Satellite symposium at TMU, June 11, 1998

Solar Neutrino Observation in Super-Kamiokande

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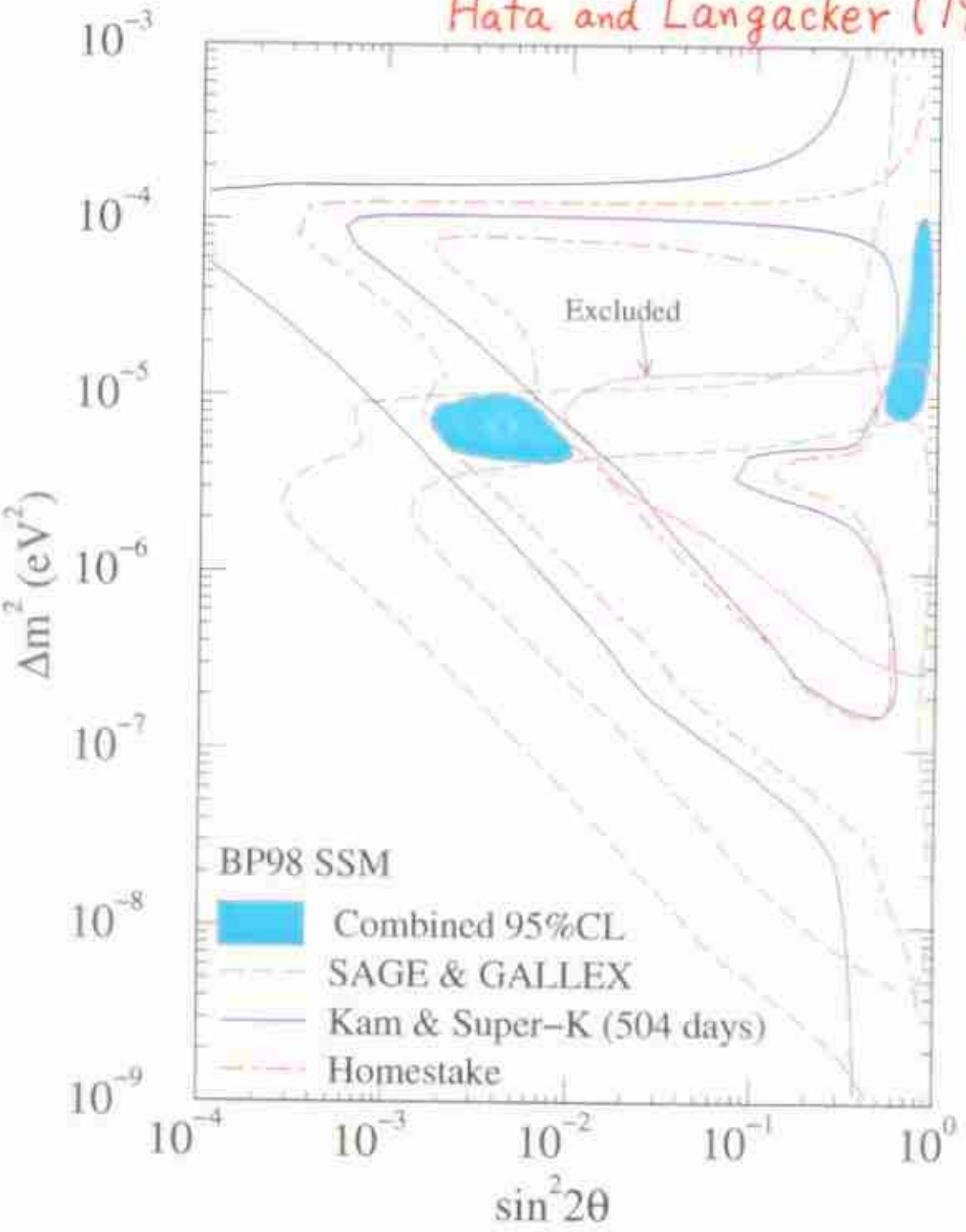
for Super-Kamiokande collaboration

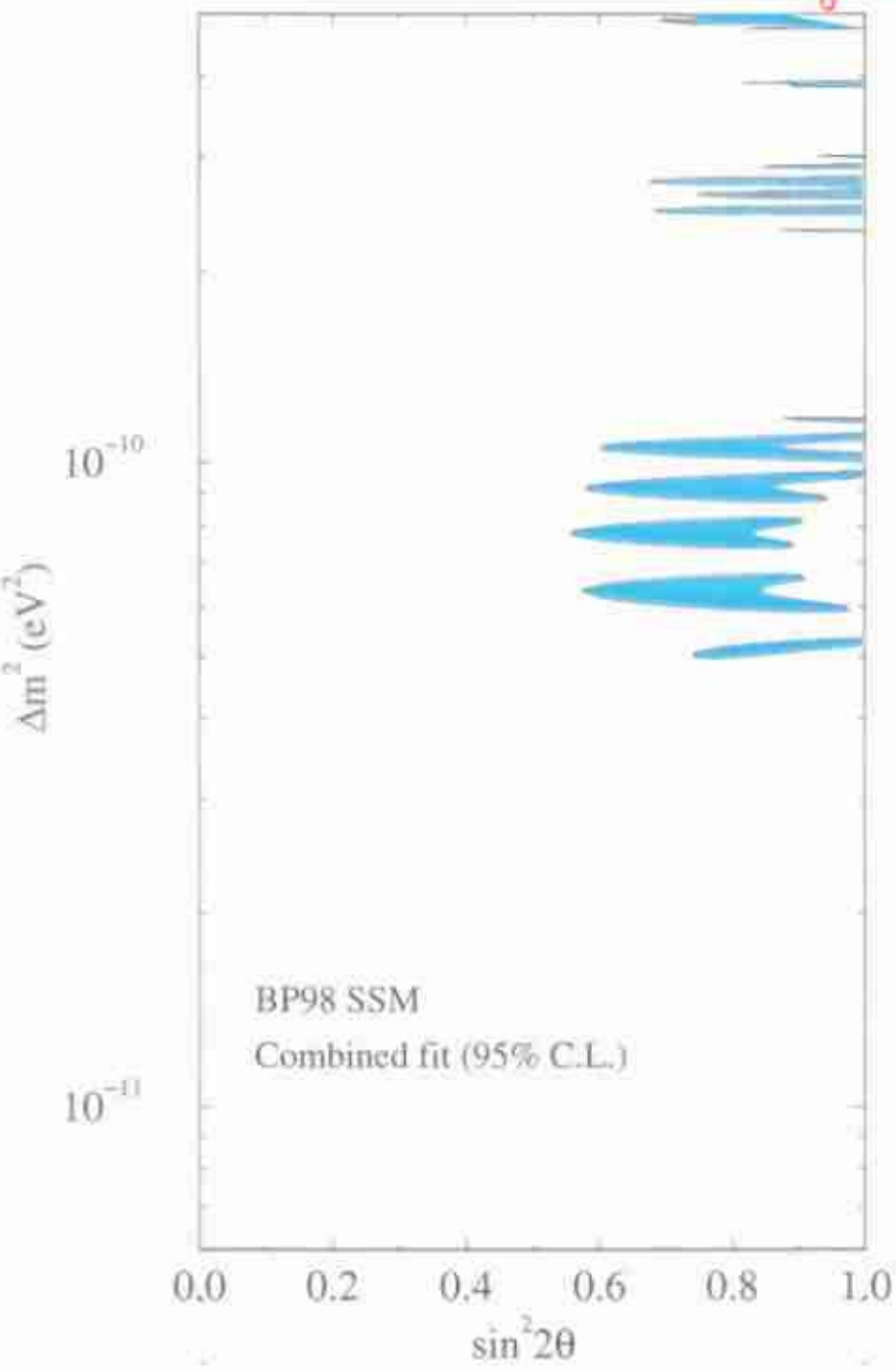
Contents:

- Introduction
- Detector
- Calibration for Solar Neutrino
- Results of 504 days' data
- Neutrino oscillation analysis
- Super Low Energy analysis (< 6.5 MeV)
- Conclusions

Hata and Langacker (1998)

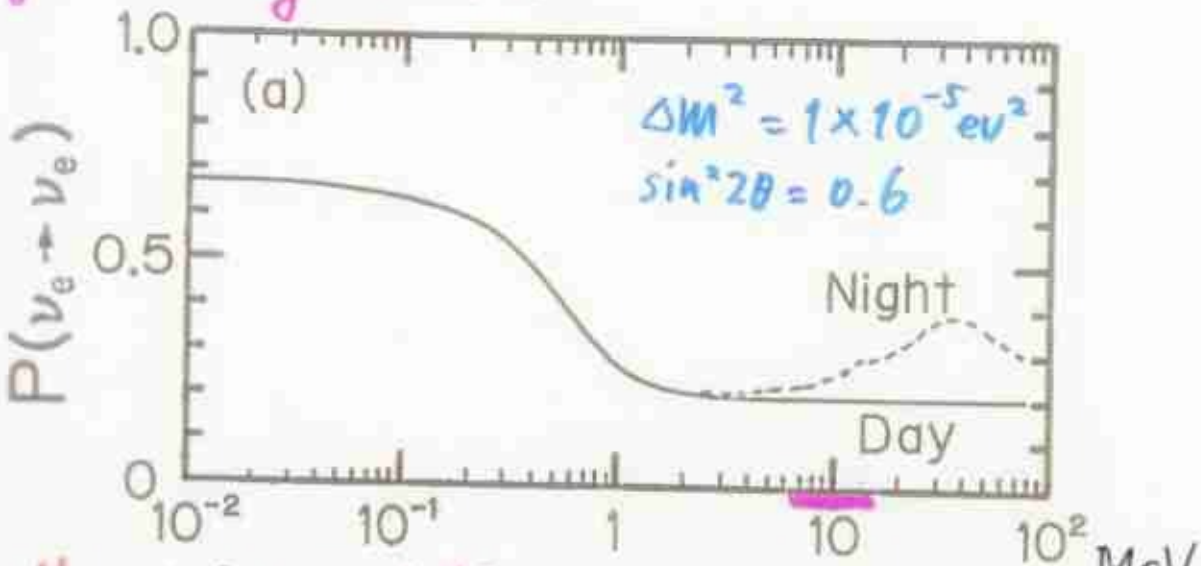


Hata and Langacker(1998)

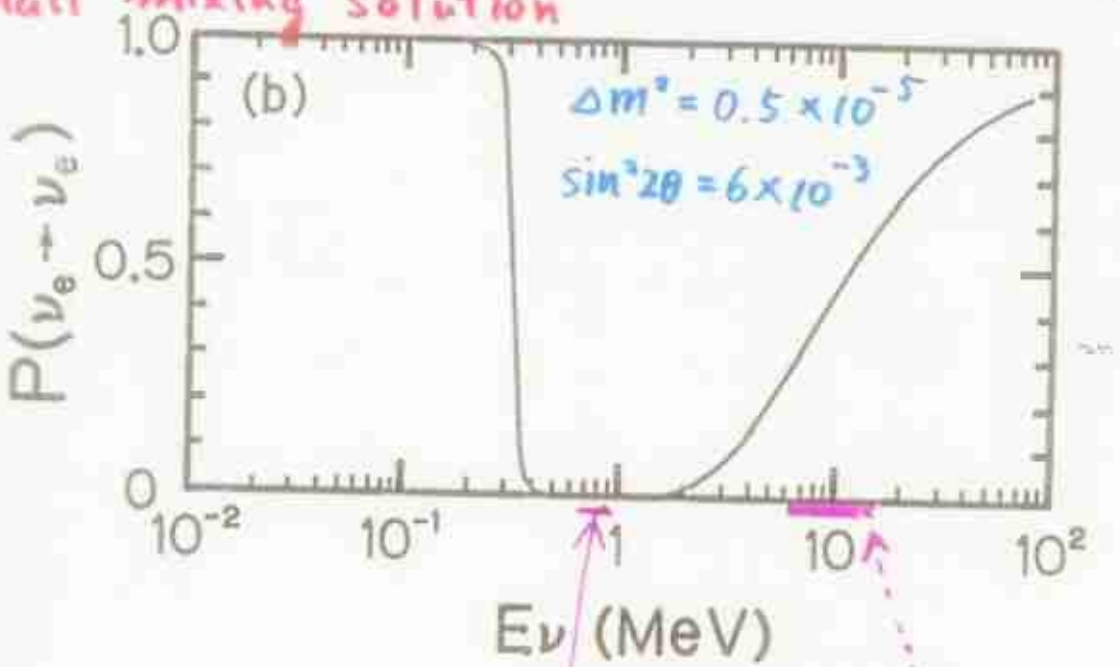


To confirm the MSW solutions.....
: Vacuum

Large mixing solution

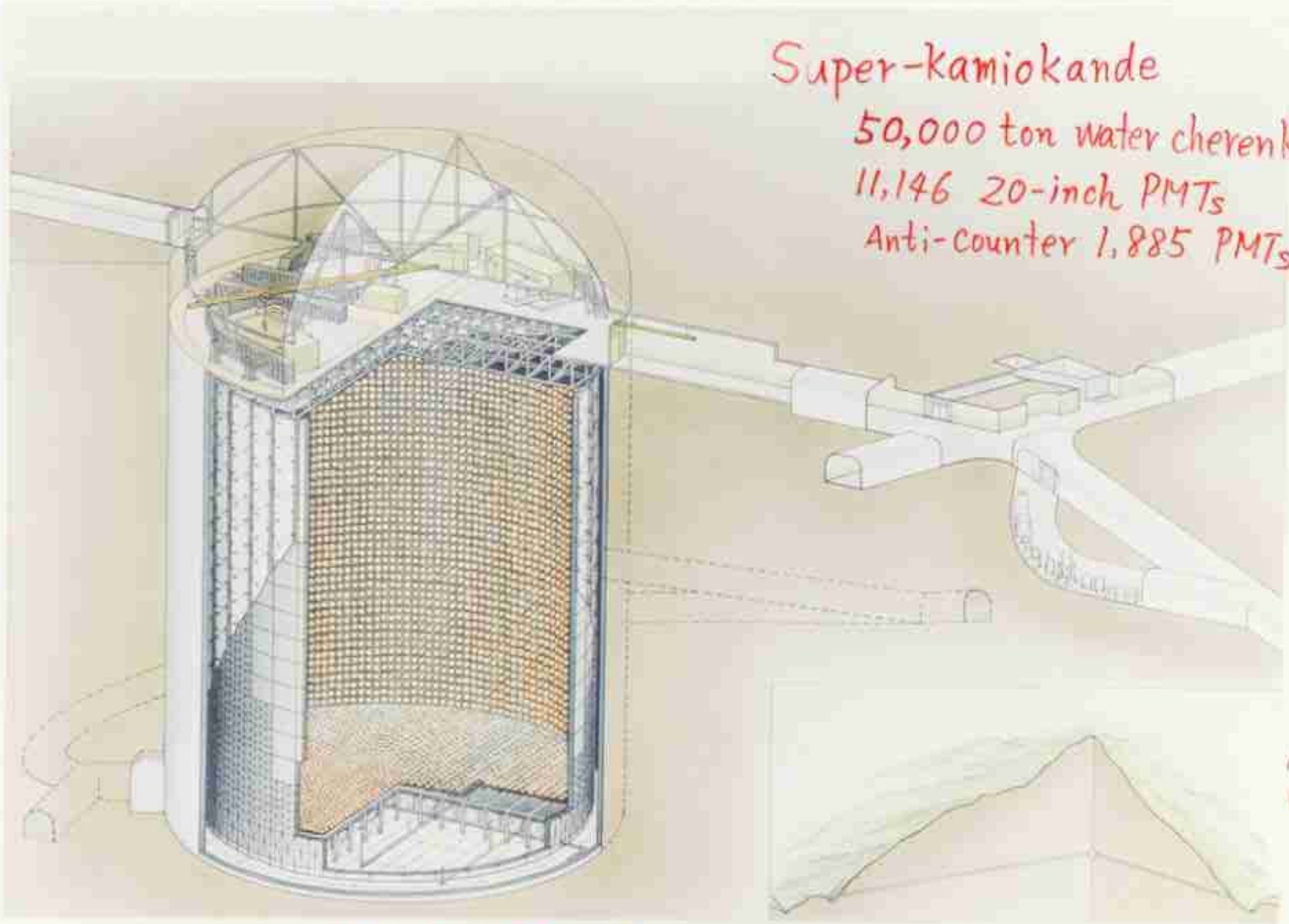


Small mixing solution



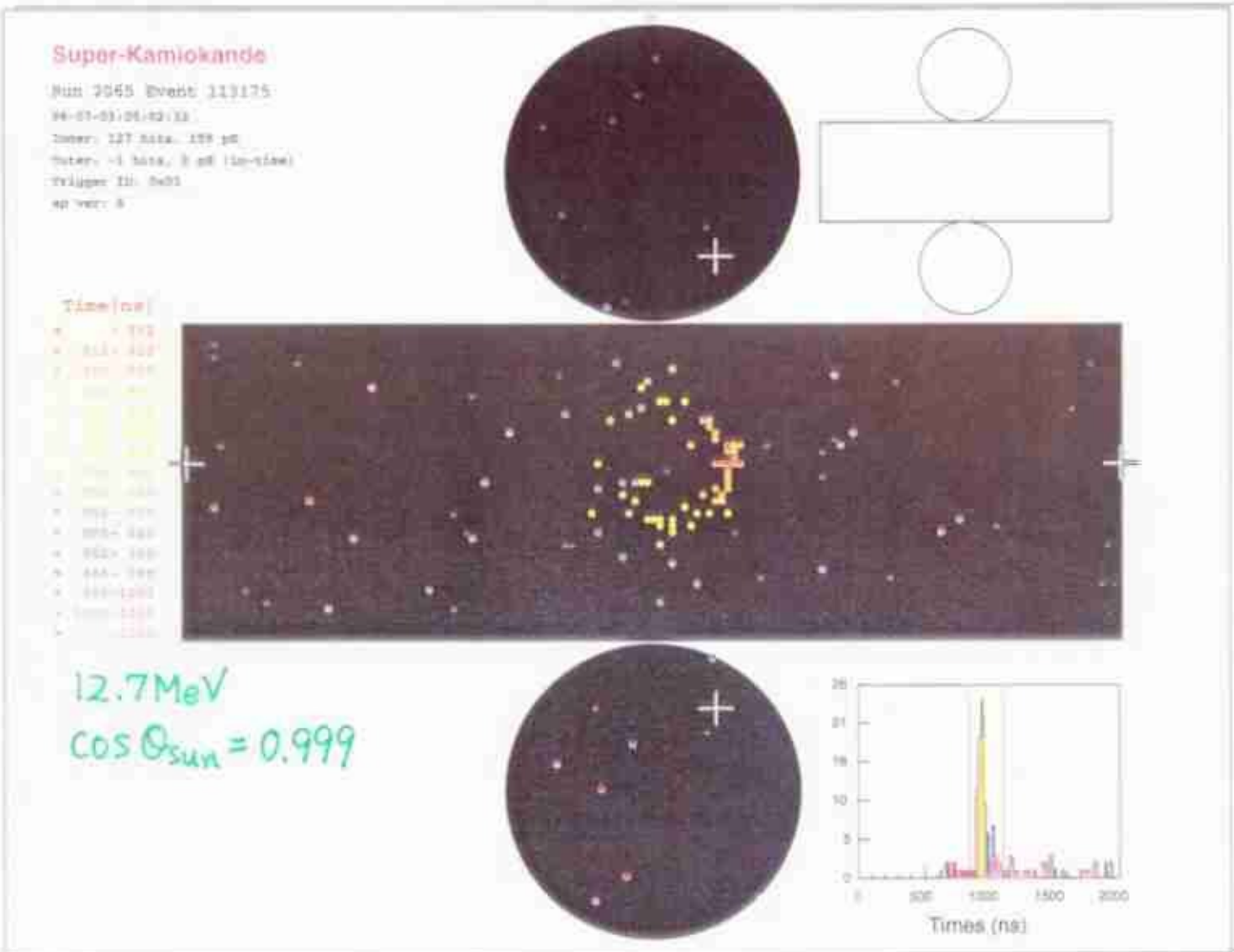
~0 at ^{7}Be

Energy region covered by Super-Kam.


Super-kamiokande
50,000 ton water cherenkov
11,146 20-inch PMTs
Anti-counter 1,885 PMTs
1000 m
underground
41m h x 39m ϕ
SUPERKAMIOKANDE
Data taking April 1996~

Typical low energy event

- Timing information → vertex position
- Ring pattern → Direction
- # of hit PMTs → Energy



12.7MeV

$\cos\theta_{sun} = 0.999$

Detect solar neutrinos by

$\nu + e^- \rightarrow \nu + e^-$ scattering

Trigger

- Low Energy (LE) trigger

  Requires ≧29 PMT hits within 200nsec

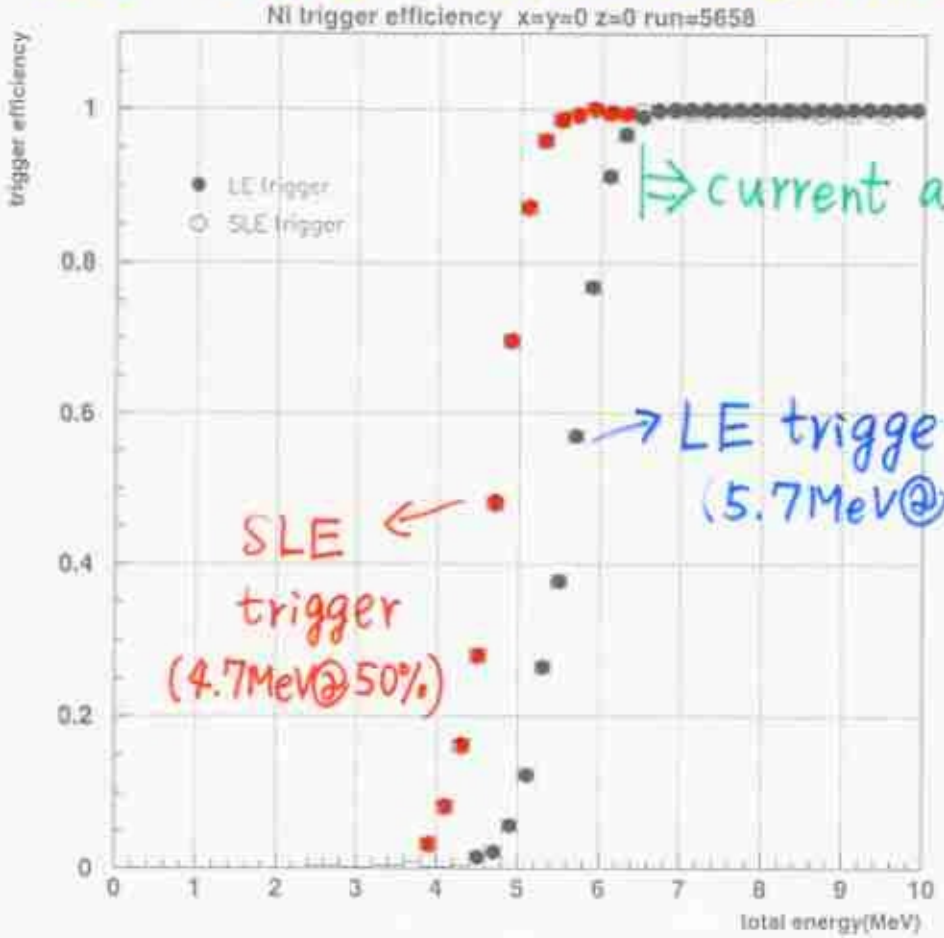
  (Effective energy threshold : ~5.7 MeV)

  Rate ~ 12 Hz

- Super Low Energy (SLE) trigger: since May 29,'97

  ≧ 24 PMT hits (i.e. lowered by 19%)

  Rate ~ 100Hz ⇒ online vertex cut by software ⇒ ~4.1 Hz



⇒ current analysis : >99%

→ LE trigger (5.7MeV@50%)

SLE trigger (4.7MeV@50%) ←

↑ trigger efficiency measured by $^{Ni}(n,\gamma)^{Ni}$ calibration source

Calibration for Solar Neutrino

(1) Electron LINAC

Mono-energetic beam covering 5-16 MeV
Collimated beam (good for calibration of angular resolution)
Position dependence of energy scale

(2) Ni(n,γ)Ni source

upto 9 MeV gamma-ray source
1-2% uncertainty in the absolute energy
Used for checking detector stability

(3) μ -> e decay electron

~1500 events/day
Monitor water transparency
Check stability of the detector

(4) ^{16}N events (produced by μ capture by ^{16}O)

~18 events/day
Cross-check absolute energy calibration

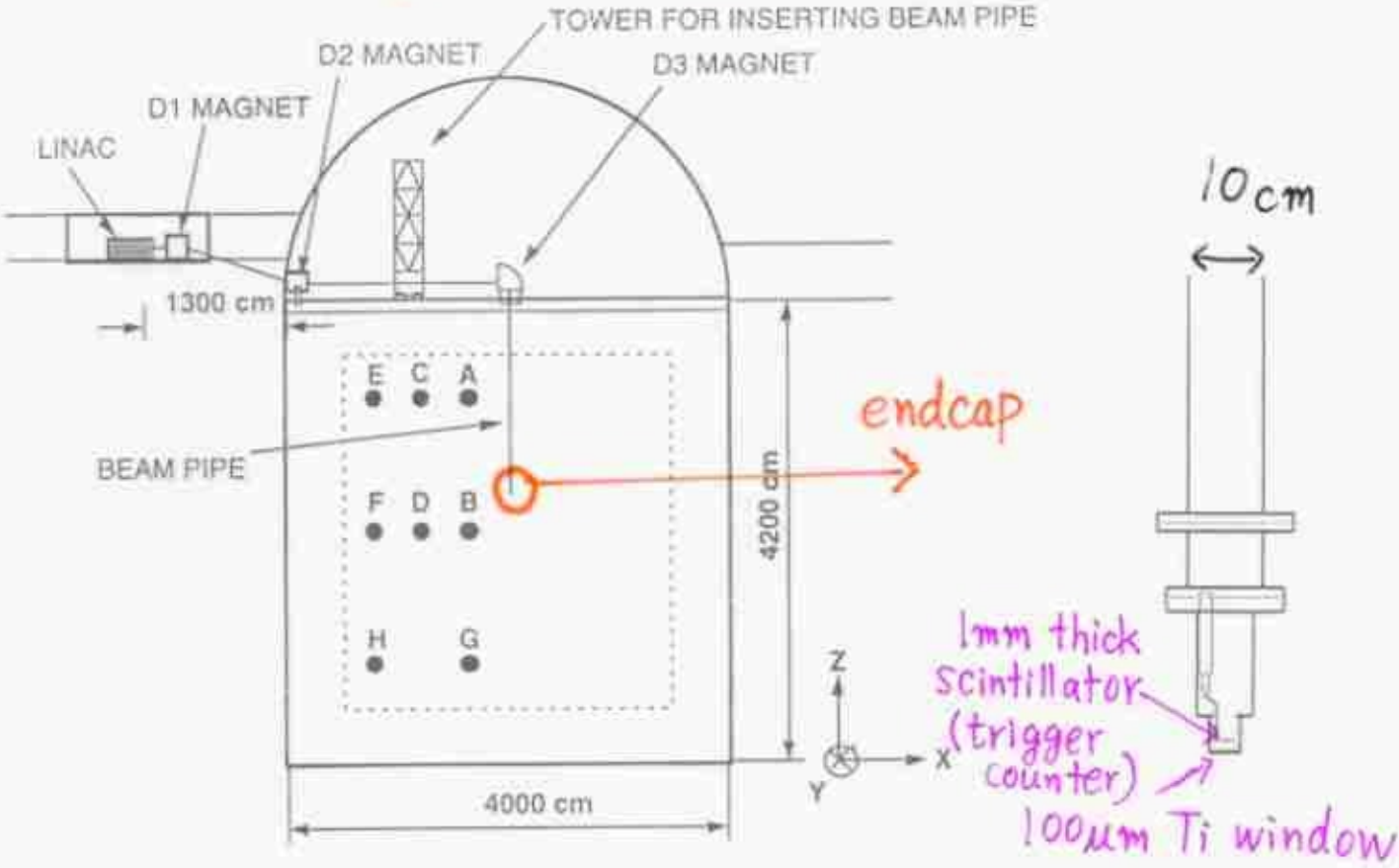
(5) Spallation products

~600 events/day
Check angle dependence of absolute energy scale
Cross-check detector stability

LINAC calibration

Calibrate

- Absolute energy scale
- Energy resolution
- Angular resolution
- Vertex resolution



Systematic LINAC data were taken at 8 positions with $E_{beam} = 5 \sim 16$ MeV (at 7 energy points).

- Beam energy spread : < 0.5% FWHM.
- Event rate : ~ 0.1 e/pulse, pulse frequency : 66Hz

* Energy of the beam is measured by Ge detector. Ge is calibrated by using γ sources and electrons from ^{207}Bi.

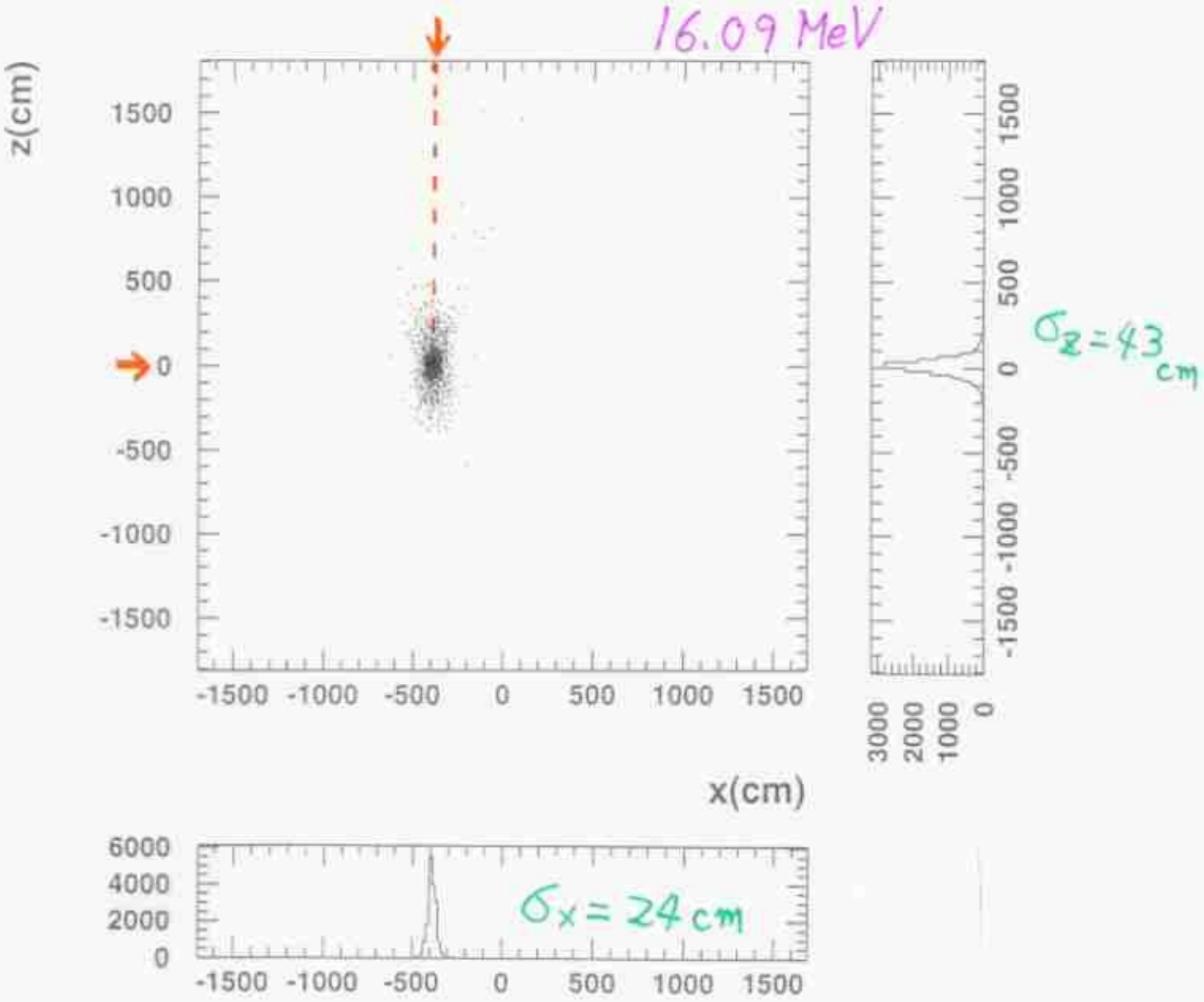
LINAC beam line

On the 5k tank

↑
90° magnet

Reconstructed Vertex position

LINAC data @ X = −3.88 m, Z = 0.27 m

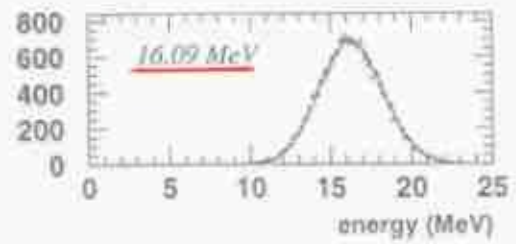


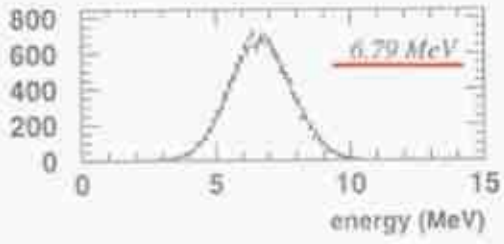
Energy Distributions

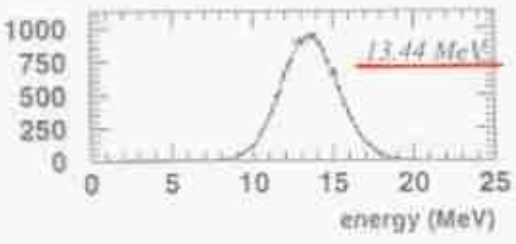
LINAC data @ X = -12m, Z = +12m

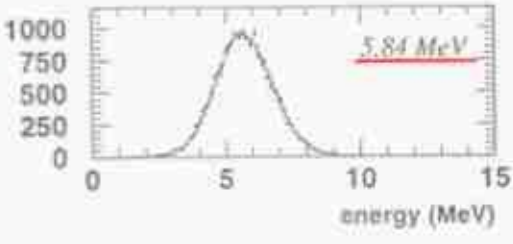
† Data

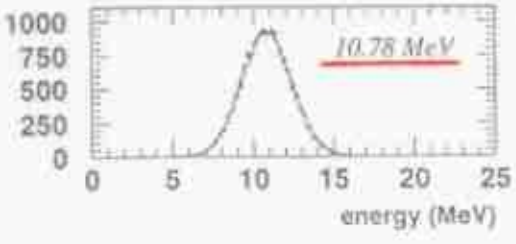
↯ Monte Carlo

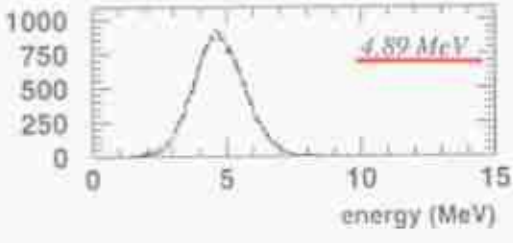


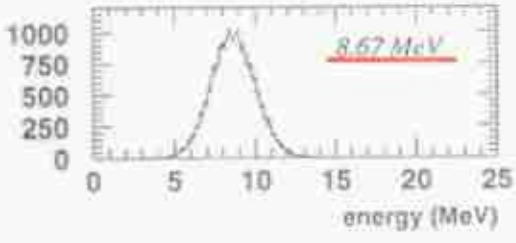








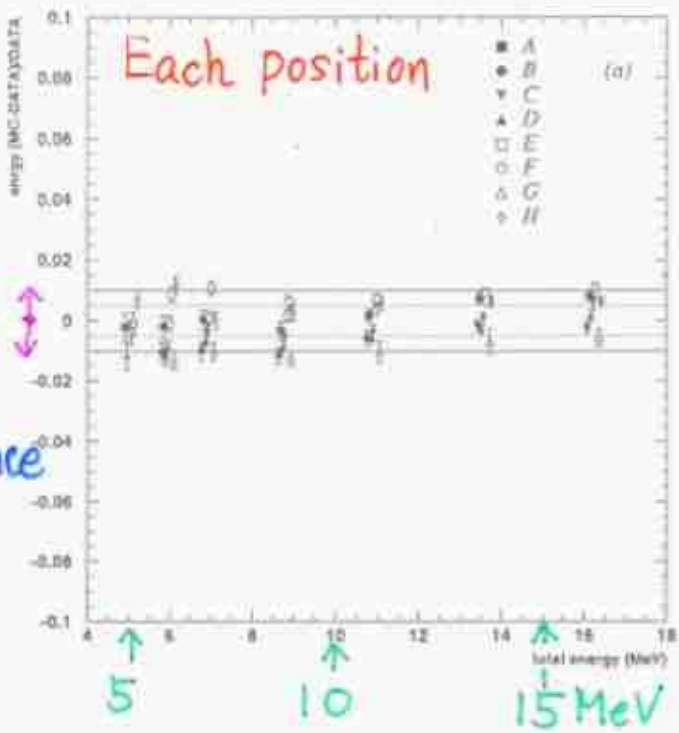




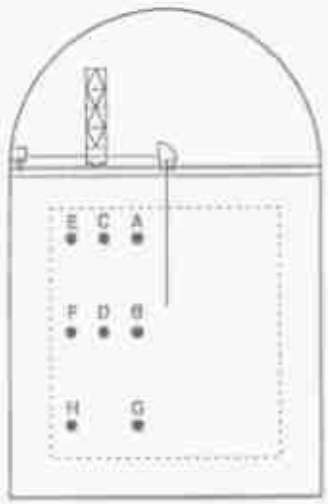
Energy scale difference

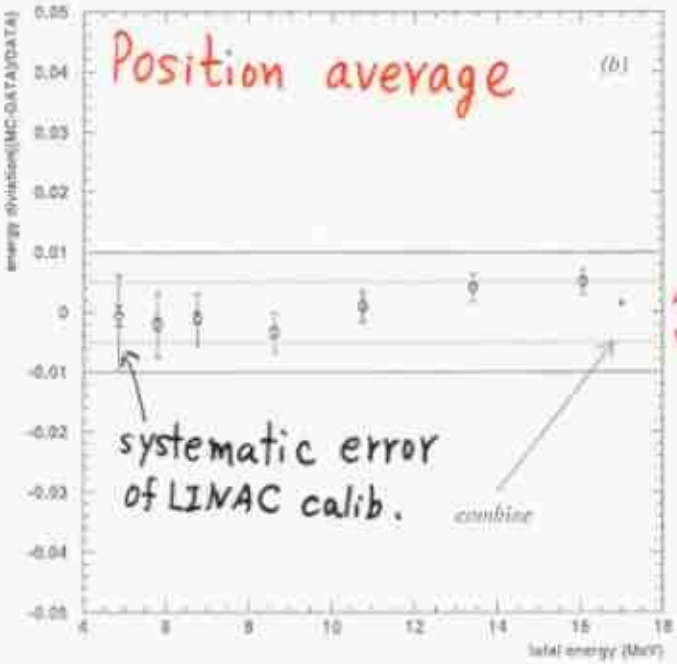
(Peak position of LINAC energy distributions compared between Data and M.C.)

$\frac{(MC-Data)}{Data}$



Position dependence
~± 0.5%

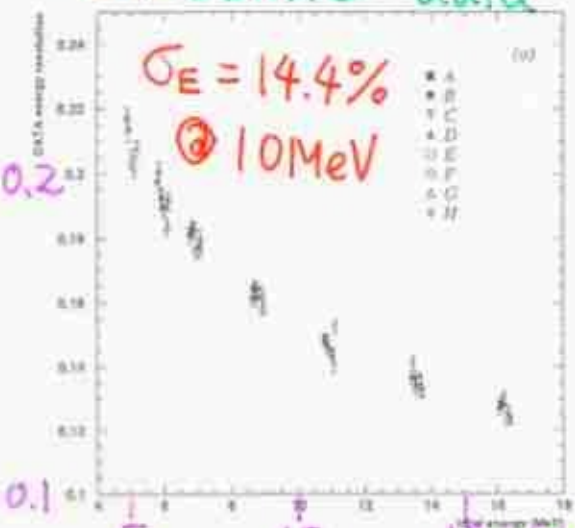




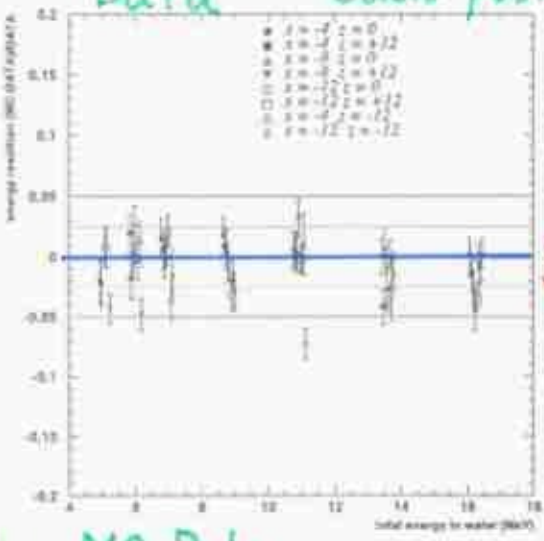
Energy dependence of absolute energy scale is less than 0.5%.

Energy Resolution ($\sigma_E = \frac{\Delta E}{E_{peak}}$)

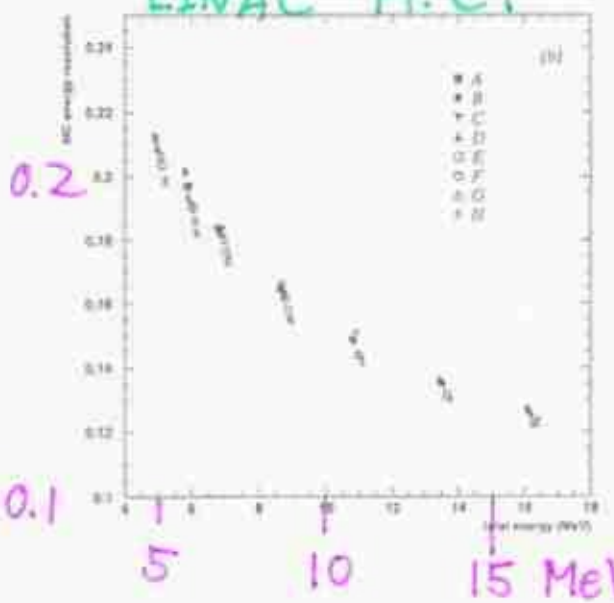
LINAC data



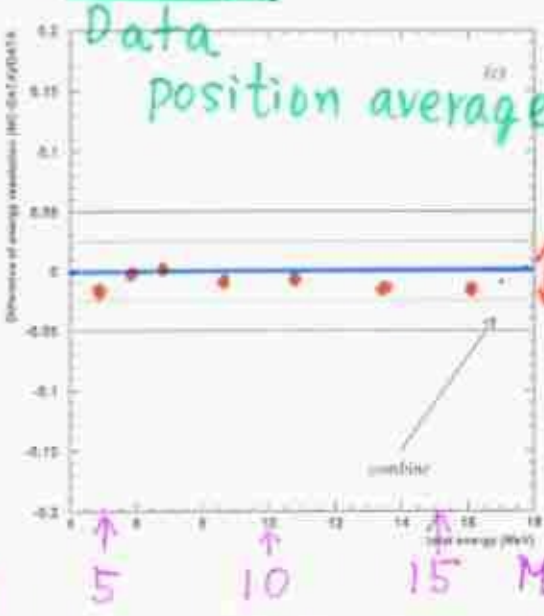
MC-Data / Data each position



LINAC M.C.



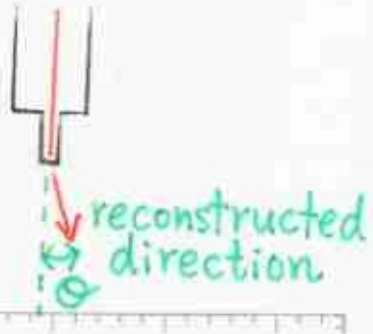
MC-Data / Data position average



σ_E of data and M.C. agree to each other within 2%.

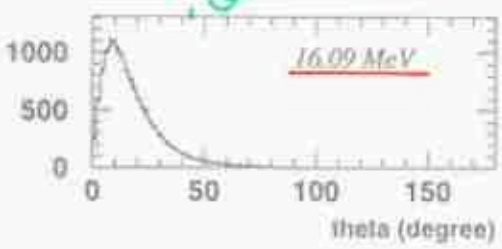
Angular distributions

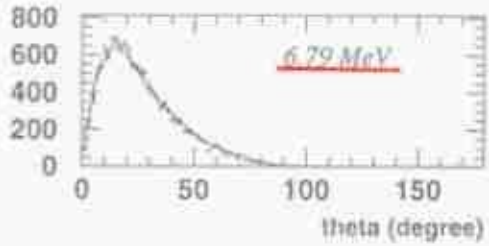
LINAC data @ X = -12m, Z = +12m

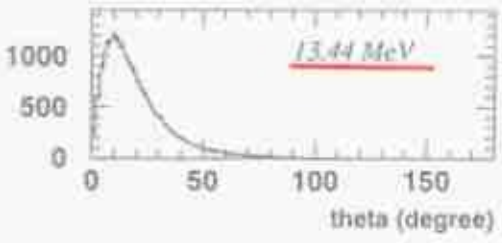


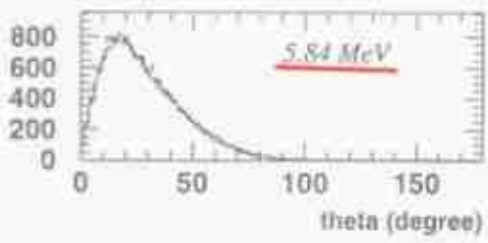
+ Data

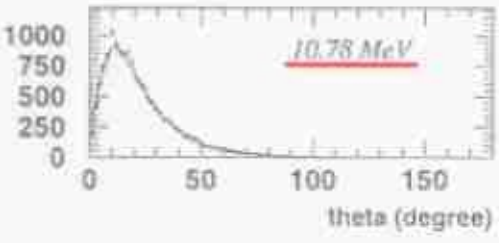
~ Monte Carlo

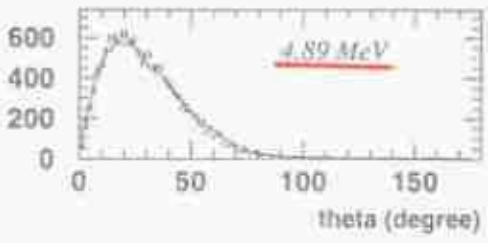


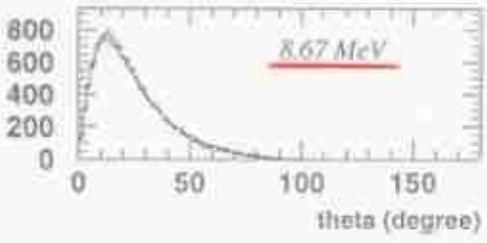




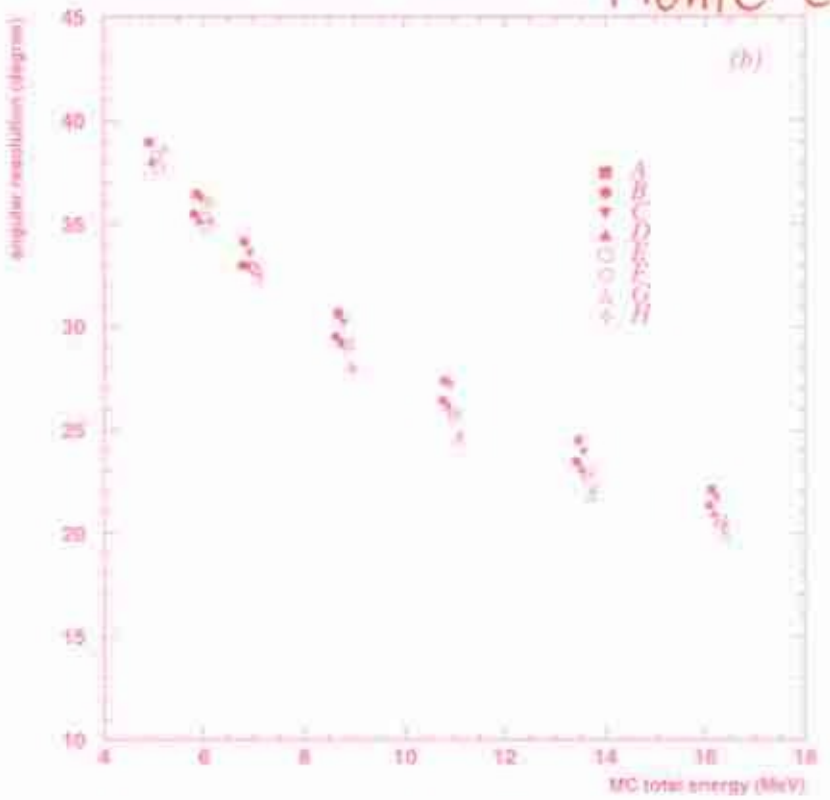






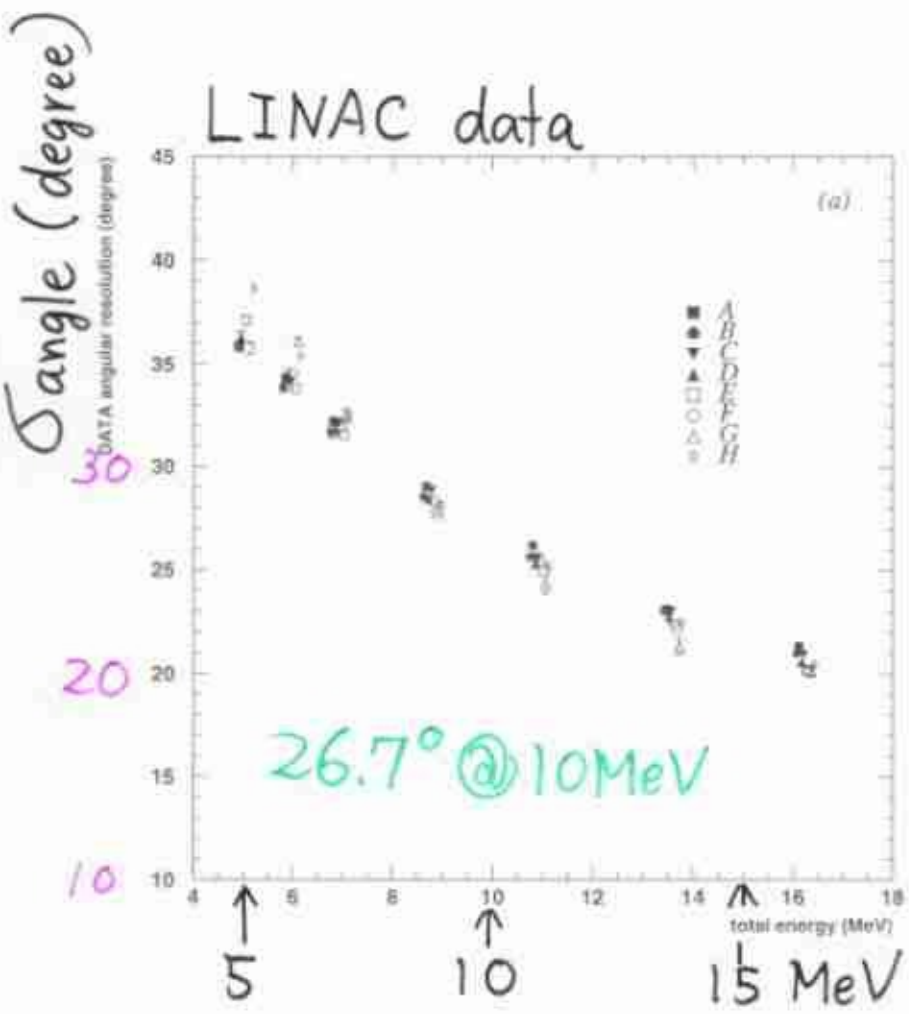


Monte Carlo



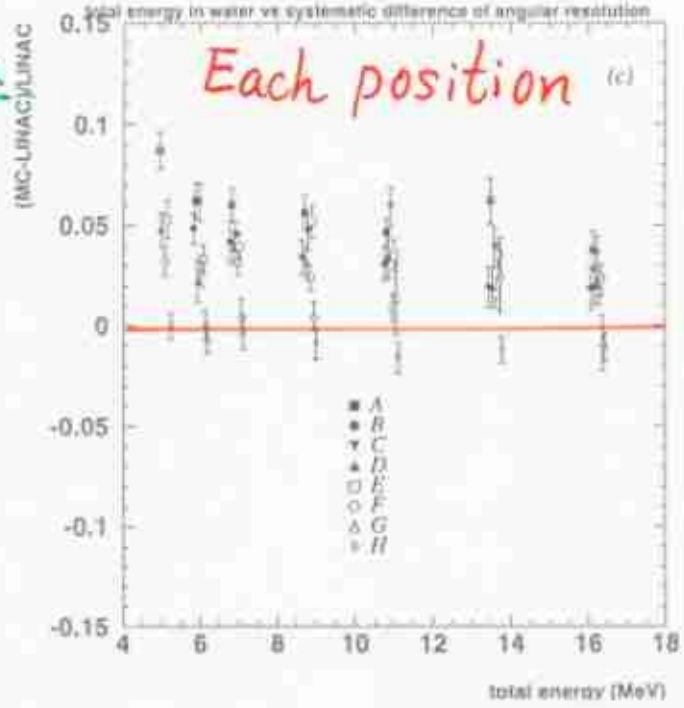
σ_{angle} of data is slightly smaller than Monte Carlo.

Angular resolution (σ_{angle})

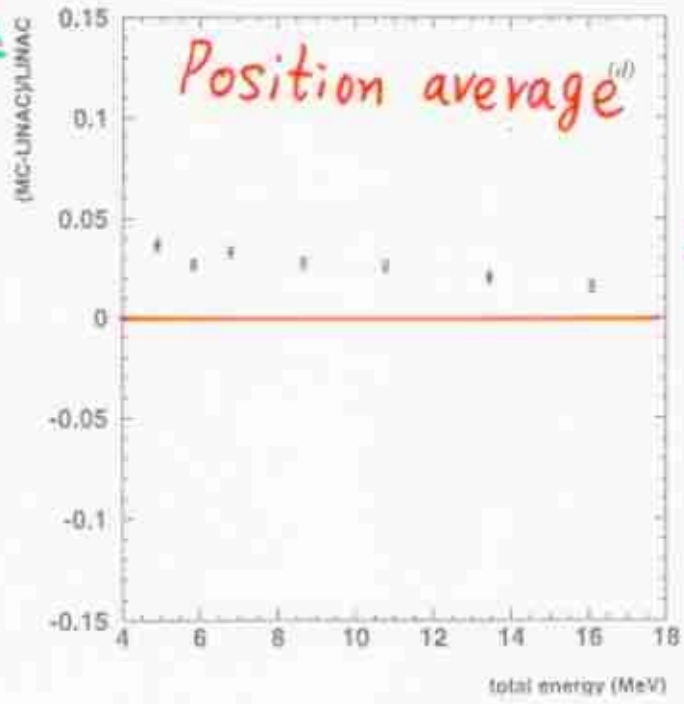


Difference of angular Resolution

MC-Data / Data



MC-Data / Data



2~3% difference.

The difference is corrected in the Solar neutrino analysis and the full size of the correction is put into the systematic error.

SPALLATION

Many of cosmic ray muons (total ~3Hz at SK) undergo nuclear interactions that lead to spallations.

$$\mu + {}^{16}O \longrightarrow \mu + X + {}^{12}B \quad (\beta @ 13MeV,\ \tau_{1/2}=20ms)$$

$${}^{8}B \quad (\beta @ 14MeV,\ \tau_{1/2}=0.8s)$$

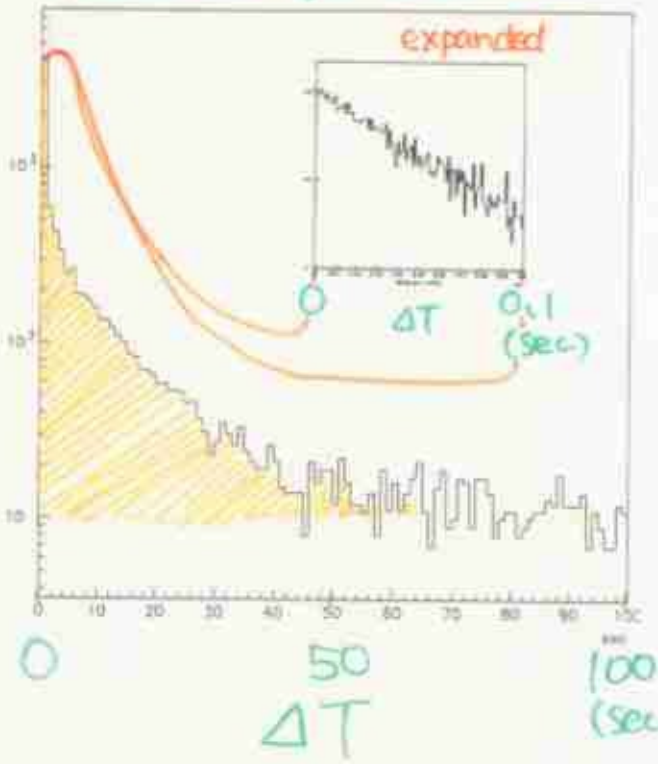
$${}^{16}N \quad (\beta @ 10MeV,\ \tau_{1/2}=7s)$$

$$\cdots\cdots$$

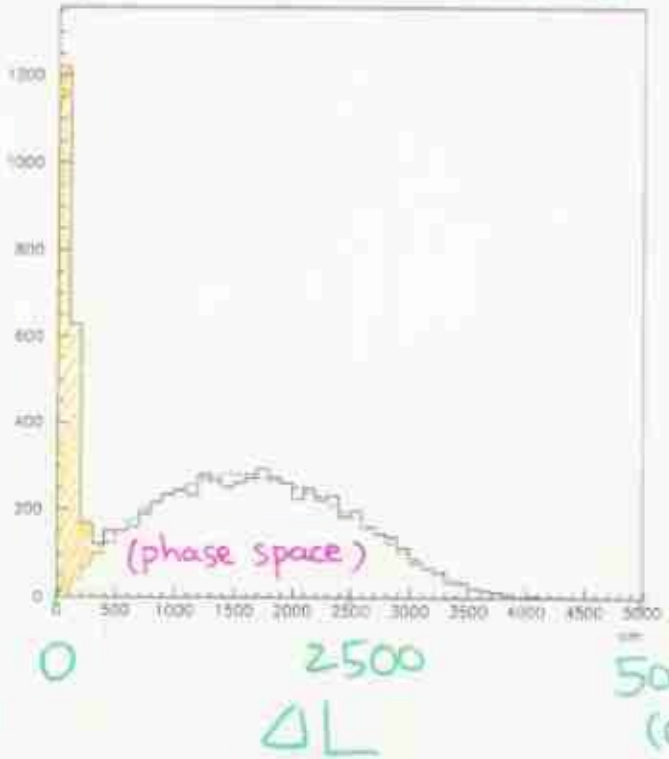
- Residual Q of muons
- ΔT, and ΔL with muons

➡ **SPALLATION CUT**

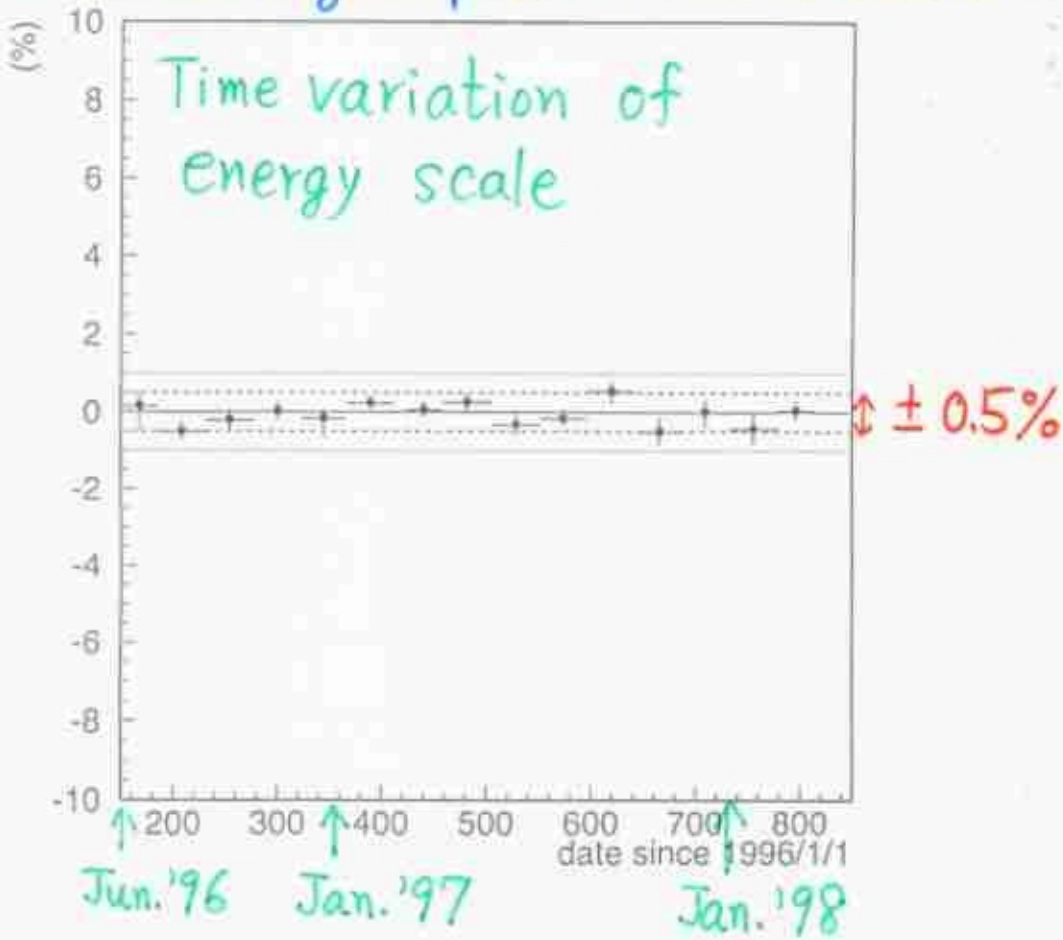
FAST DECAYS following μ with high Qres

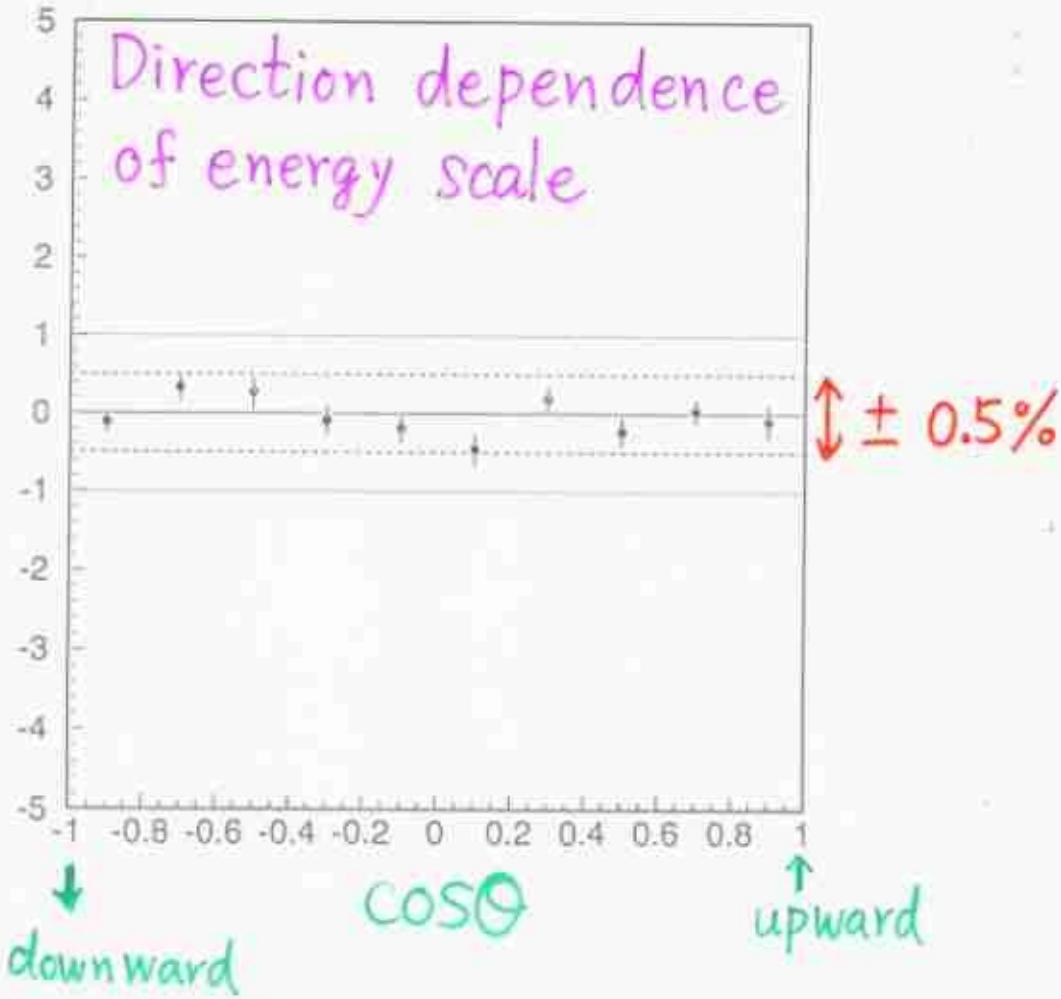


Clustered vertices after μ with moderate Qres



Calibration using Spallation events





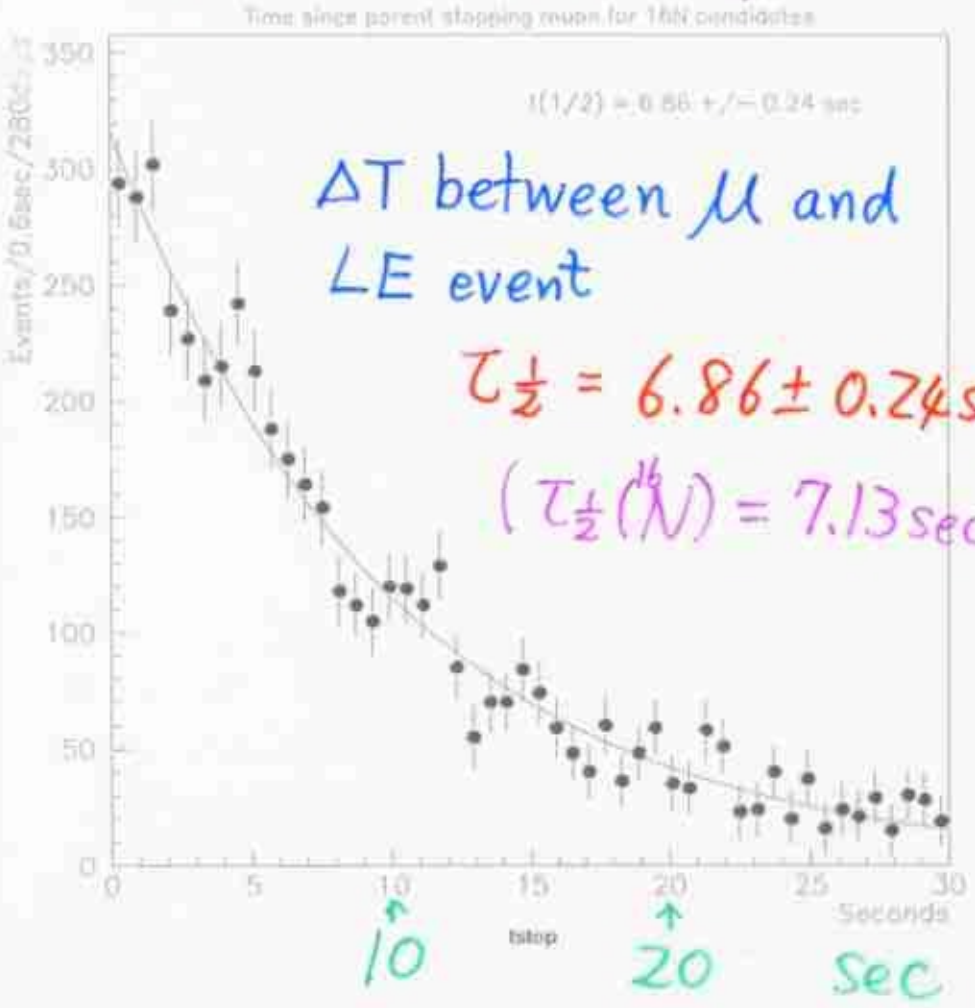
^{16}N calibration

$\mu^- + {}^{16}O \rightarrow \nu_\mu + {}^{16}N$

${}^{16}N \rightarrow {}^{16}O + e^- + (\gamma)$

- 66.2% 6.13MeV γ + 4.29MeV β^-
- 28.0% 10.42MeV β^-
- 4.8% 7.12MeV γ + 3.30MeV β^-
- ⋮

Uncertainty is less than 0.1%



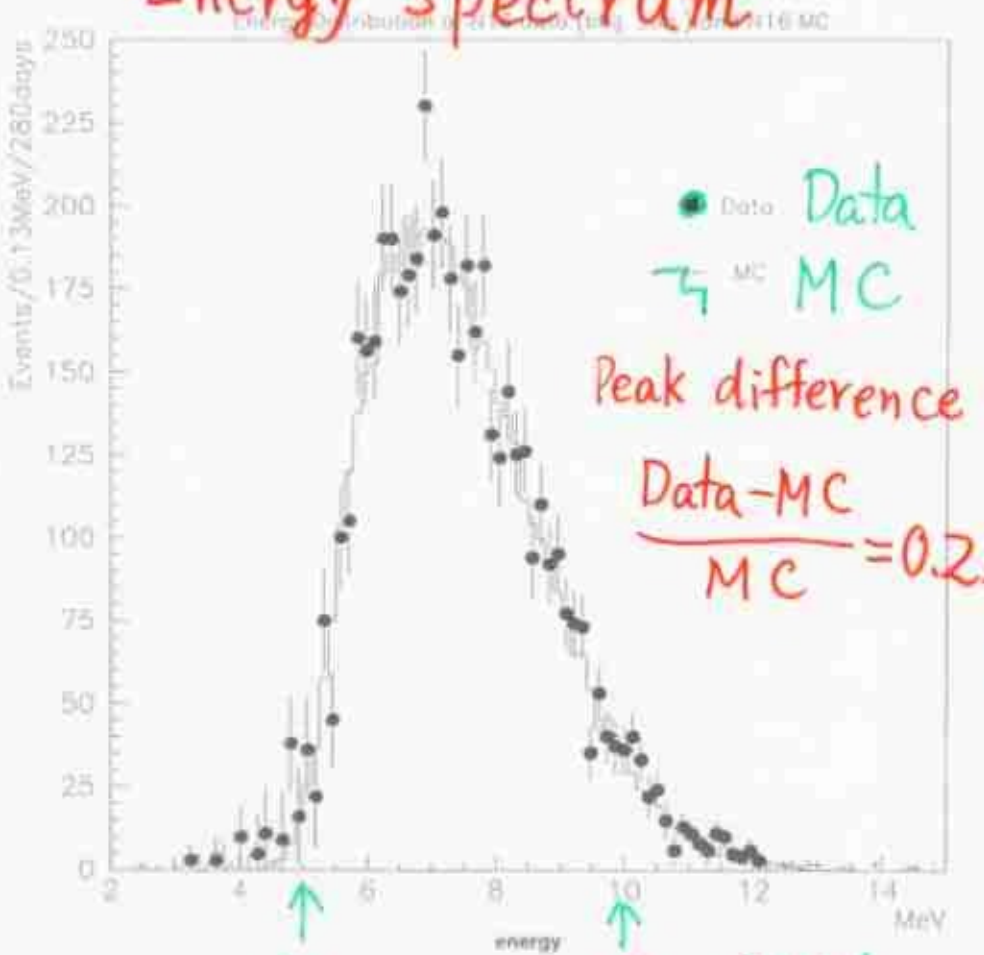
ΔT between μ and LE event

$\tau_{\frac{1}{2}} = 6.86 \pm 0.24$ sec

($\tau_{\frac{1}{2}}(^{16}N) = 7.13$ sec)

10 20 sec

Energy Spectrum



Data Data

MC MC

Peak difference

$\frac{\text{Data} - \text{MC}}{\text{MC}} = 0.2 \pm^{0.6}_{0.8}$ %

5 10 MeV

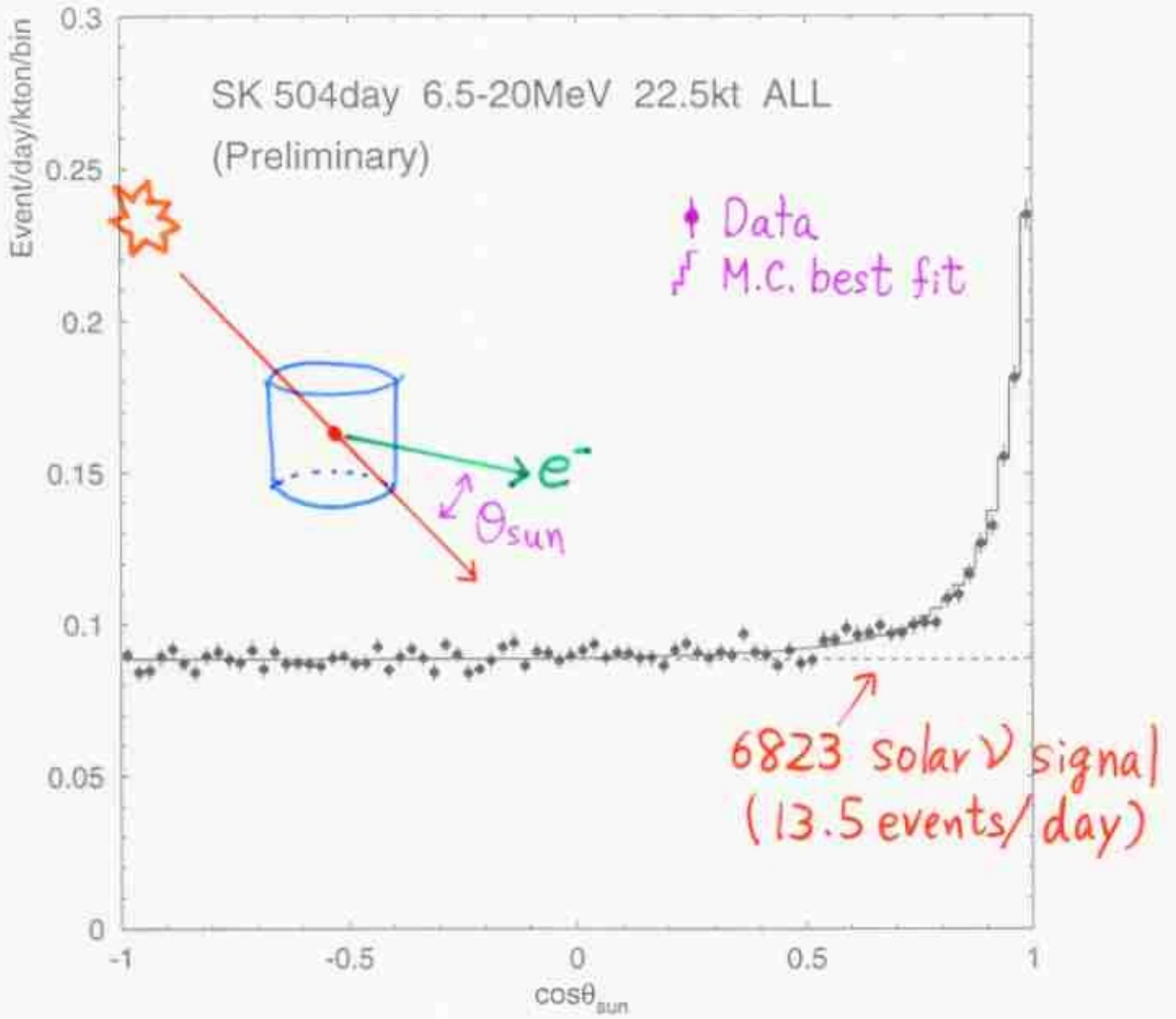
LOW-ENERGY DATA REDUCTION

- MAY 31,1996 ~ MAR 25, 1998
- Live time 504 day

		Number of events	
RAW DATA		~7×10^8	8.19×10^6
FIRST REDUCTION	Total charge < 1000 p.e.	5.03×10^8	(1.06×10^5)
	Time to prev. event > 20μs	4.27×10^8	
	Event status flag	4.21×10^8	
	Outer detector hits < 20	3.91×10^8	
	Noise event cut 1	3.90×10^8	
	Flash PMT events cut	3.88×10^8	(1.06×10^6)
VERTEX RECONSTRUCTION			
SECOND REDUCTION	Very low-energy events cut	3.86×10^8	
	Goodness of fitting cut	3.84×10^8	
	Pre-cut (1.5m, ~5.0MeV)	2.12×10^7	(1.05×10^6)
	Noise event cut 2	8.64×10^6	(1.00×10^6)
SPALLATION CUT			(20% dead time)
	Fid. vol. cut (2m, 22.5kt)	4.33×10^6	
	Bad run cut	3.91×10^6	
	Energy cut (6.5-20MeV)	126277	
GAMMA CUT			(7.8% dead time)
	Noise event cut 3	90070	(0.15% dead time)
	Eye-scan, $\Delta T > 50\mu s$	87209	
FINAL DATA SAMPLE		**22.5kt, 6.5-20MeV**	
		87051	

( ) ... M.C. 22.5kt, 6.5-20MeV

Direction to the Sun



^8B flux : $2.44 \pm 0.05 \pm {}^{0.09}_{0.07}$ [$\times 10^6$ /cm²/sec]

Data/SSM (BP95): $0.368 \pm {}^{0.008}_{0.007} \pm {}^{0.013}_{0.011}$

Data/SSM (BP98): $0.474 \pm {}^{0.010}_{0.009} \pm {}^{0.017}_{0.014}$

Systematic Errors

for 22.5 kton,
6.5-20MeV sample

(in %)

	Flux	Seasonal	D/N	Spectrum
Energy Scale & Resolution	+2.2 −2.1	+1.2 −1.1	+1.2 −1.1	correlated errors see figure
^{8}B spectrum error	+1.2 −1.1	−	−	
Trigger Efficiency	+0.2	+0.2	−	6.5–7:+1.2 7– : 0
Noise event Cut	±0.7	−	−	±0.7
Direction	+2.2	−	−	±1.0
Reduction	±0.2	−	±0.1	±0.2
non-flat B.G.	±0.1	±0.1	±0.4	±0.1
Spallation Dead Time	±0.2	±0.6	±0.6	−
Vertex Shift	−1.3	−	−	±1.0
Cross Section	±0.5	−	−	±0.5
Live Time	±0.1	±0.1	±0.1	−
Total	+3.5 −2.9	+1.4 −1.3	+1.4 −1.3	see figure

Solar Neutrino Flux

Result of 504 days' data :

$2.44 \pm 0.05(\text{stat})\ {}^{+0.09}_{-0.07}(\text{sys})\ [10^6/\text{cm}^2/\text{sec}]$

SSM predictions :

$6.62\ [10^6/\text{cm}^2/\text{sec}]$ (BP95; Rev. Mod. Phys.67(1995)781)

$5.15\ [10^6/\text{cm}^2/\text{sec}]$ (BP98; astro-ph/9805135)

Data/SSM :

$0.368\ {}^{+0.015}_{-0.013}$ (stat & sys) (BP95)

$0.474\ {}^{+0.019}_{-0.017}$ (stat & sys) (BP98)

Assuming energy independent ν_e <-> $\nu_\mu(\nu_\tau)$ oscillations, estimate ν_e flux using SSM predictions :

$$f(\nu_e) + (1-f(\nu_e)) \times \frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e)} = \text{Data/SSM}$$

$\frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e)} \sim \frac{1}{5.6}$

Estimate ν_e flux

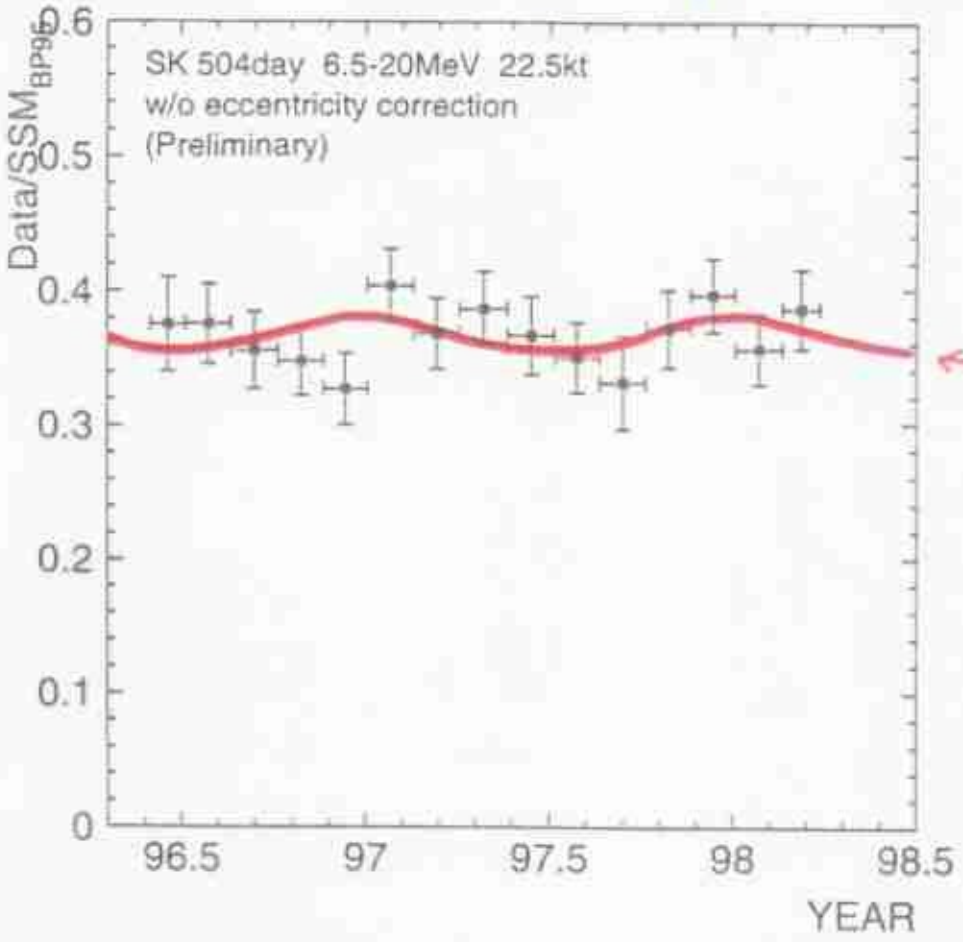
$f(\nu_e) = 0.232$ (BP95) (63% of total)

$f(\nu_e) = 0.360$ (BP98) (76% of total)

Error of SuperK is small enough to discuss the difference between $f(\nu_{\text{total}})$ and $f(\nu_e)$. 8.66 (5.76) difference. (Sk error only.)

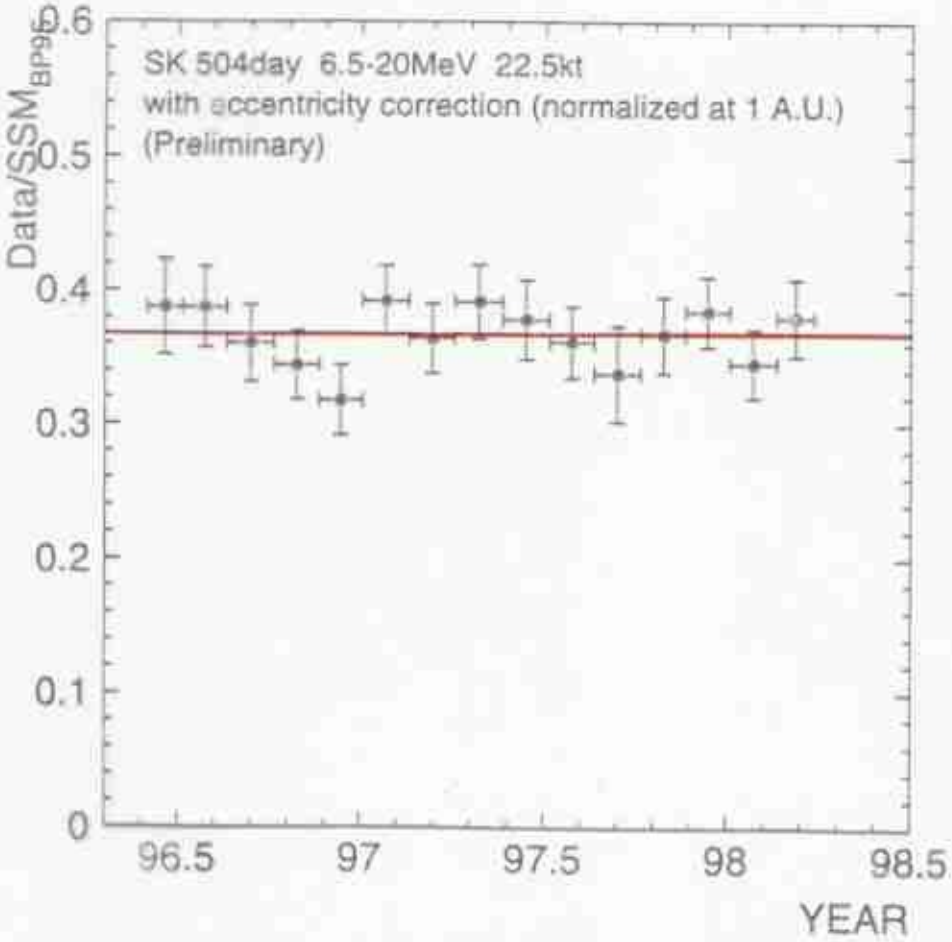
Quite interesting to see CC result of SNO

Flux in every ~1.5 month period

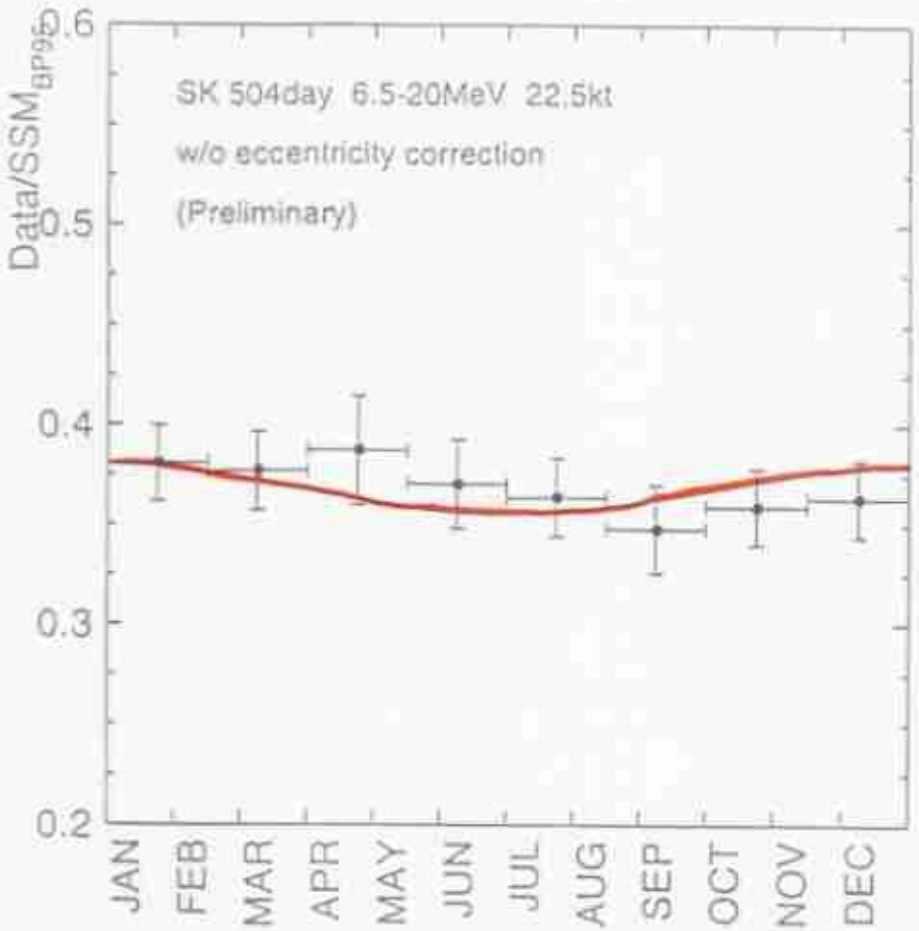


← expected flux variation due to the eccentricity of the earth.

$\chi^2 = 8.78/14$
(84.4% C.L.)

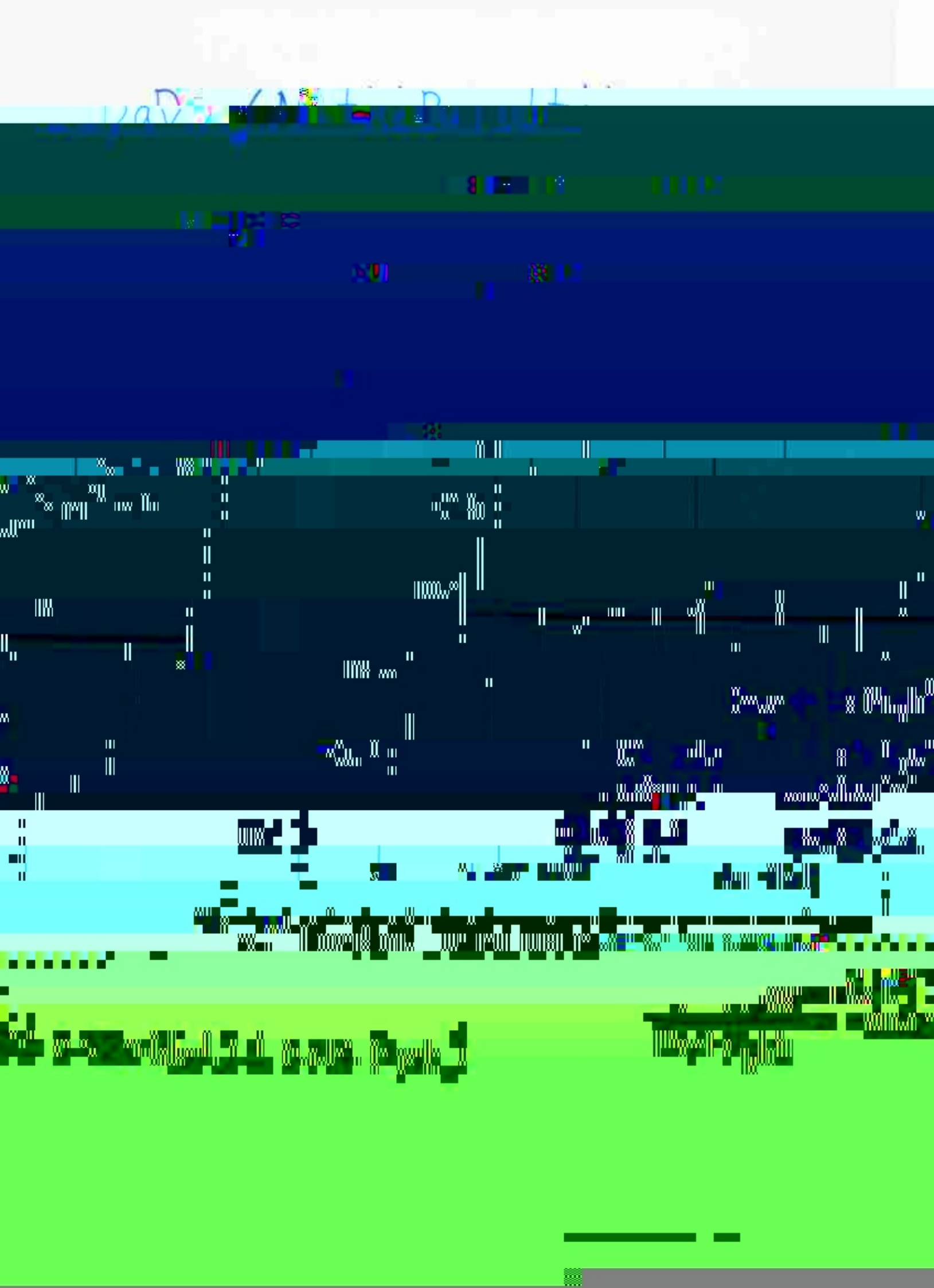


Seasonal variation



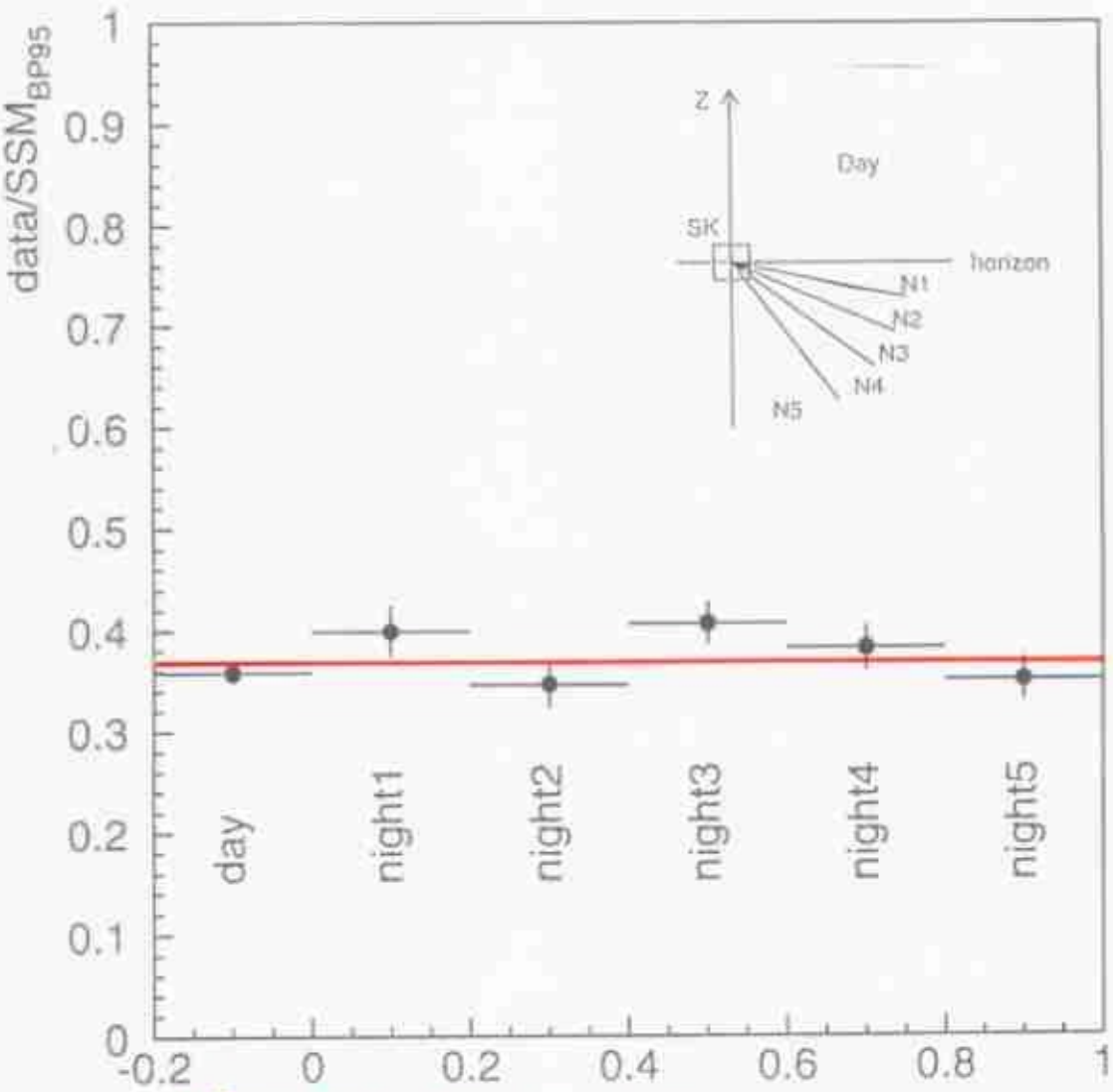
$\chi^2 = 3.36/7$

85.0% C.L.

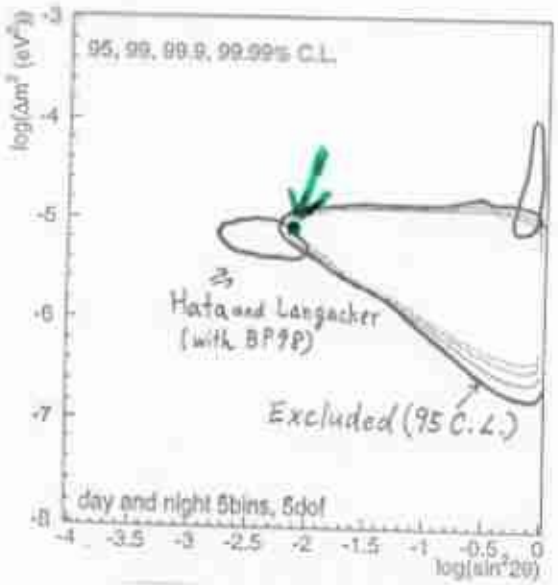


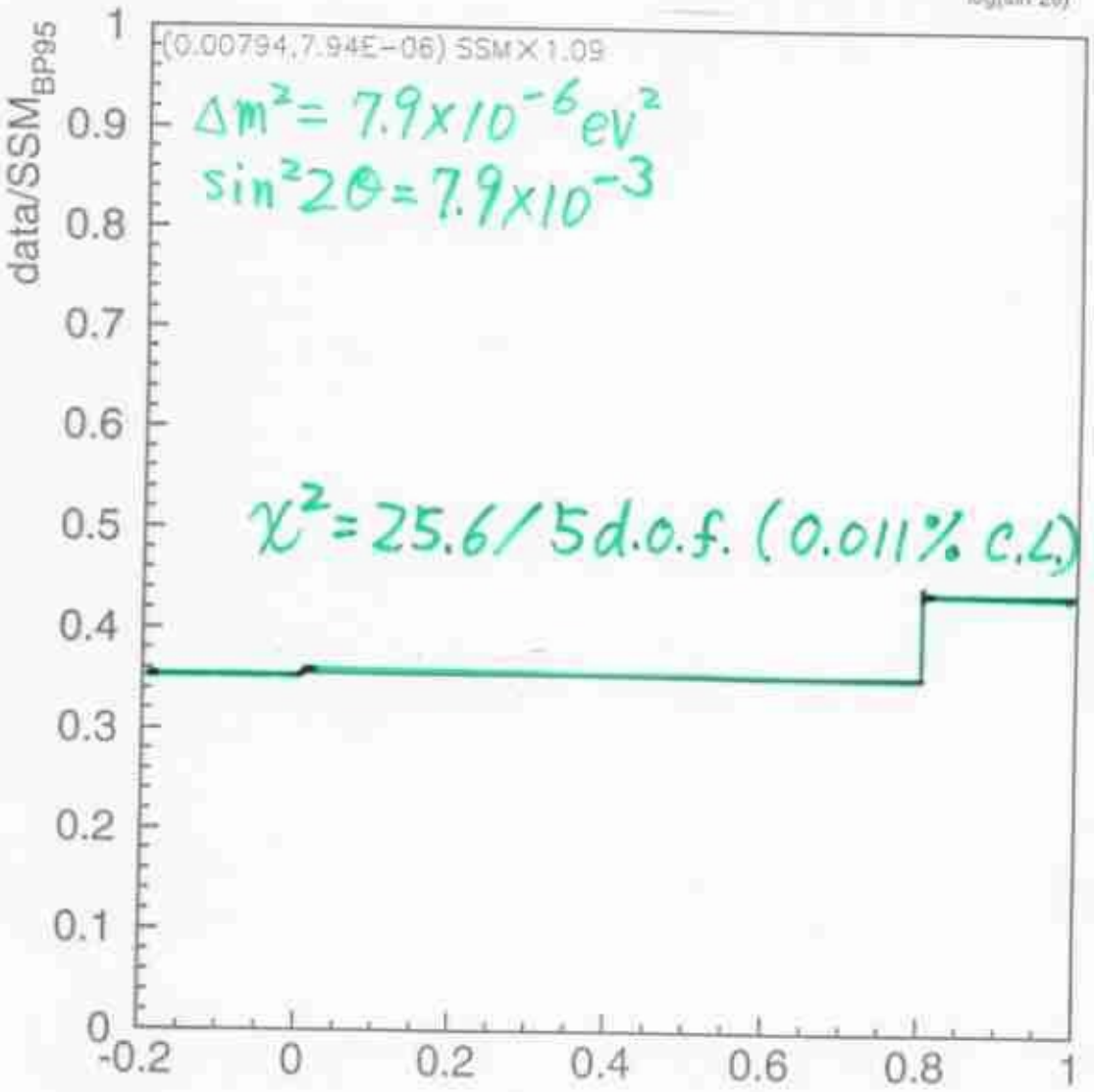

Excluded region. Day/Night

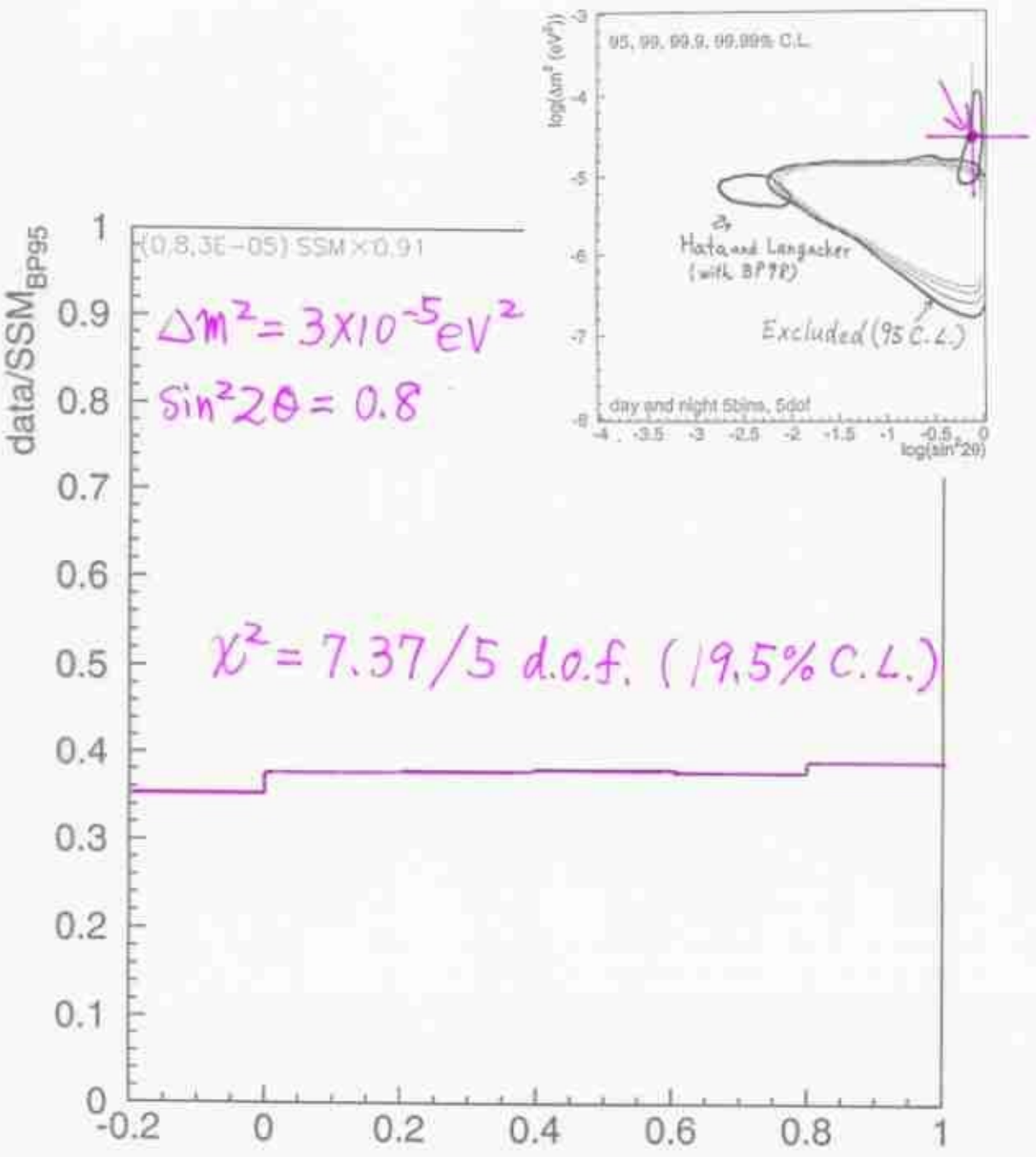
Day / Night analysis



$\chi^2 = 7.3/5$ d.o.f. (19.9% C.L.)

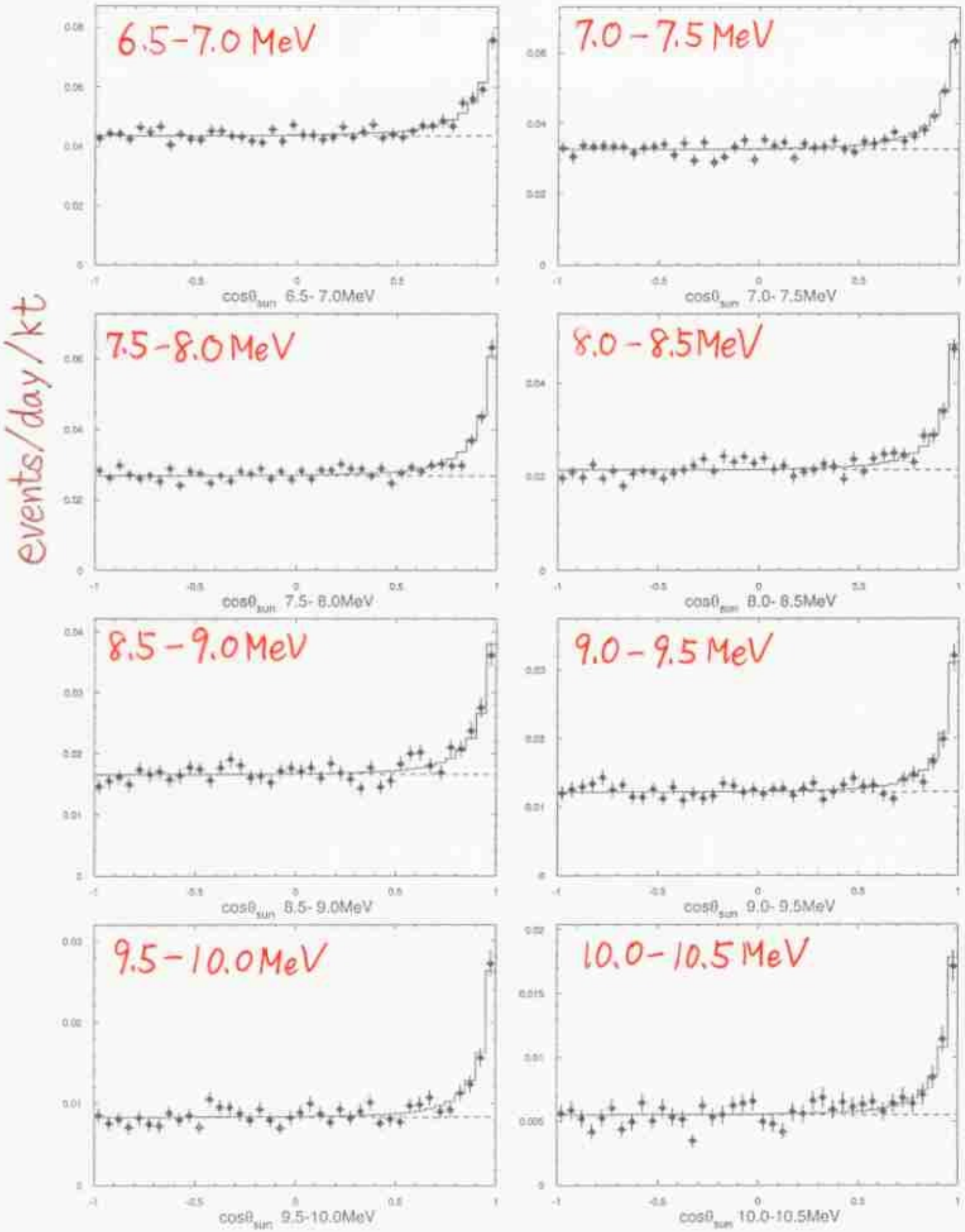

95, 99, 99.9, 99.99% C.L.
log(Δm² (eV²))
-3
-4
-5
-6
-7
-8
Hata and Langacker
(with BP98)
Excluded (95 C.L.)
day and night 5bins, 5dof
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
log(sin²2θ)


data/SSM_BP95
(0.00794,7.94E-06) SSM X 1.09
Δm² = 7.9x10⁻⁶ eV²
sin²2θ = 7.9x10⁻³
χ² = 25.6/5 d.o.f. (0.011% C.L.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.2
0
0.2
0.4
0.6
0.8
1

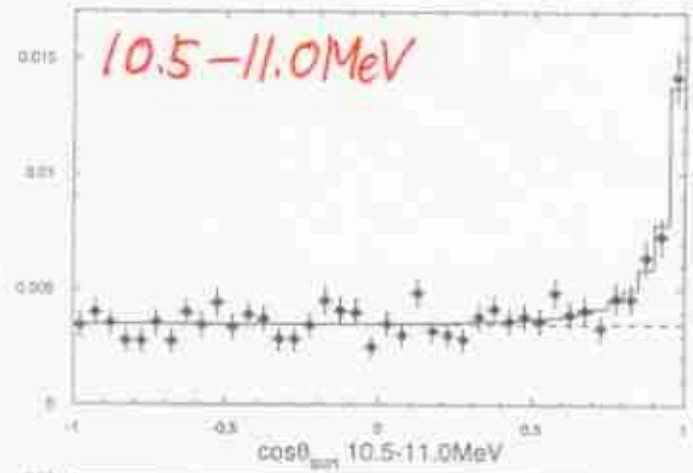

95, 99, 99.9, 99.99% C.L.
log(Δm² (eV²))
Hata and Langacker (with BP98)
Excluded (95 C.L.)
day and night 5bins, 5dof
log(sin²2θ)
(0.8,3E-05) SSM×0.91
Δm² = 3×10⁻⁵ eV²
sin²2θ = 0.8
χ² = 7.37/5 d.o.f. (19.5% C.L.)
data/SSM_BP95

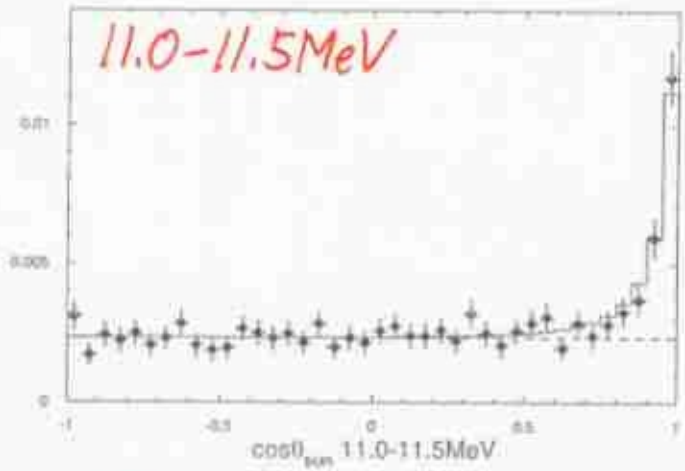
$\cos\theta_{sun}$ for each energy bin

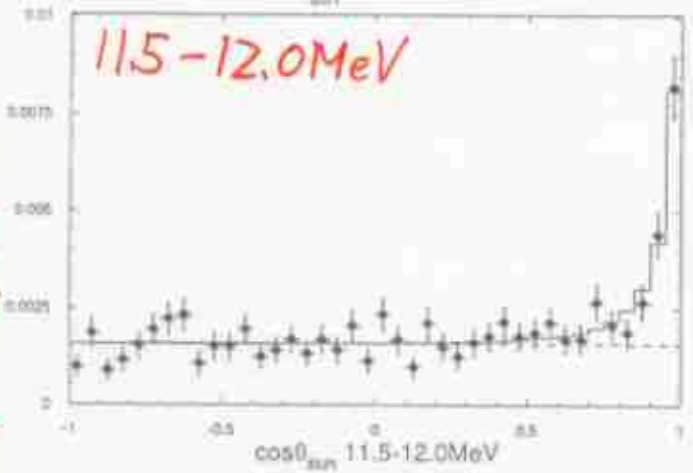
SK 504day 6.5-20MeV 22.5kton

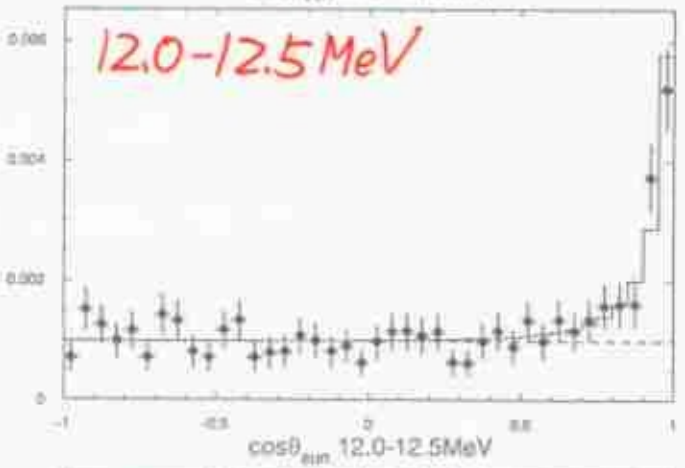


SK 504day 6.5-20MeV 22.5kton

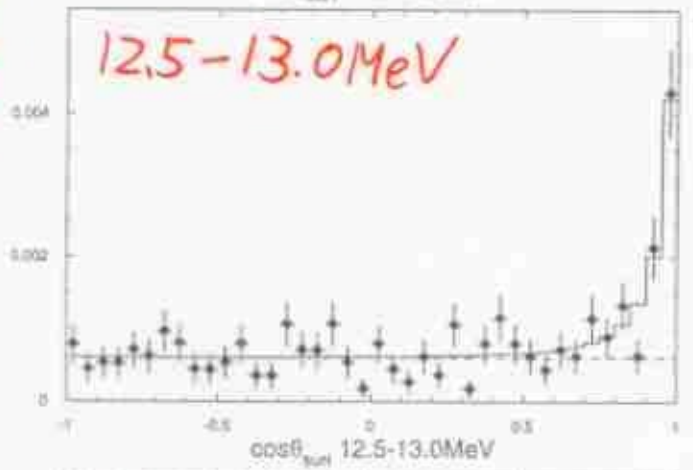


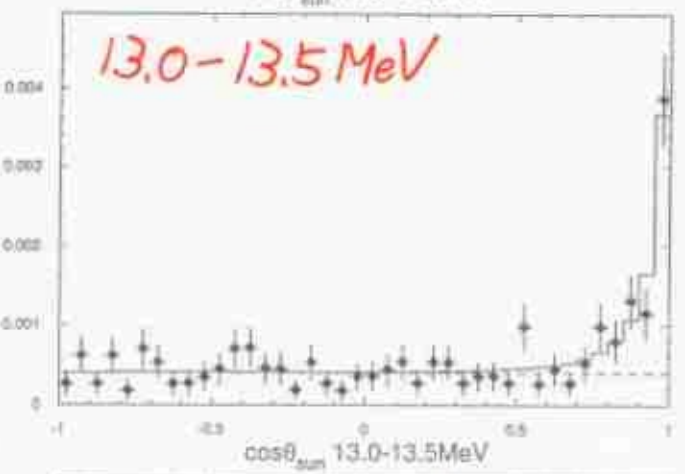


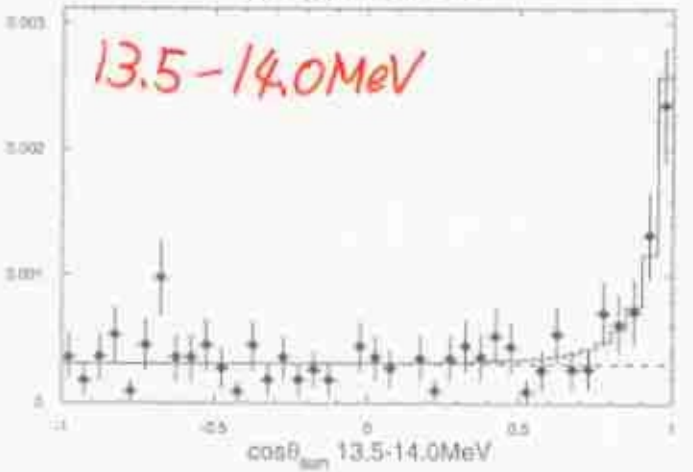


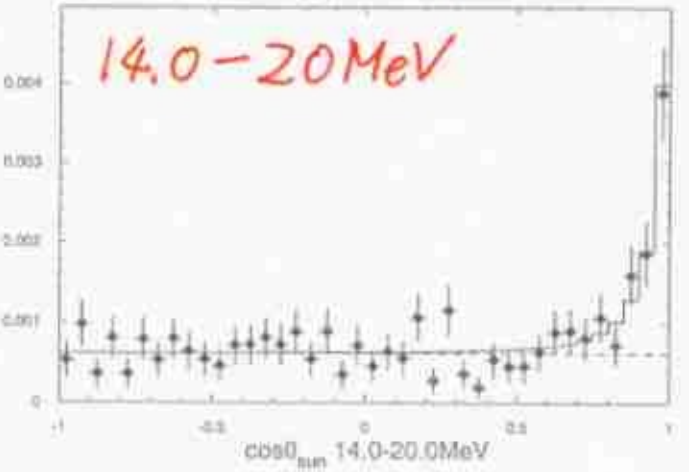


events / day / kt





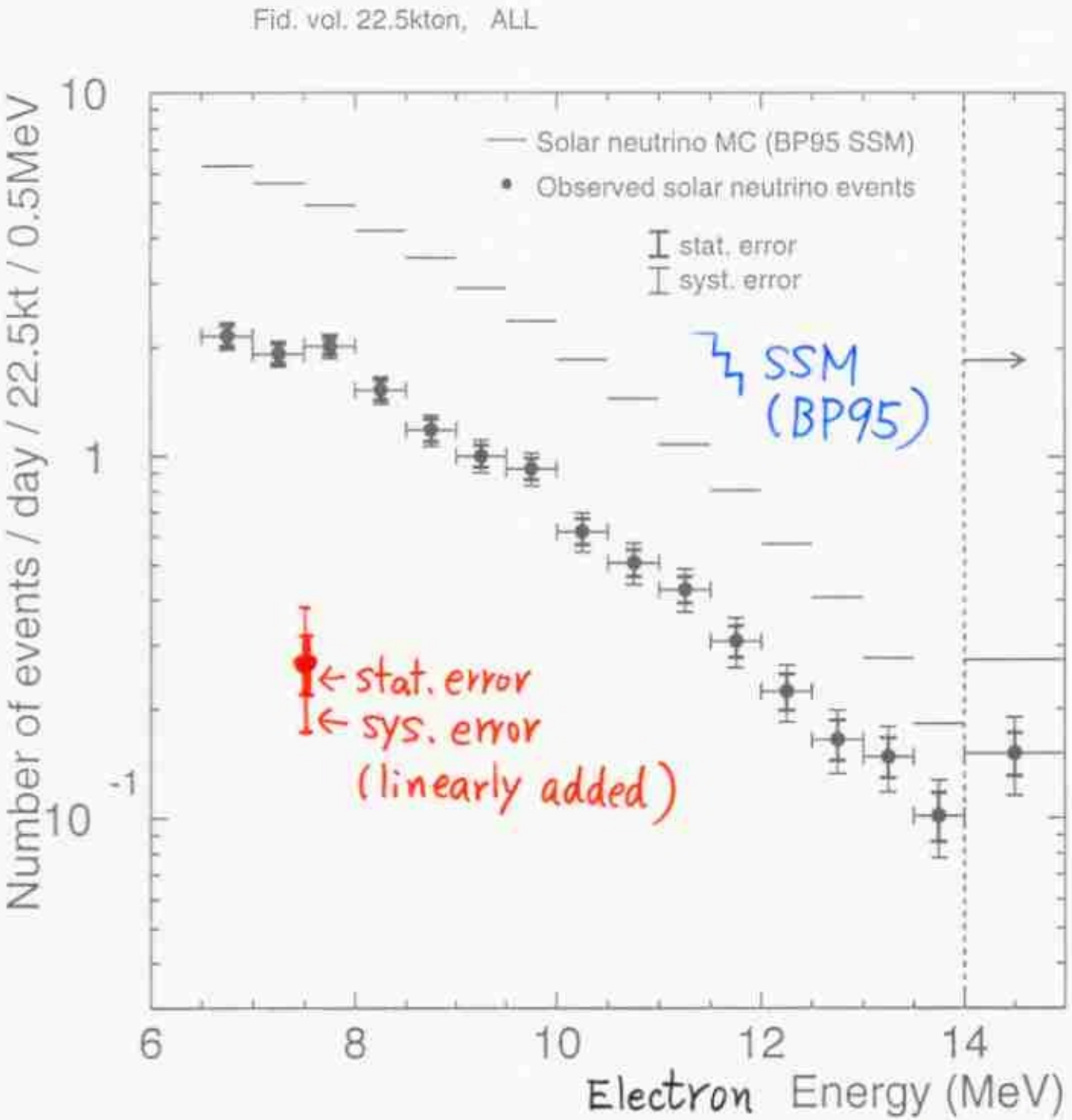




Energy Spectrum of Solar νs

(Preliminary)

Super-Kamiokande 504day

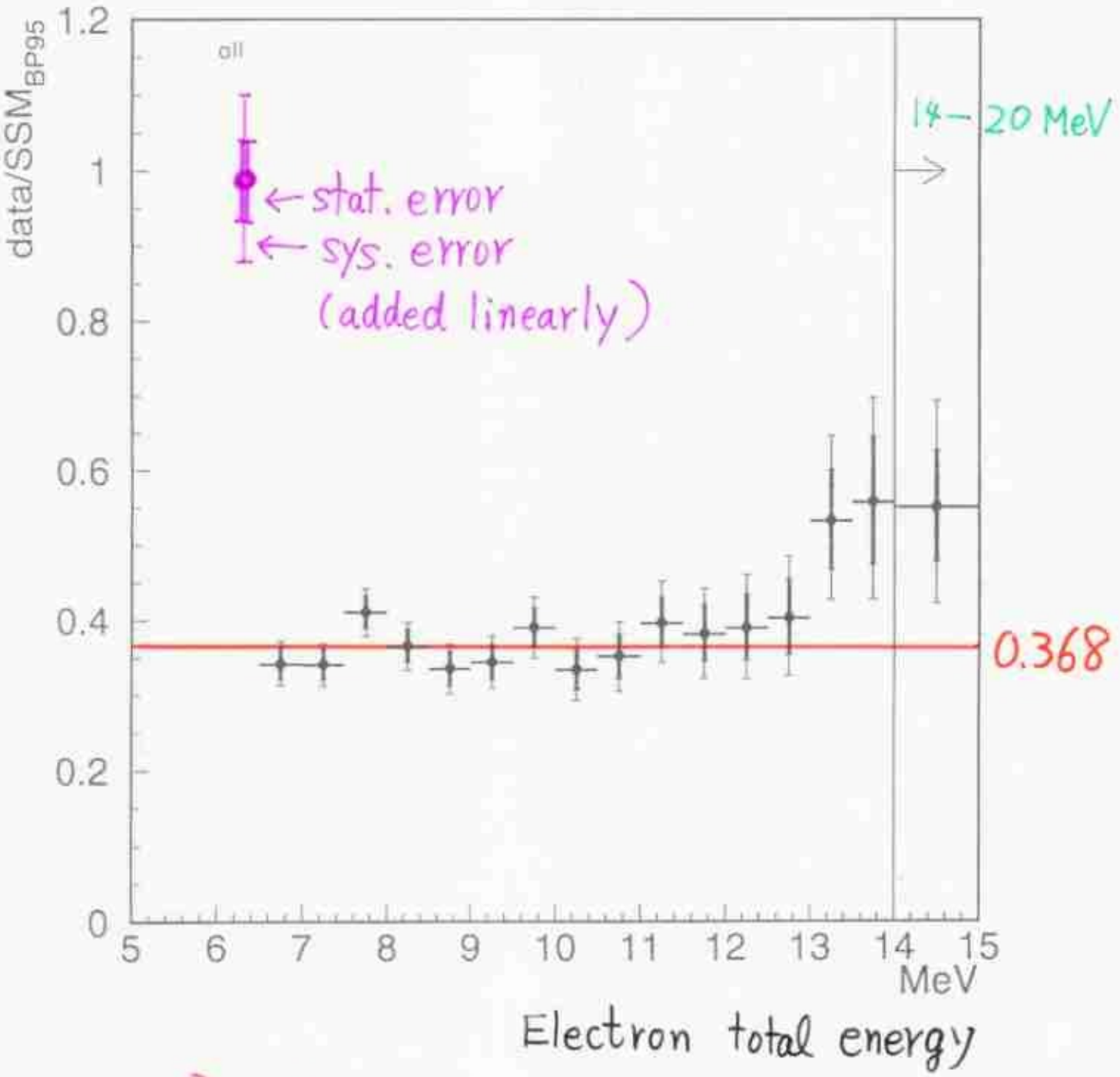


BP95: Bahcall and Pinsonneault, Rev. Mod. Phys. 67 (1995) 781.

^{8}B spectrum: Bahcall et al., Phys. Rev. C54 (1996) 411.

νe cross section: Bahcall et al, Phys. Rev. D51 (1995) 6146.

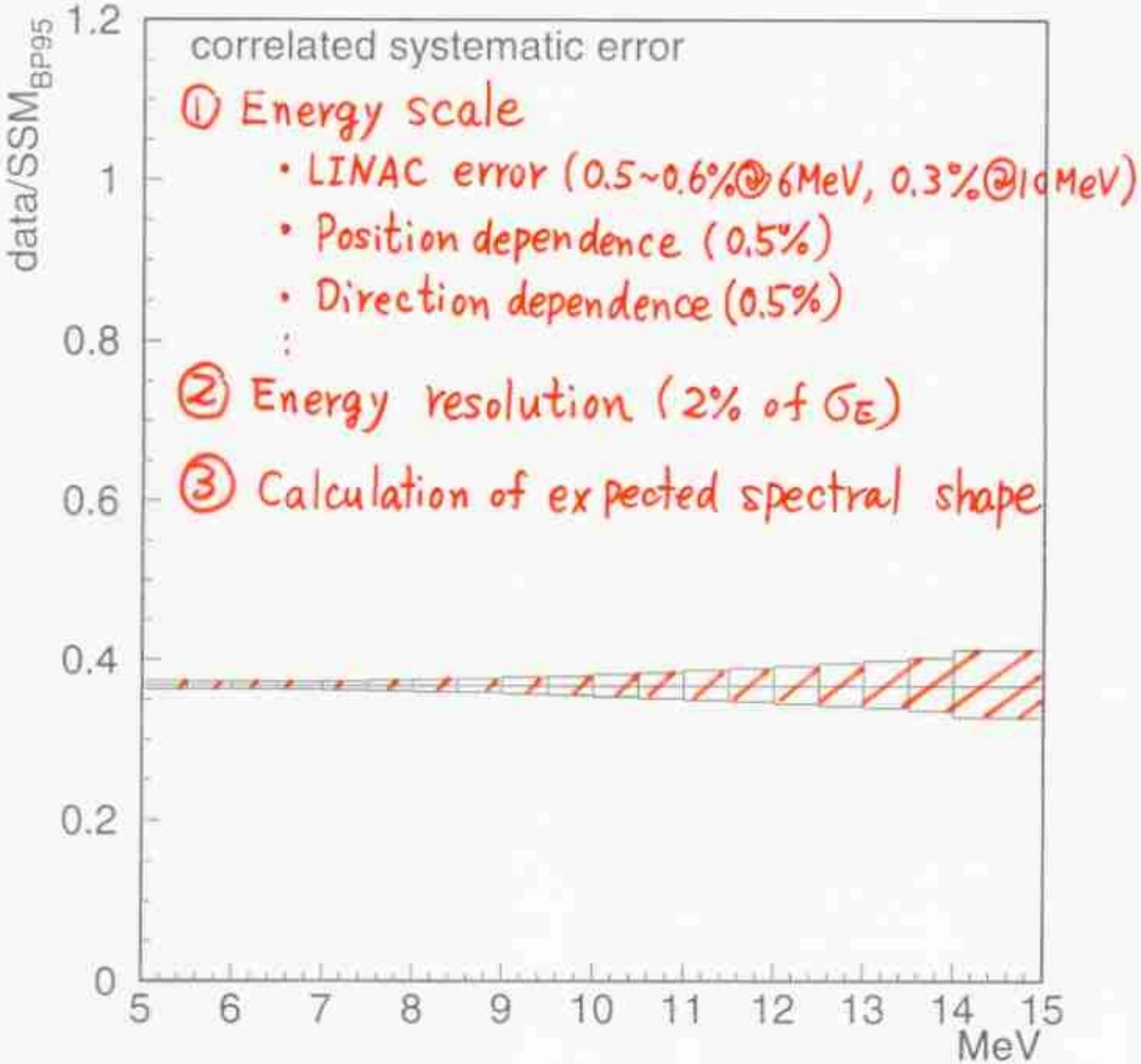
Energy Spectrum ($\frac{\text{Data}}{\text{SSM}_{BP95}}$)

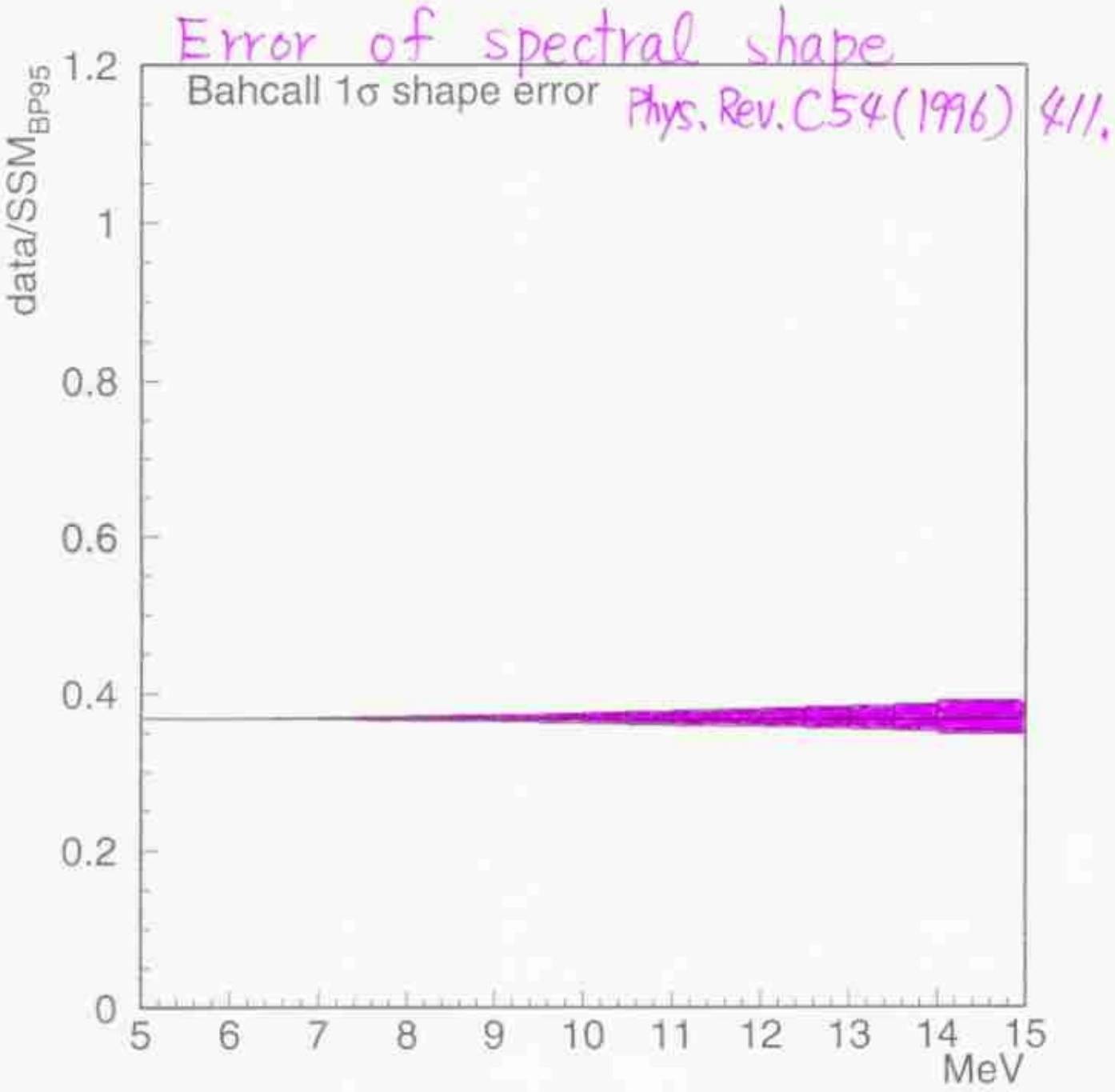


χ^2 for flat : 25.13/15 d.o.f. 4.8% C.L.
(this figure)

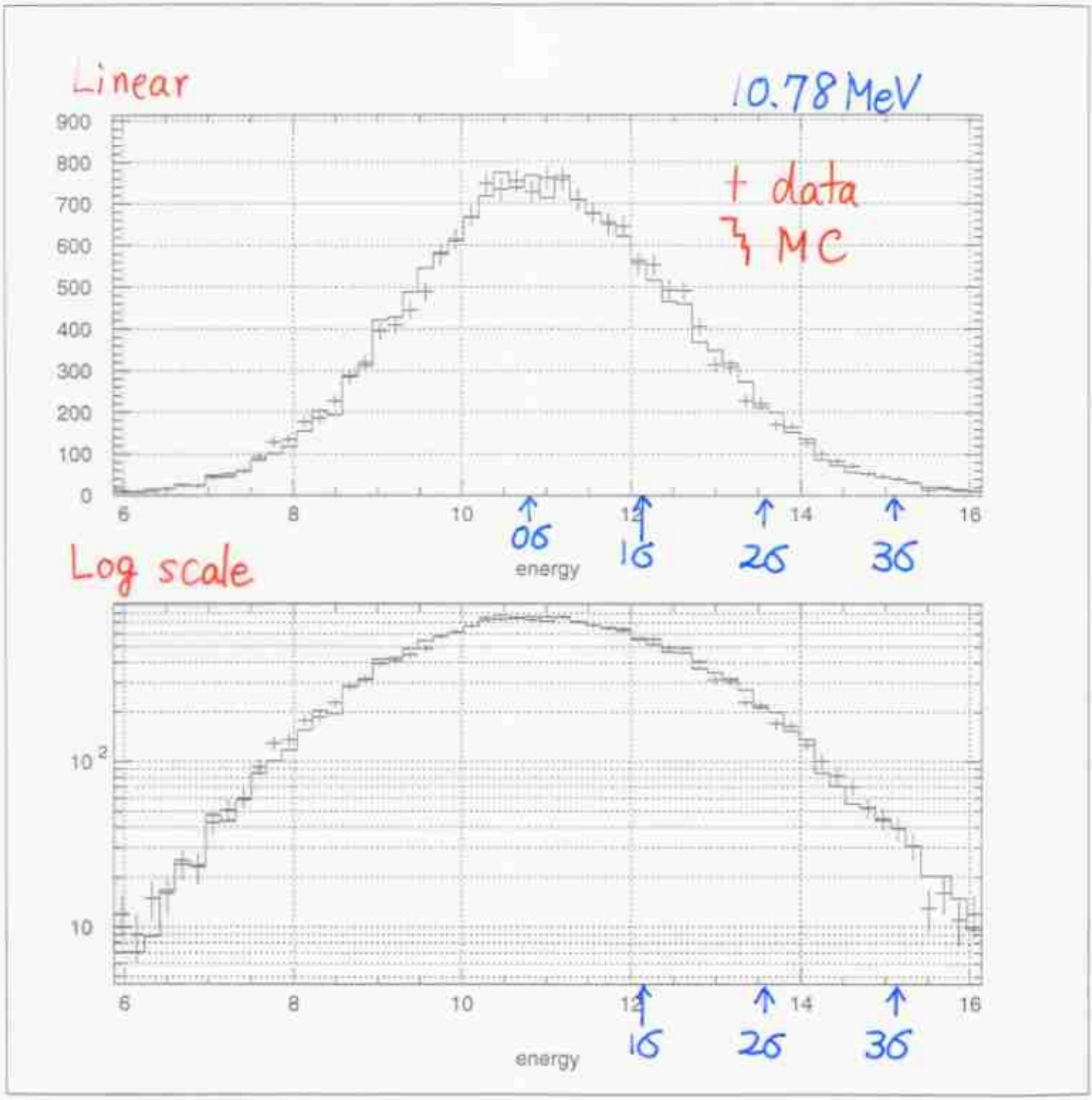
(50.17/31 d.o.f. 1.6% C.L.
(day, night spectrum))

Correlated systematic error for energy spectrum




Error of spectral shape
Bahcall 1σ shape error
Phys. Rev. C54 (1996) 411.
data/SSM$_{BP95}$
1.2
1
0.8
0.6
0.4
0.2
0
5
6
7
8
9
10
11
12
13
14
15
MeV

LINAC energy spectrum



Data and MC agree to each other.

Resolution tail is well understood.

Definitions of χ^2

Day/Night

$$\chi^2 = \sum_{i = D,N1\text{-}N5} \left\{ \frac{\left(\frac{\text{Data}}{\text{SSM}}\right)_i - \left(\frac{\text{w/ oscil}}{\text{w/o oscil}}\right)_i \times \alpha}{\sigma_i} \right\}^2$$

$$\sigma_i = \sqrt{\sigma^2_{\text{stat},i} + \sigma^2_{\text{syst},i}} \qquad \alpha : \text{free}$$

Energy spectrum (flux independent)

Day, Night

$$\chi^2 = \sum_{D,N} \sum_{i=1}^{16} \left\{ \frac{\left(\frac{\text{Data}}{\text{SSM}}\right)_i - \left(\frac{\text{w/ oscil}}{\text{w/o oscil}}\right)_i \times \alpha \times F_i(\varepsilon_s, \varepsilon_r, \ldots)}{\sigma_i} \right\}^2 + \left(\frac{\varepsilon_s}{\sigma_s}\right)^2 + \left(\frac{\varepsilon_r}{\sigma_r}\right)^2 + \ldots$$

16 Energy bins

31 d.o.f.

$$\sigma_i = \sqrt{\sigma^2_{\text{stat},i} + \sigma^2_{\text{uncorr-syst},i}} \qquad \alpha : \text{free} \leftarrow \text{flux}$$

$F_i(\varepsilon_s, \varepsilon_r, \ldots)$: response function of correlated errors

σ_s : scale error

σ_r : resolution error

.....

Total (Flux, Energy, D/N) (with flux constraint)

$$\chi^2 = \sum_{D,N} \sum_{i=1}^{16} \left\{ \frac{\left(\frac{\text{Data}}{\text{SSM}}\right)_i - \left(\frac{\text{w/ oscil}}{\text{w/o oscil}}\right)_i \times \alpha \times F_i(\varepsilon_s, \varepsilon_r, \ldots)}{\sigma_i} \right\}^2 + \left(\frac{1-\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\varepsilon_s}{\sigma_s}\right)^2 + \left(\frac{\varepsilon_r}{\sigma_r}\right)^2 + \cdots$$

$$\sigma_i = \sqrt{\sigma^2_{\text{stat, i}} + \sigma^2_{\text{uncorr-syst, i}}}$$

α : bias for absolute flux

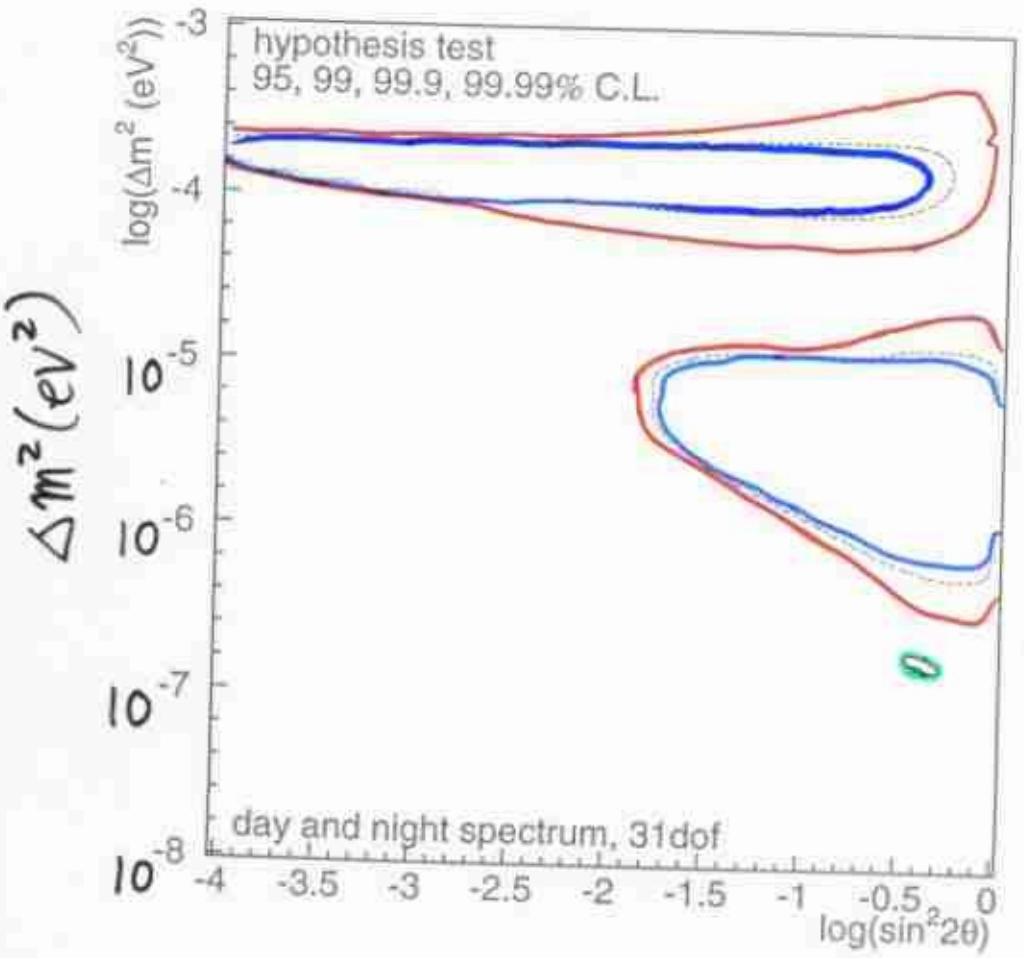
$F_i(\varepsilon_s, \varepsilon_r, \ldots)$: response function of correlated errors

σ_α : flux error (theoretical) → +19% −14%

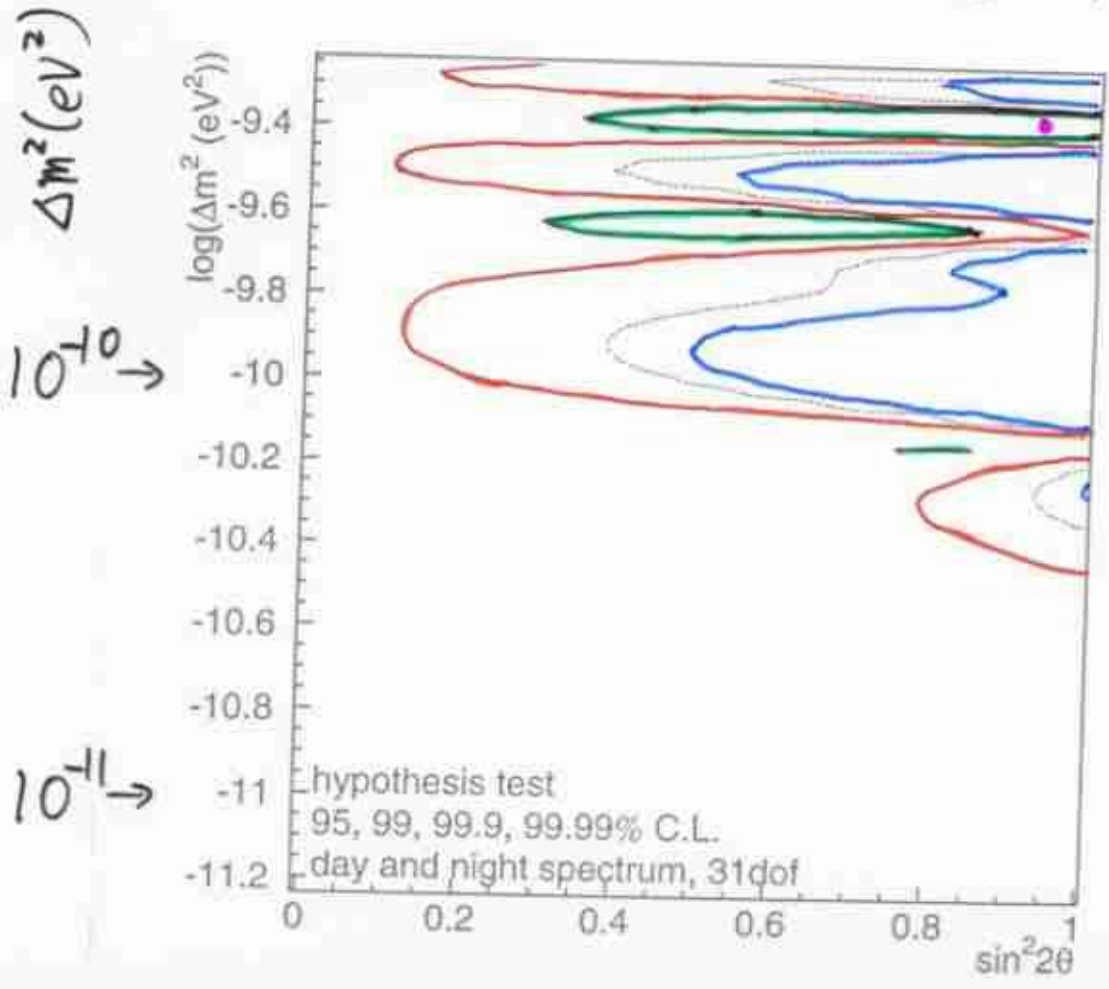
σ_s : scale error

σ_r : resolution error

χ^2-contour (Spectrum ⊕ Day/Night)



— 5%
— 1%
— 0.01%

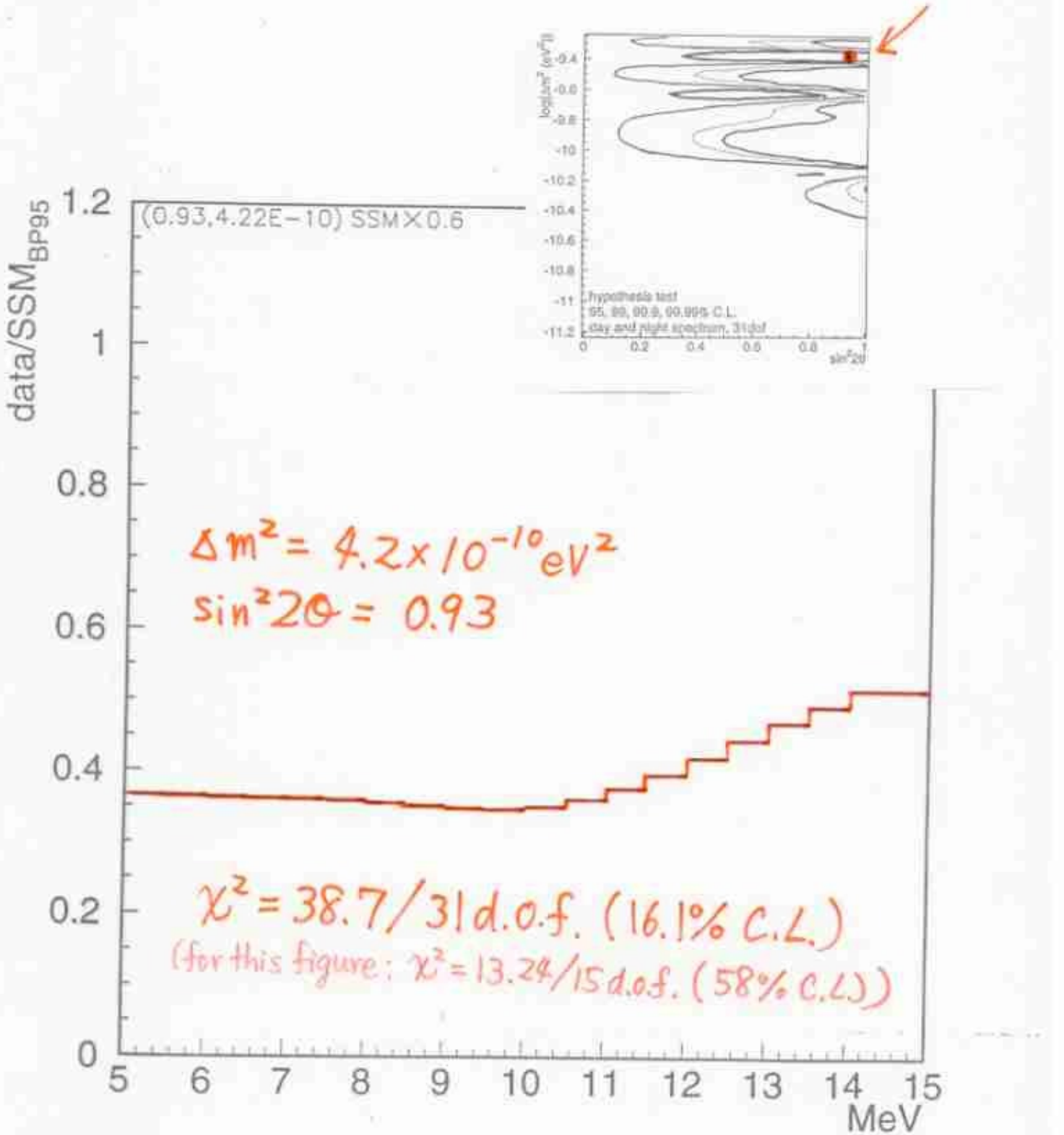


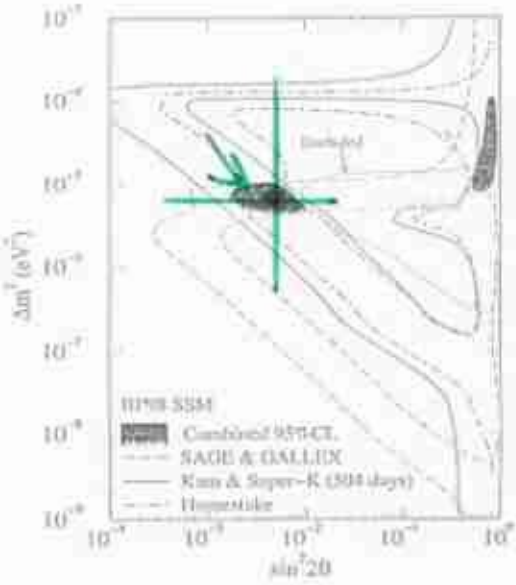
10^{-10} →

10^{-11} →

χ^2_{min} : 38.7
(31 d.o.f.)
16.1% C.L.

$\alpha = 0.78$
(BP98)


(0.93,4.22E−10) SSM×0.6
data/SSM$_{BP95}$
1.2
1
0.8
0.6
0.4
0.2
0
5
6
7
8
9
10
11
12
13
14
15
MeV
$\Delta m^2 = 4.2 \times 10^{-10}\ eV^2$
$\sin^2 2\theta = 0.93$
$\chi^2 = 38.7/31$ d.o.f. (16.1% C.L.)
(for this figure: $\chi^2 = 13.24/15$ d.o.f. (58% C.L.))
hypothesis test
95, 99, 99.9, 99.99% C.L.
day and night spectrum, 31dof
$\log(\Delta m^2\ (eV^2))$
$\sin^2 2\theta$

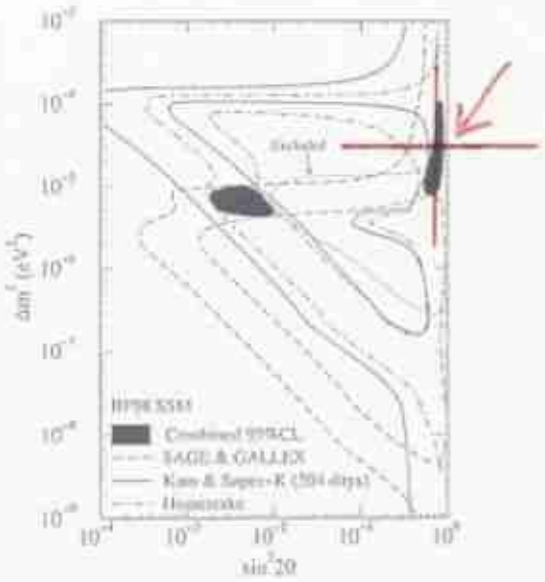


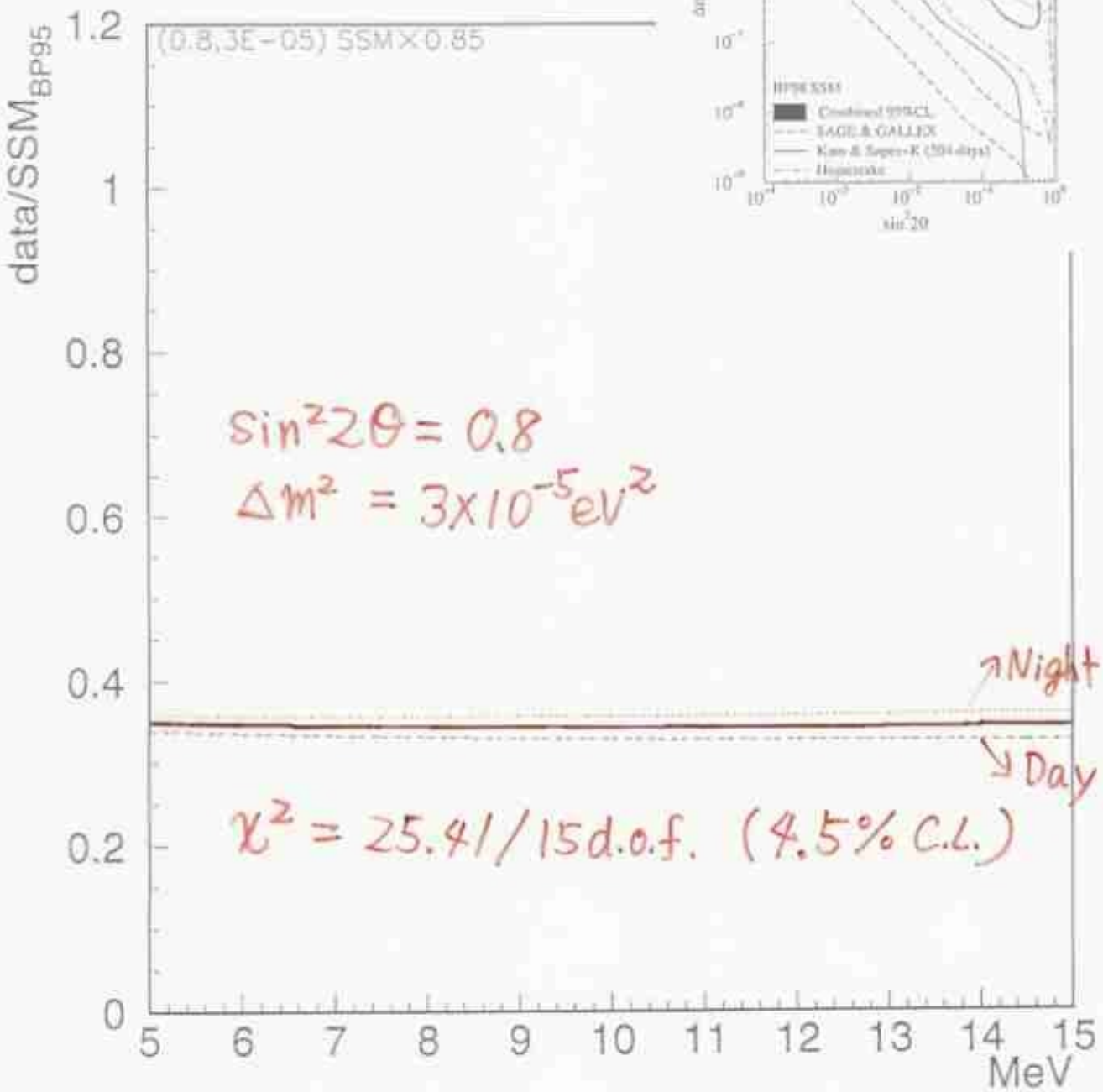
$\Delta m^2 = 7.1 \times 10^{-6}\ eV^2$

$\sin^2 2\theta = 5 \times 10^{-3}$

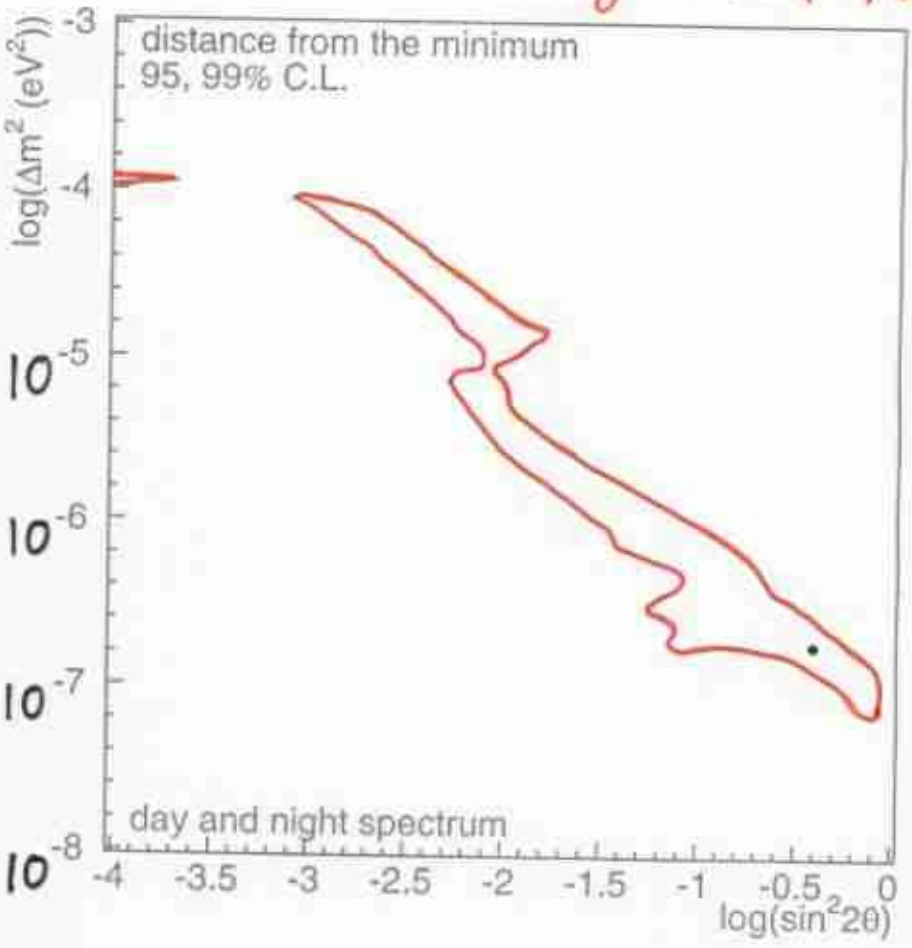
$\chi^2 = 48.0/31$ d.o.f. (2.7% C.L.)

(for this figure: $\chi^2 = 22.97/15$ d.o.f. (8.5% C.L.))


Excluded
BP98 SSM
Combined 99%CL
SAGE & GALLEX
Kam & Super-K (504 days)
Hopestake
Δm^2 (eV^2)
$\sin^2 2\theta$


(0.8,3E-05) SSM×0.85
data/SSM$_{BP95}$
1.2
1
0.8
0.6
0.4
0.2
0
5
6
7
8
9
10
11
12
13
14
15
MeV
$\sin^2 2\theta = 0.8$
$\Delta m^2 = 3\times10^{-5}\,eV^2$
↗Night
↘Day
$\chi^2 = 25.41/15$ d.o.f. (4.5% C.L.)

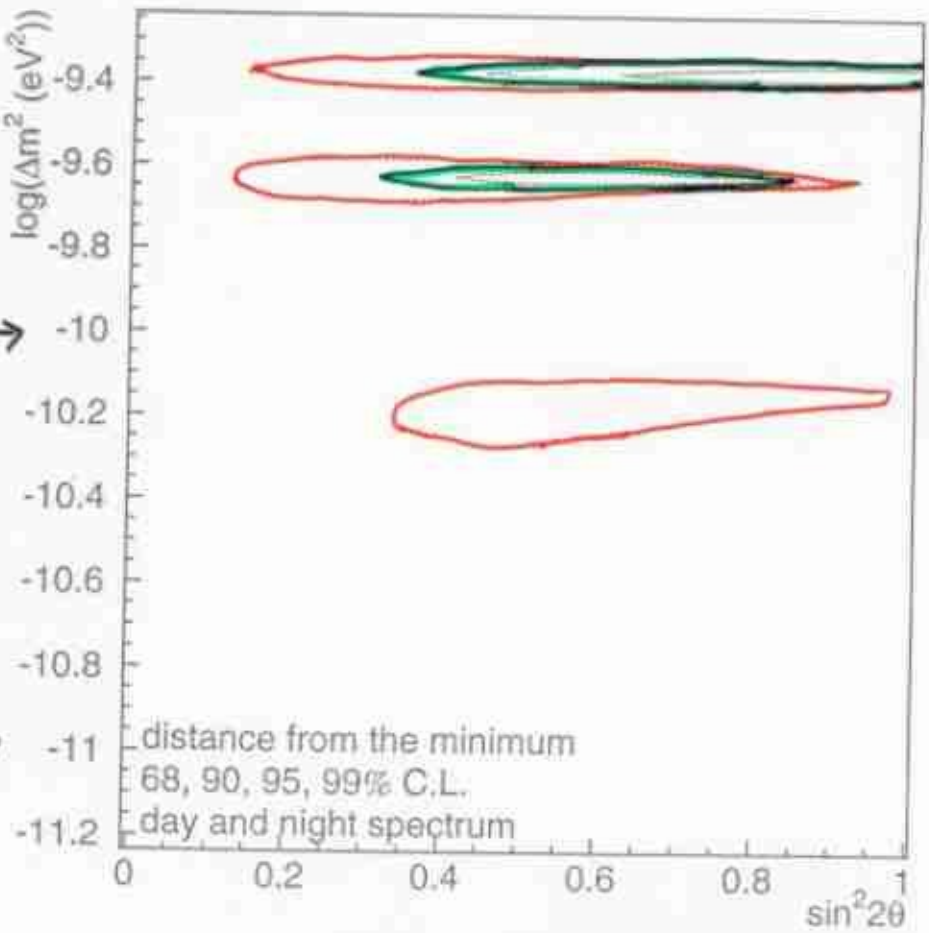
Allowed region (w/o flux constraint)



$\Delta m^2 (eV^2)$

— 95% C.L.

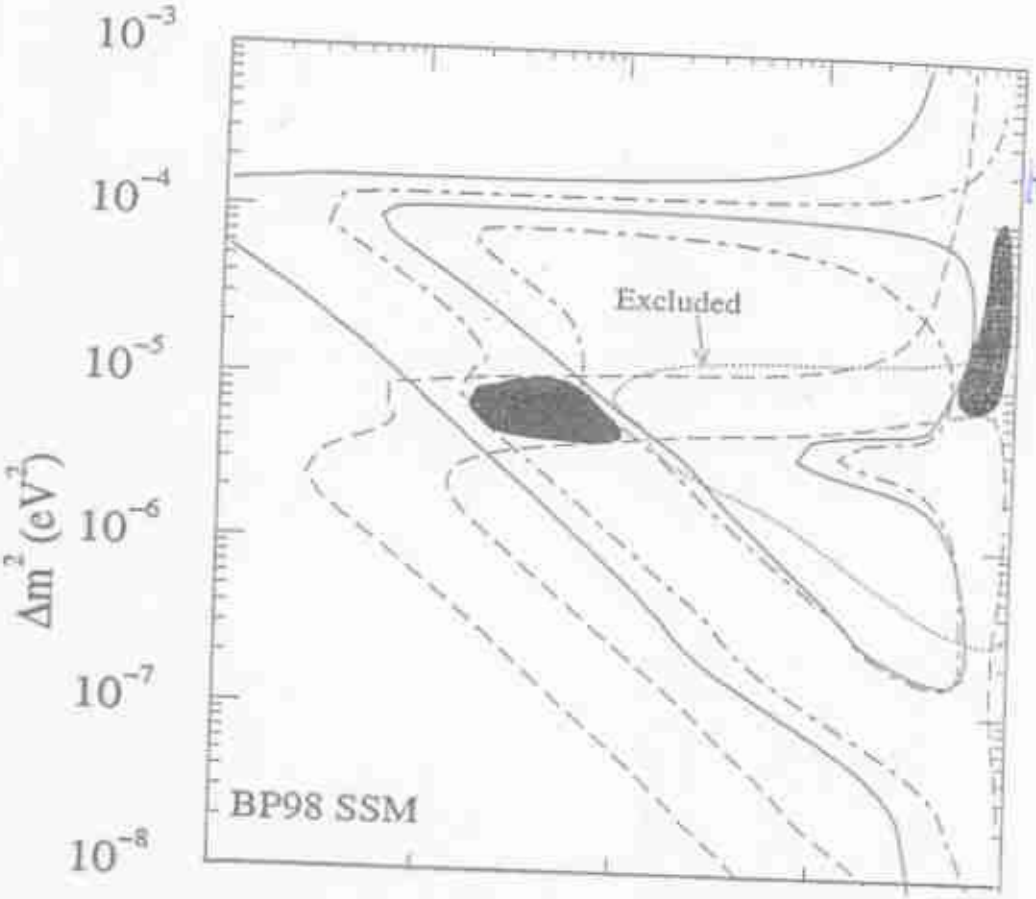
— 99% C.L.



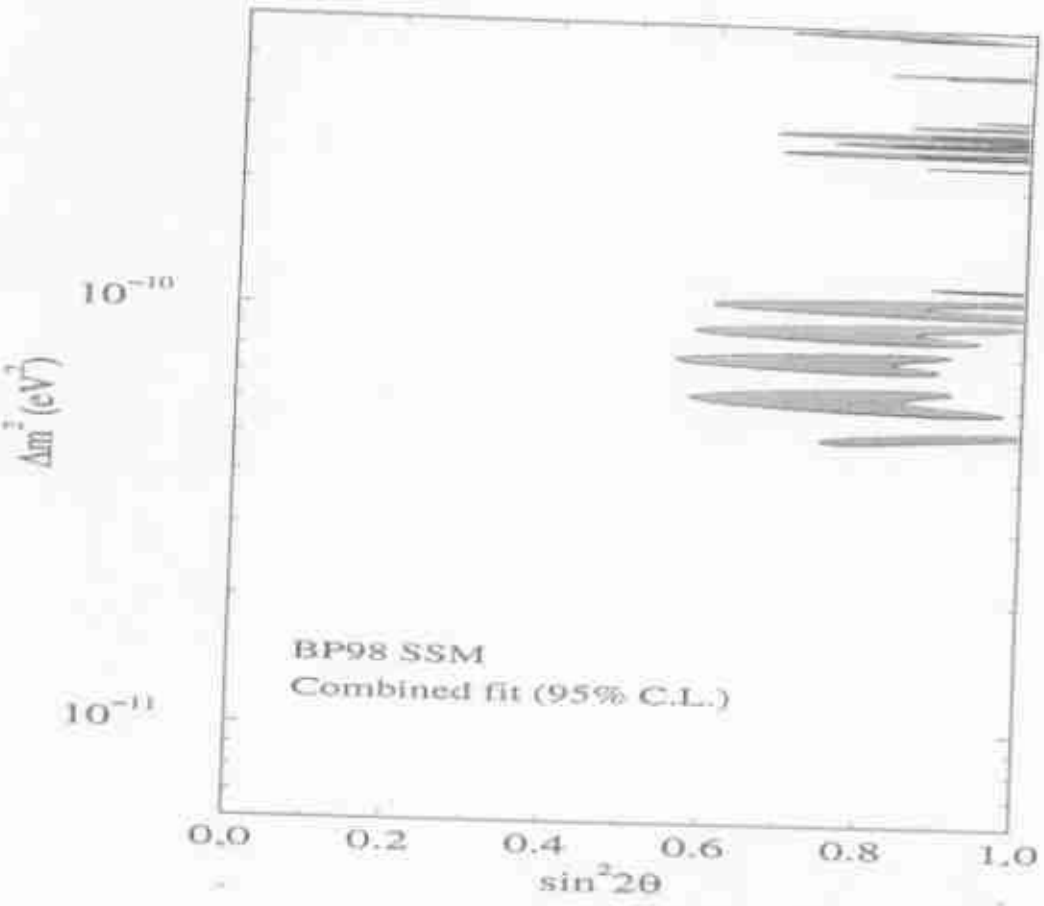
10^{-10} →

$\Delta m^2 (eV^2)$

10^{-11} →

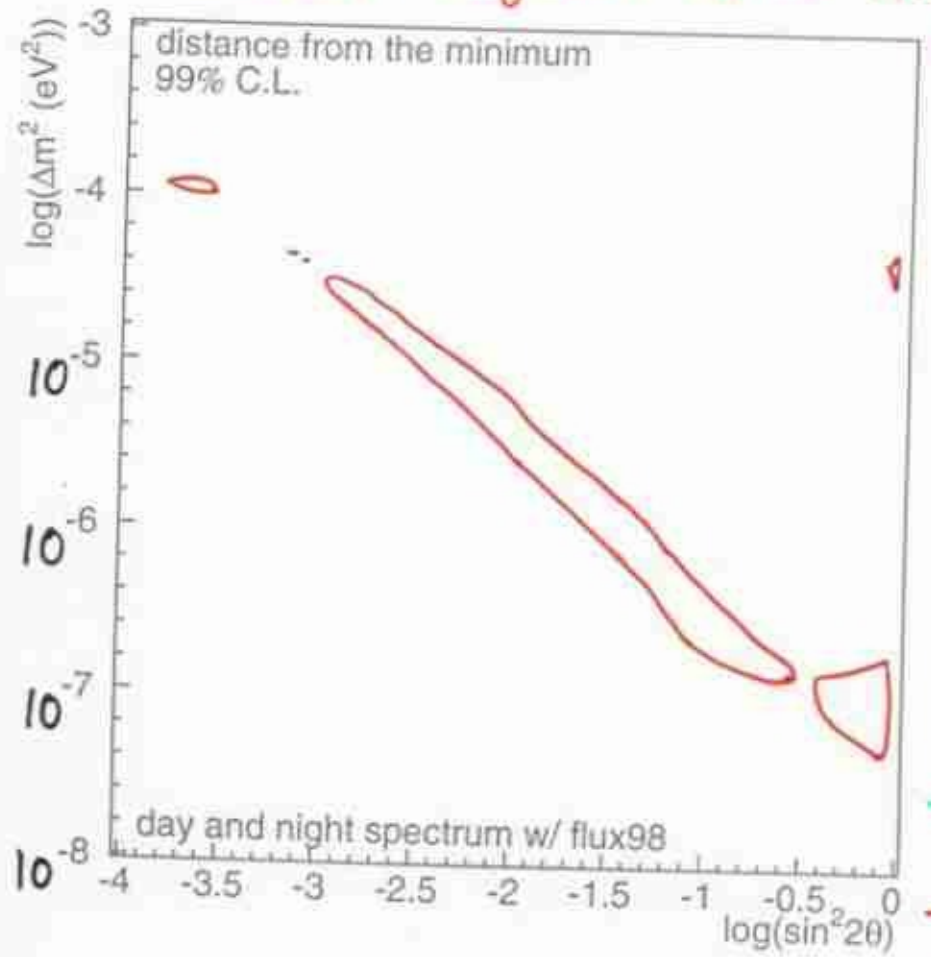


Hata & Langacker (BP98)



Allowed region (with flux constraint)

BP98

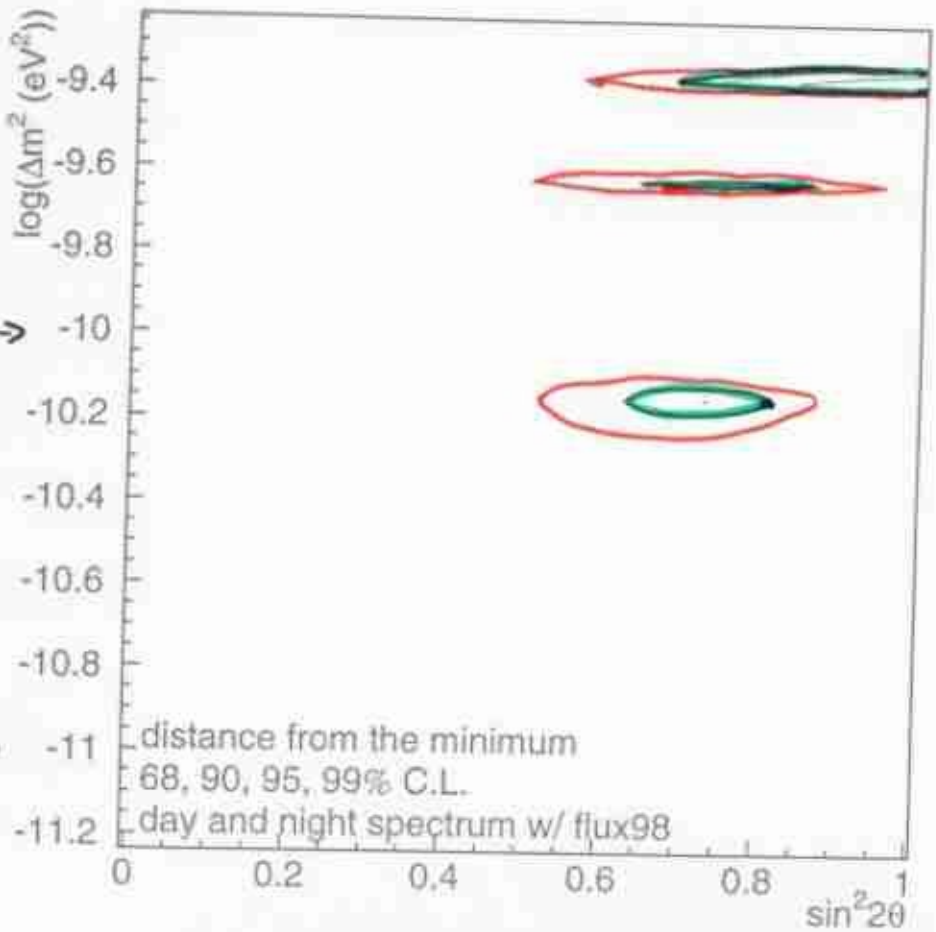


$\Delta m^2 (eV^2)$

10^{-5} 10^{-6} 10^{-7} 10^{-8}

— 95% C.L.

— 99% C.L.



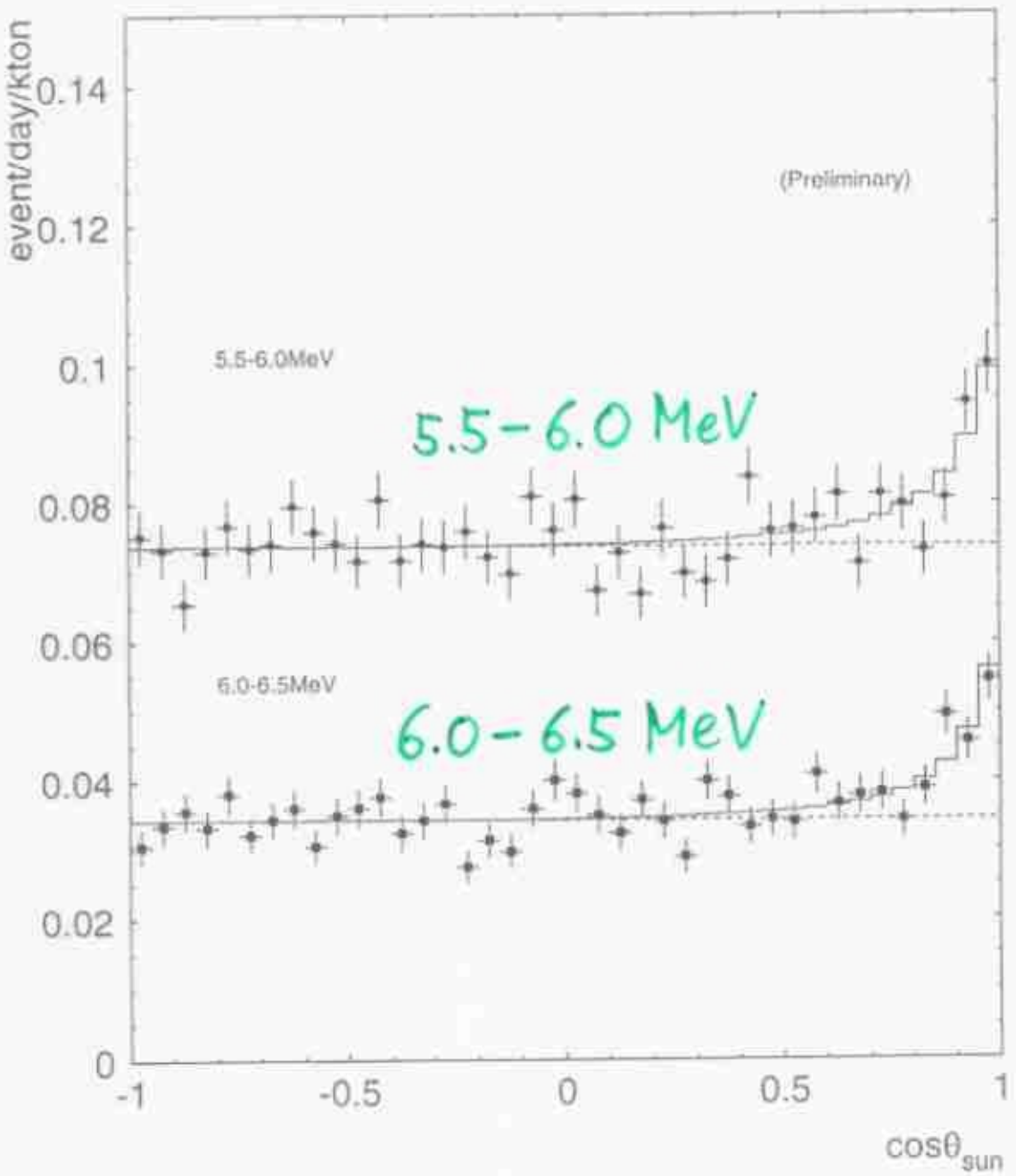
$\Delta m^2 (eV^2)$

10^{-10} →

10^{-11} →

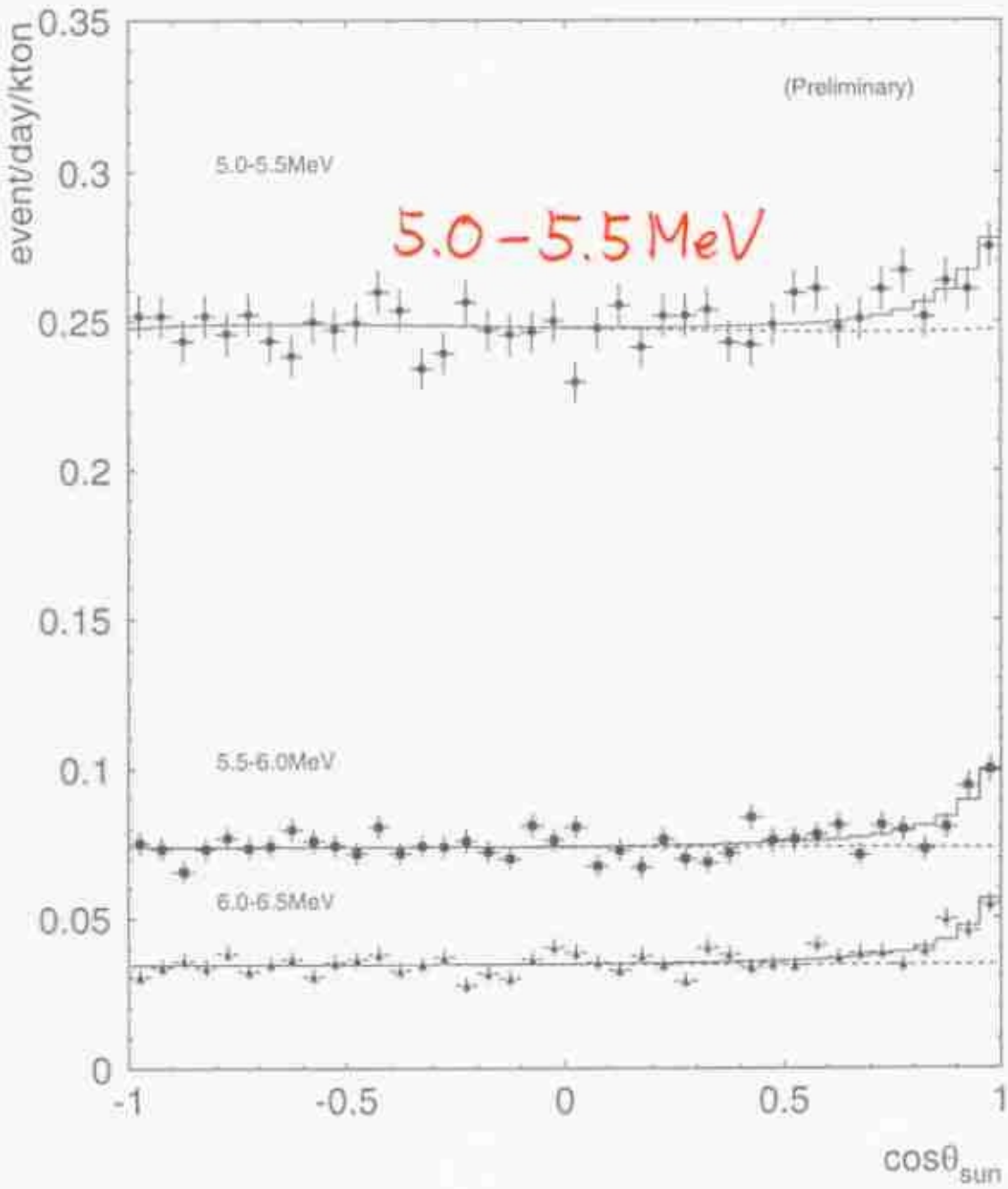
CosΘ_{sun} for SLE data

SK SLE 218day 22.5kton



Solar ν signal is clearly seen!

SK SLE 218day 22.5kton



Conclusions

(1) Precise energy calibration by LINAC.

(2) Flux of ^{8}B (504 days' data)

2.44 ± 0.05(stat) +0.09/-0.07(sys) [10^{6} /cm^{2}/sec]
(0.368 for BP95 and 0.474 for BP98)

(3) No seasonal variations are observed.

(4) No Day/Night difference.
(D-N)/(D+N) = -0.023 ± 0.020 ± 0.014

(5) Energy spectrum analysis.
- "No Oscillation" is disfavored at ~5 % C.L.
- Large Angle solution is disfavored at ~5 % C.L.
- Need more statistics for discussing
Vacuum/[redacted]/Large Angle solutions.

small angle

(6) Super Low Energy analysis is in progress.
- Solar Neutrino signal is seen in
5.5 - 6.5 MeV energy bins. (even in 5.0 - 5.5 MeV).
- Flux for those energy bins will be obtained soon.