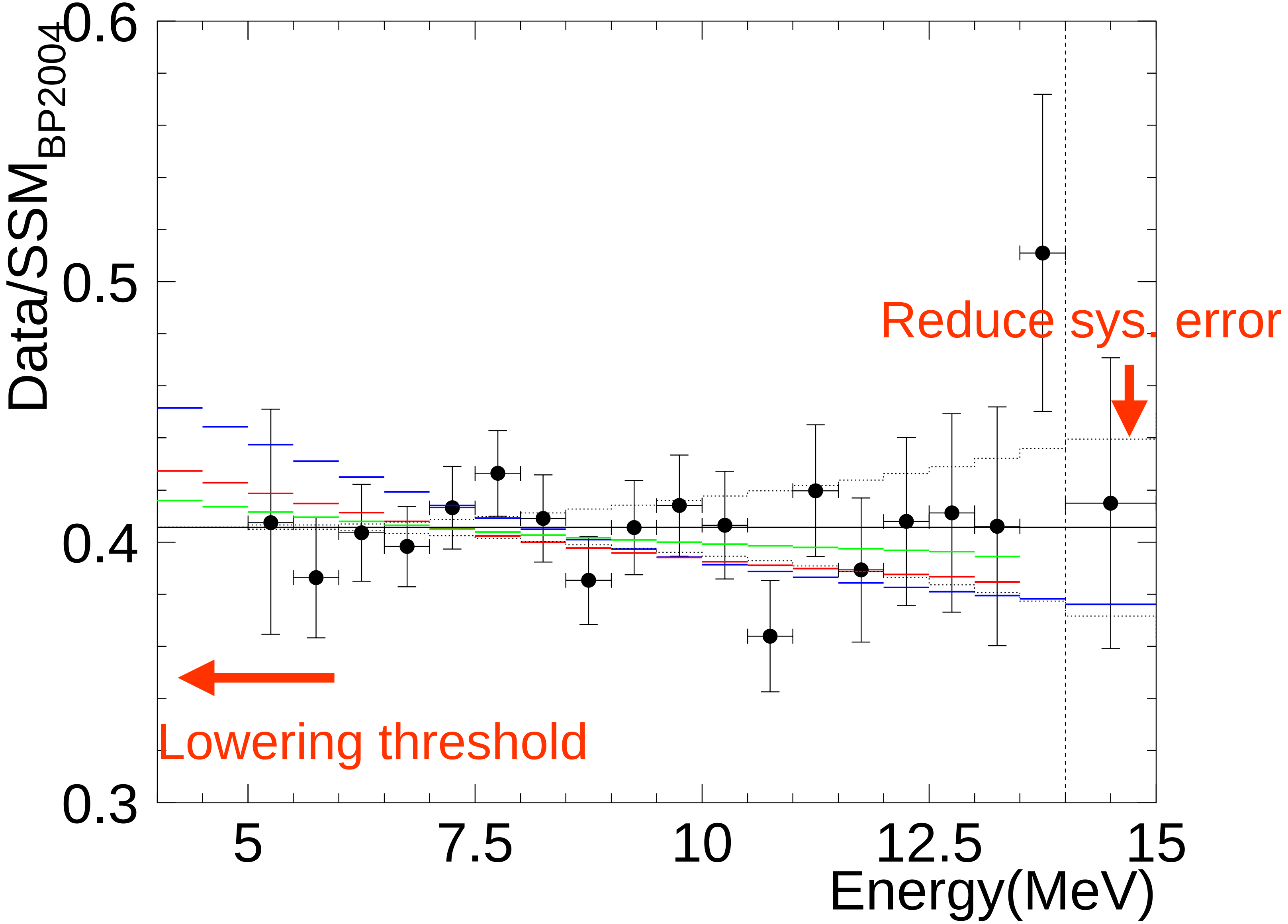
Energy spectrum of solar neutrino





- Spectrum up-tern at sub-MeV region
- pp - ^{7}Be neutrino is suppressed 50~70%

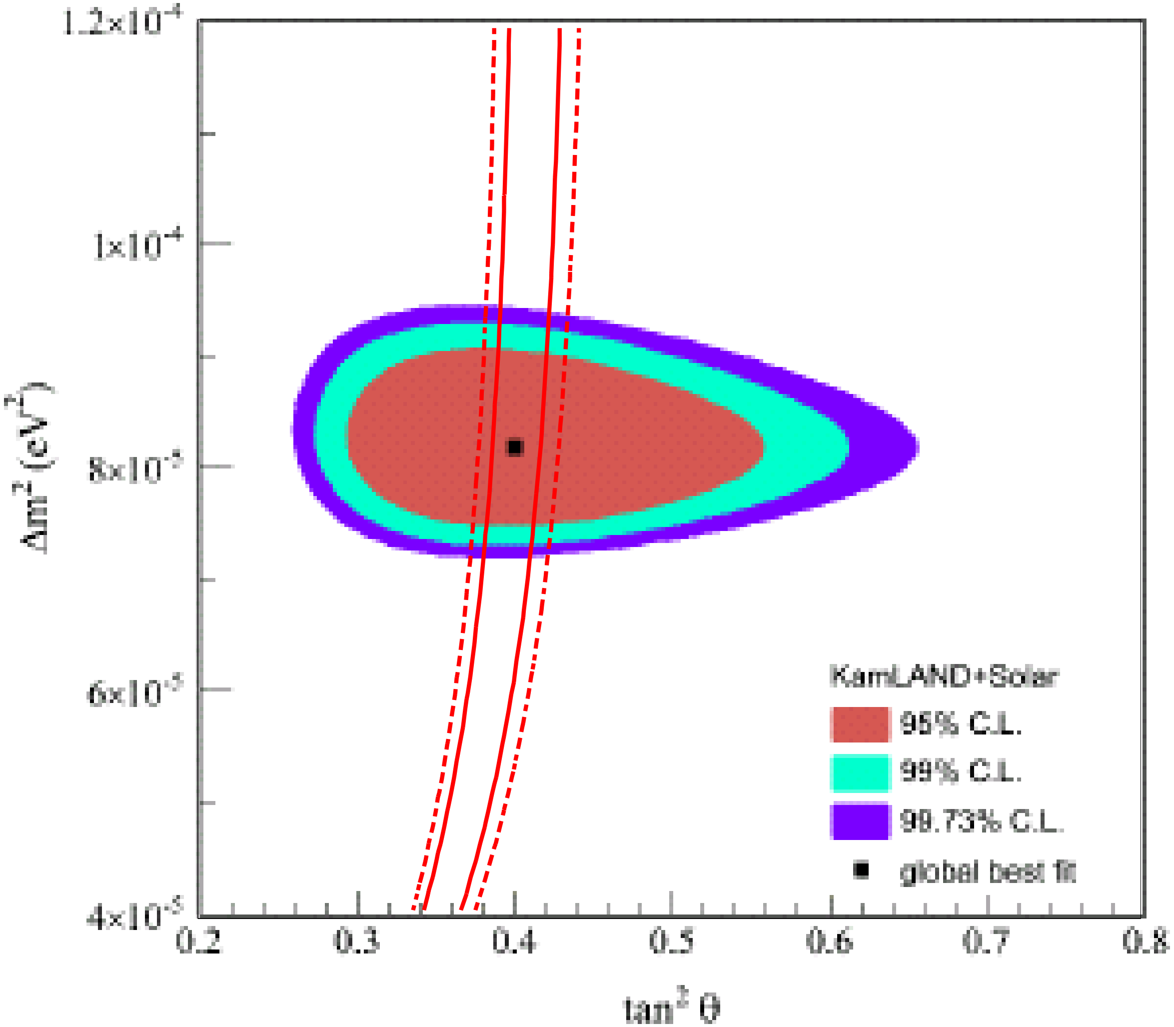
Spectrum at SK



Proposed experiments

- ^{7}Be-experiments
  - [ES] Borexino(LS), KamLAND(LS)
  - [CC] LENS-Sol(ν_e $^{115}In \rightarrow e^- {}^{115}Sn$, e, γ : InL-LS) (also pep, CNO)
  - [CC] Lithium(ν_e $^7Li \rightarrow e^-$ ^7Be: Radio-Chemical)(also pep, CNO)
- pp-(^{7}Be)-experiments
  - [ES] XMASS(Xe), HERON(He), CLEAN(Ne)
  - [CC] MOON(ν_e $^{100}Mo \rightarrow e^- {}^{100}Tc$, β: Mo-foil+Pl.Sci)
- pep & CNO
  - [ES] SNO-scintillator

XMASS



om KamLAND

pp neutrino flux measurement by:

- 10 ton Xe detector
- νe scattering
- 5years
- Statistic + SSM err.