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Results from Super-Kamiokande

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for Super-Kamiokande collaboration

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- Atmospheric Neutrinos
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  - Evidence for ν_μ oscillations
- Solar Neutrinos
- Conclusions

The Super-Kamiokande Collaboration (~120 physicists)

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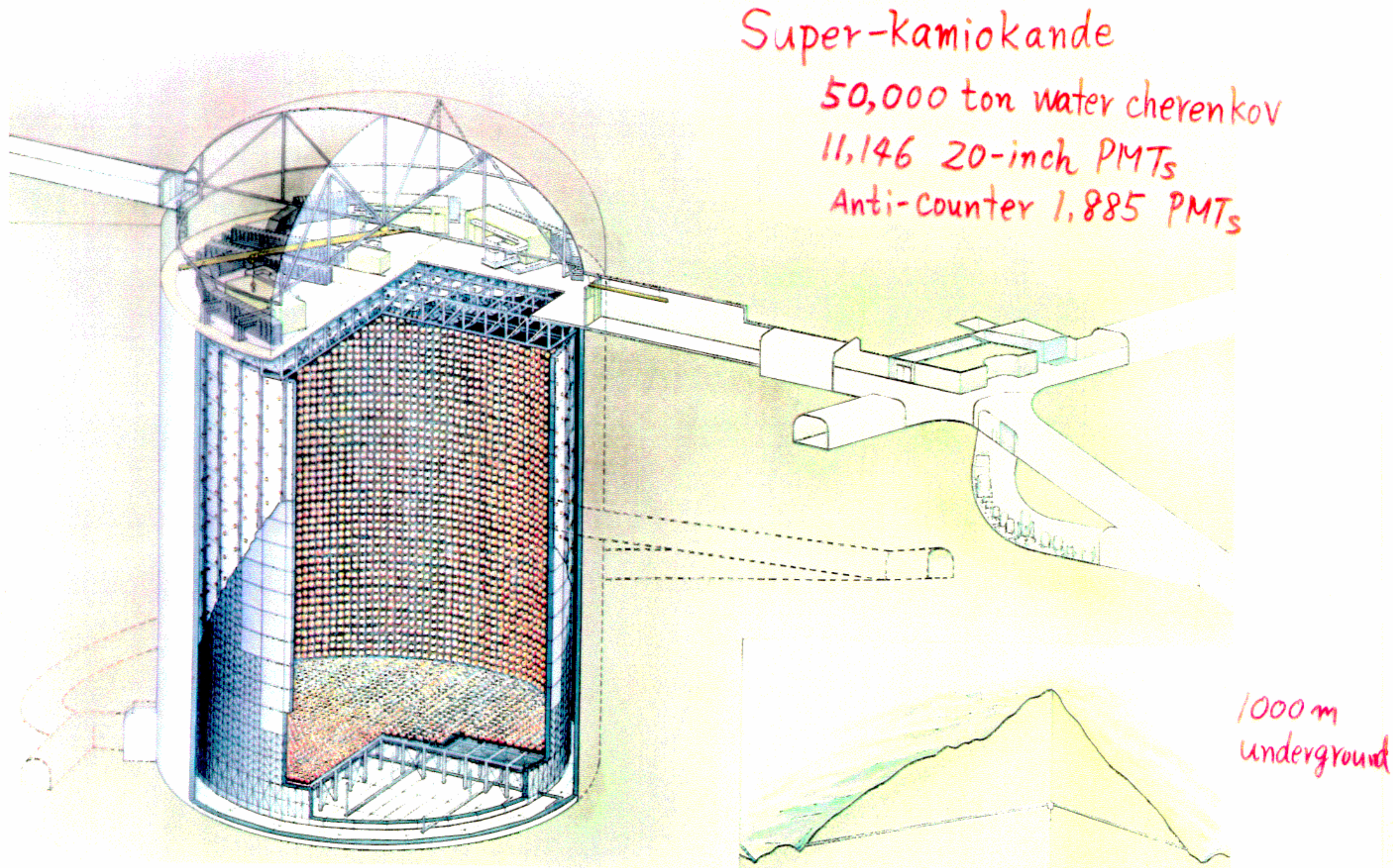


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO NIKKEN SEKKEI

Trigger

- Low Energy (LE) trigger

  Requires ≧ 29 PMT hits within 200 nsec

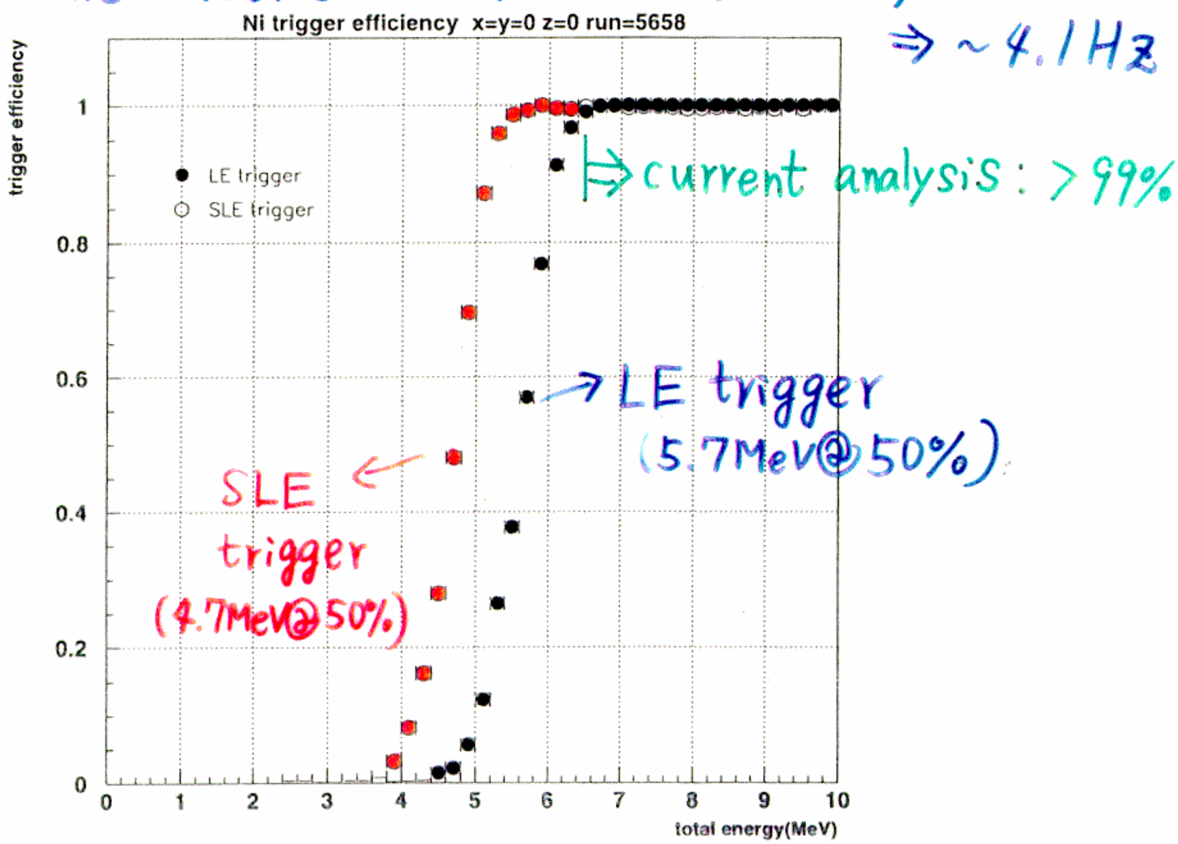
  (Effective energy threshold : ~5.7 MeV)

  Rate ~ 12 Hz

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

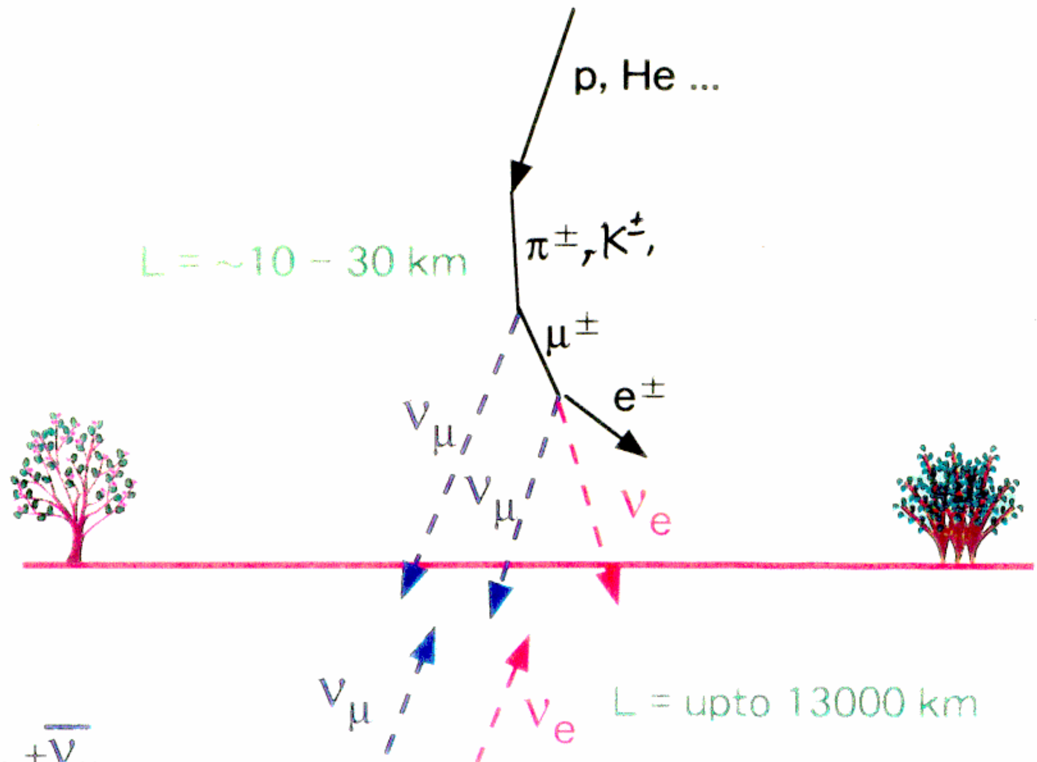
  ≧ 24 PMT hits (i.e. lowered by 19%)

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



↑ trigger efficiency measured by Ni (n,γ) Ni calibration source

Atmospheric Neutrinos



$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} = \sim 2$$ @ low energy ($E_\nu < 1\,GeV$)

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \nearrow$$ @ high energy

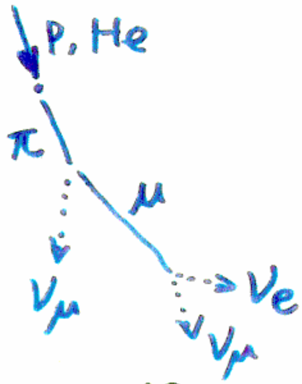
(error in flux ~25%
(error in $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$ ~ 5%

Neutrino Oscillation

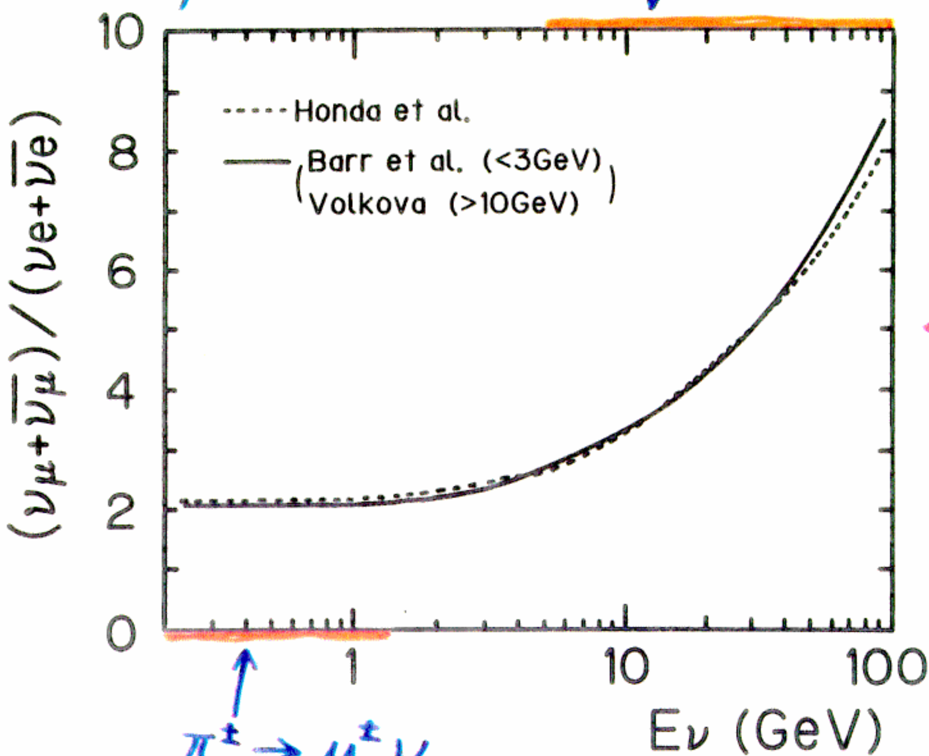
➡ $\left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{observed} \Big/ \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{calculated} \neq 1$

➡ Zenith angle dependence of $\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$

Atmospheric neutrinos



$\pi^\pm \to \mu^\pm \nu_\mu$
$\quad \hookrightarrow e^\pm \nu_\mu \nu_e$



<5% accuracy

$\pi^\pm \to \mu^\pm \nu_\mu$
$\quad \hookrightarrow e^\pm \nu_\mu \nu_e$

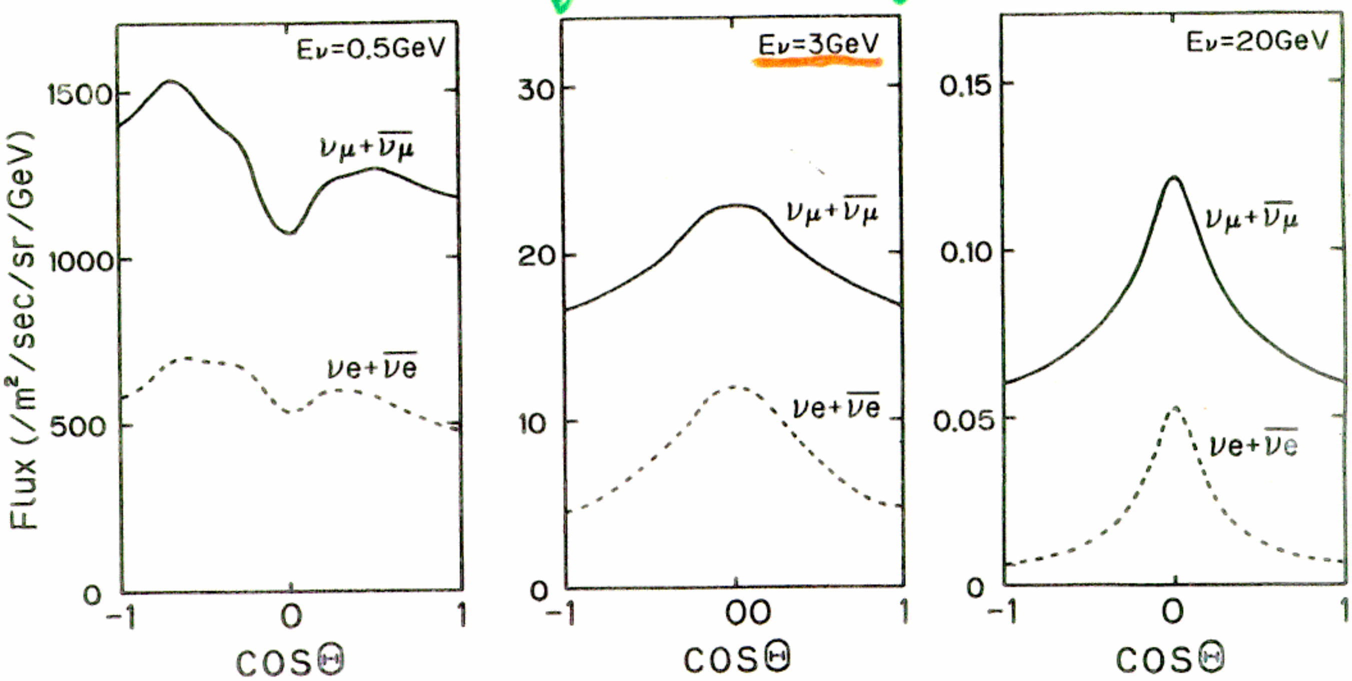
Neutrino oscillations:

$$\frac{\left(\nu_\mu+\overline{\nu_\mu} \,/\, \nu_e+\overline{\nu_e}\right)_{\text{Observed}}}{\left(\nu_\mu+\overline{\nu_\mu} \,/\, \nu_e+\overline{\nu_e}\right)_{\text{Calculated}}} \neq 1$$

Zenith angle

~13000km ~20km

Up-going ↓ Down-going ↓



For E_ν > a few GeV;

$$\frac{\text{Calculated flux (Up)}}{\text{(Down)}} = 1 \; (\pm < \text{a few } \%)$$

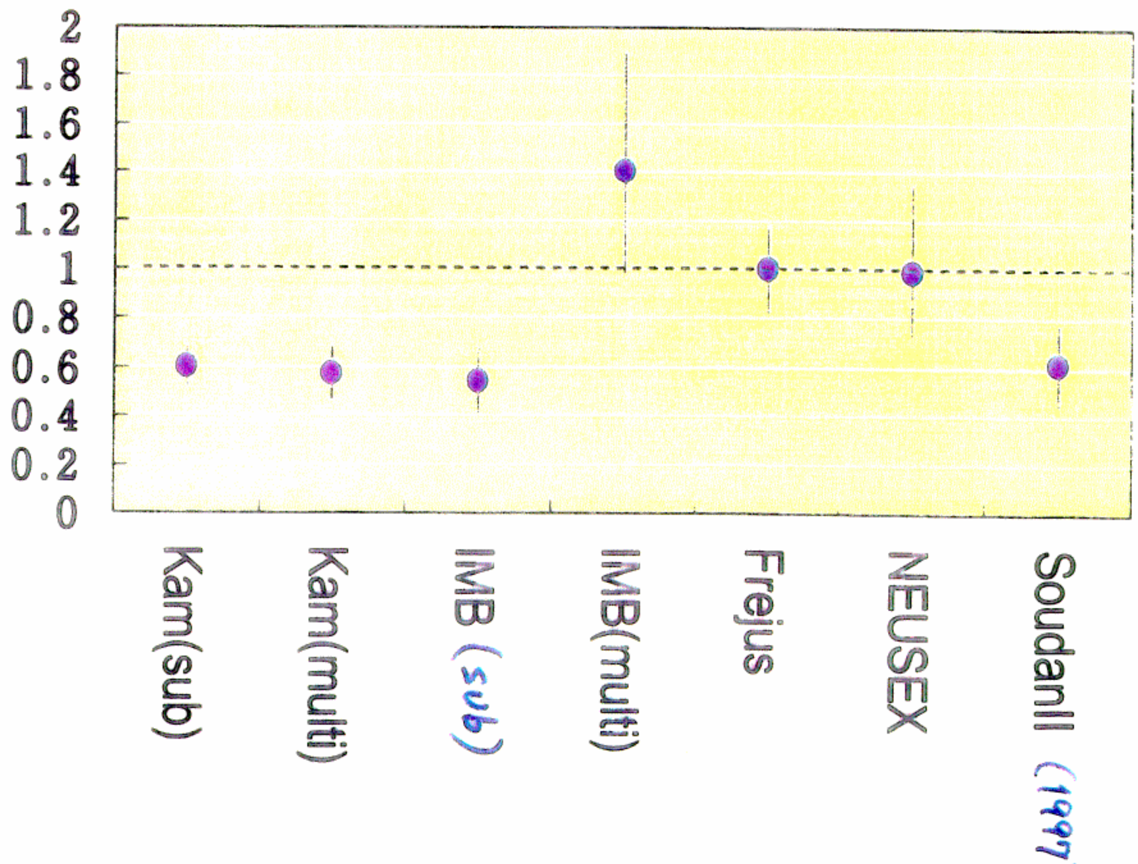
⇓

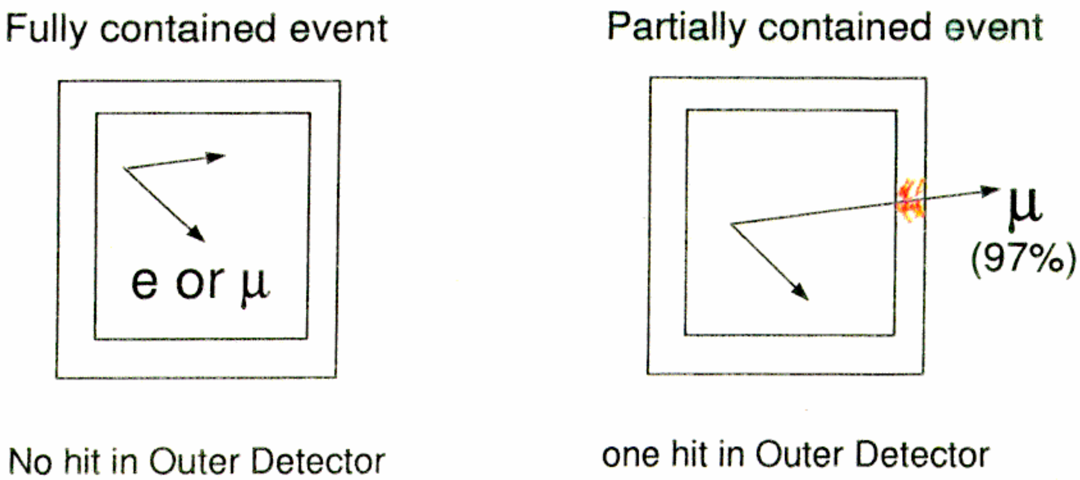
Zenith angle dependence
(Up/Down asymmetry)

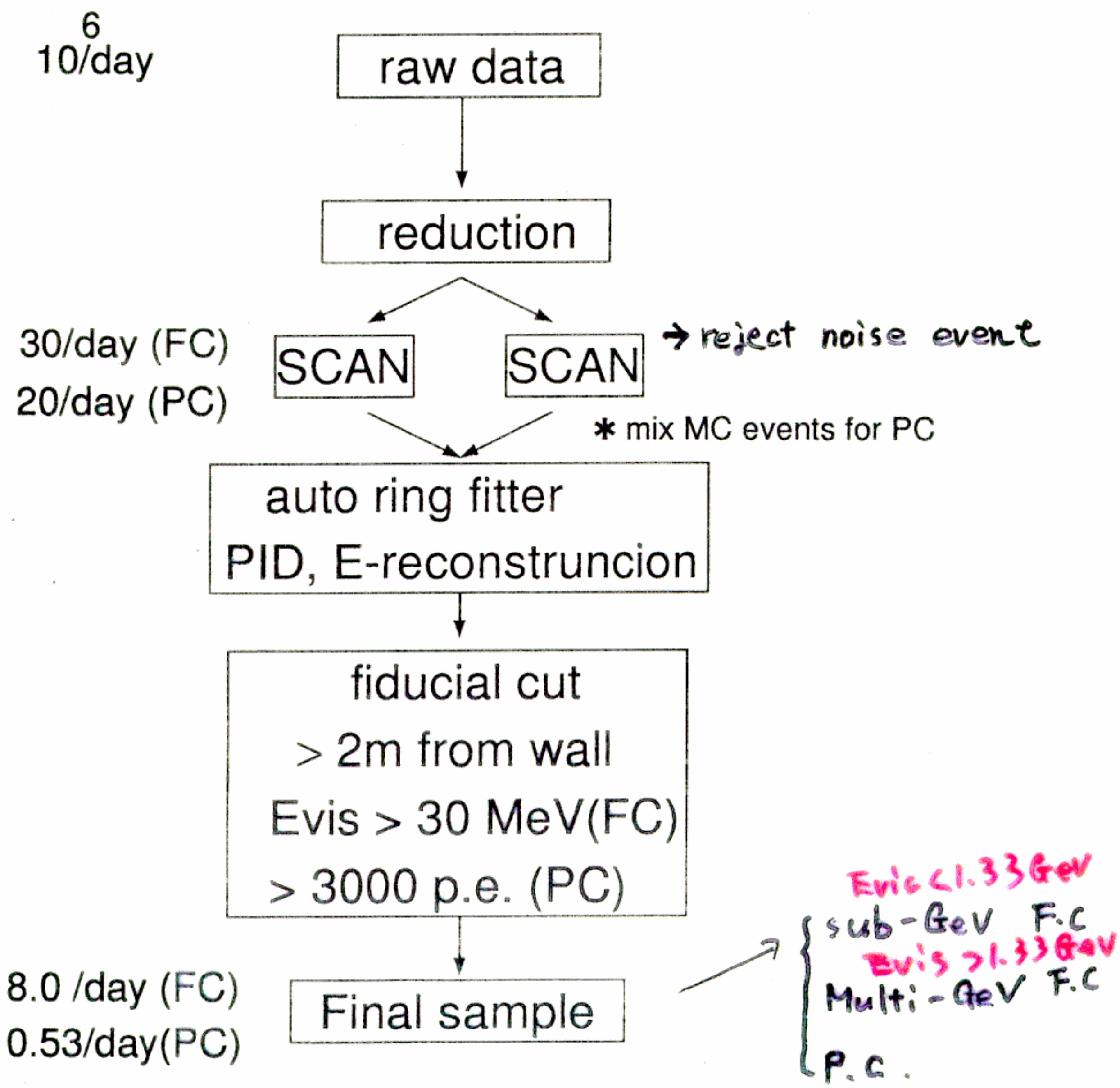
Atmospheric ν History

KAM(sub-GeV)	$0.60^{+0.06}_{-0.05}\pm0.05$	7.7ktyr
(multi-GeV)	$0.57^{+0.08}_{-0.07}\pm0.07$	8.2,6.0ktyr
IMB	$0.54\pm0.05\pm0.12$	7.7ktyr
(multi-GeV)	$1.40^{+0.41}_{-0.30}\pm0.3$	2.1ktyr
Frejus(FC+PC)	$1.00\pm0.15\pm0.08$	1.56ktyr
NUSEX	$0.99^{+0.35}_{-0.25}$	0.4ktyr
SoudanII	$0.61\pm0.15\pm0.05$	3.2ktyr

$$\frac{(\mu/e)\ \text{data}}{(\mu/e)_{MC}}$$

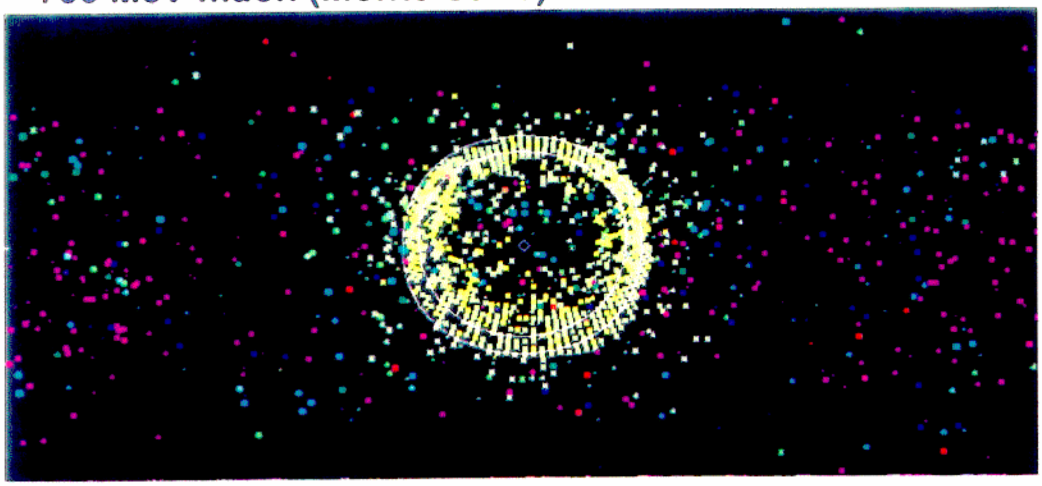



Fully contained event
e or μ
No hit in Outer Detector
Partially contained event
μ
(97%)
one hit in Outer Detector


10^6/day
raw data
reduction
30/day (FC)
20/day (PC)
SCAN
SCAN
→ reject noise event
* mix MC events for PC
auto ring fitter
PID, E-reconstruncion
fiducial cut
> 2m from wall
Evis > 30 MeV(FC)
> 3000 p.e. (PC)
8.0 /day (FC)
0.53/day(PC)
Final sample
Evis<1.33GeV
sub-GeV F.C
Evis>1.33GeV
Multi-GeV F.C
P.C.

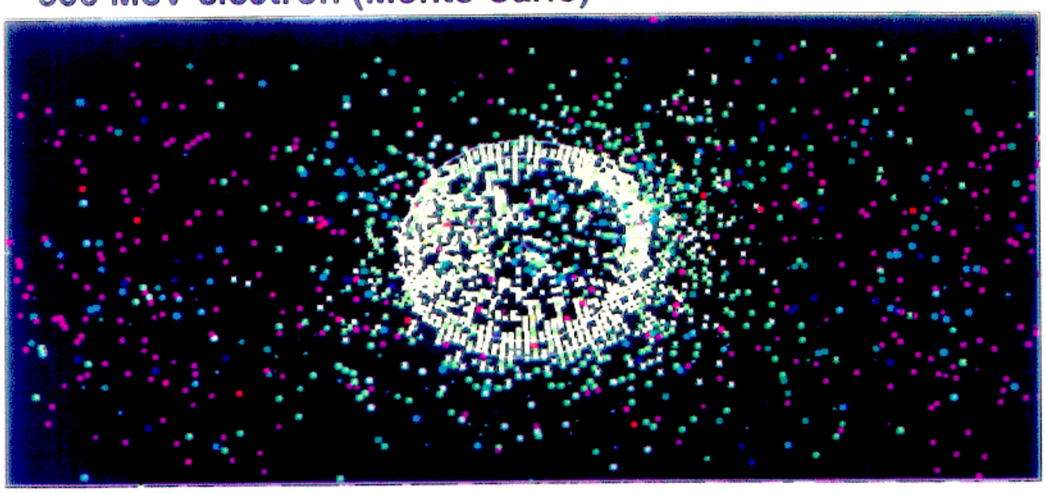
PARTICLE IDENTIFICATION

700 MeV muon (Monte Carlo)



4023 photoelectrons, 1553 hits — non-showering

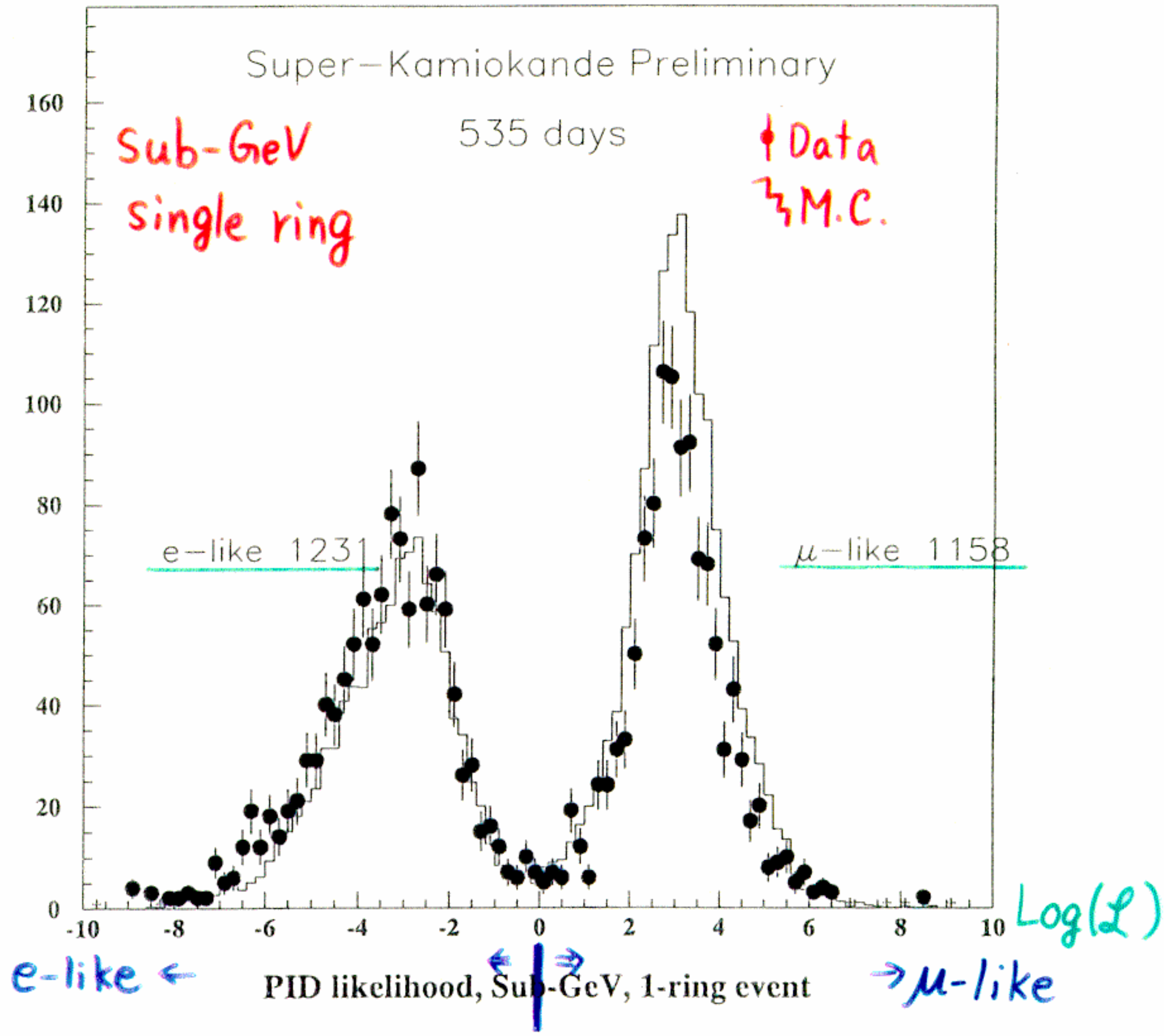
500 MeV electron (Monte Carlo)



3917 photoelectrons, 2086 hits — showering

projected view of detector as seen from fit vertex
color represents residual time from vertex

Likelihood for Particle identification



- mis-identification : 0.6 ± 0.1% for sub-GeV
  ~2% for multi-GeV
- Checked with e/μ beams @ KEK (E261A)

Sub-GeV

$E_{vis} < 1.33$ GeV

$P_e > 100$ MeV/c

$P_\mu > 200$ MeV/c

33.0 kt · yr
(535 days)

	Data	MC
1 ring		
e-like	1231	1049.1
μ-like	1158	1573.6
Multi Ring	911	980.7

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.63 \,{}^{+0.026}_{-0.025} \pm 0.05$$

Multi-GeV

33.0 kt · yr
(535 days)

- Fully Contained (Evis > 1.33 GeV)

	Data	MC
1 ring		
e-like	290	236.0
μ-like	230	297.5
Multi Ring	533	560.1

- Partially Contained

	Data	MC
Total=μ–like	301	371.6

※ CC νμ /all P.C. = 0.98

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.65 \pm 0.05 \pm 0.08$$

source of e-like/μ-like events (M.C. simulation)

sub GeV 1-ring

		e-like		μ-like	
$\nu_e, \bar{\nu}_e$ CC	QE (quesi-elastic)	4720	70.89%	20	0.19%
	non-QE	1303	19.57%	8	0.07%
$\nu_\mu, \bar{\nu}_\mu$ CC	QE	20	0.30%	8137	75.78%
	non-QE	80	1.20%	2166	20.17%
NC		535	8.04%	407	3.79%

e-like $\nu_e, \bar{\nu}_e$ CC: ~90%; μ-like $\nu_\mu, \bar{\nu}_\mu$ CC: 96%

Multi GeV 1-ring

		e-like		μ-like	
$\nu_e, \bar{\nu}_e$ CC	QE	552	40.86%	1	0.05%
	non-QE	641	47.45%	3	0.15%
$\nu_\mu, \bar{\nu}_\mu$ CC	QE	15	1.11%	1080	52.27%
	non-QE	56	4.15%	977	47.29%
NC		87	6.44%	5	0.24%

e-like $\nu_e, \bar{\nu}_e$ CC: 88%; μ-like $\nu_\mu, \bar{\nu}_\mu$ CC: 99%

P.C.

		e-like		μ-like	
$\nu_e, \bar{\nu}_e$ CC	QE	–	–	6	0.33%
	non-QE	–	–	21	1.14%
$\nu_\mu, \bar{\nu}_\mu$ CC	QE	–	–	339	18.44%
	non-QE	–	–	1458	79.33%
NC		–	–	14	0.76%

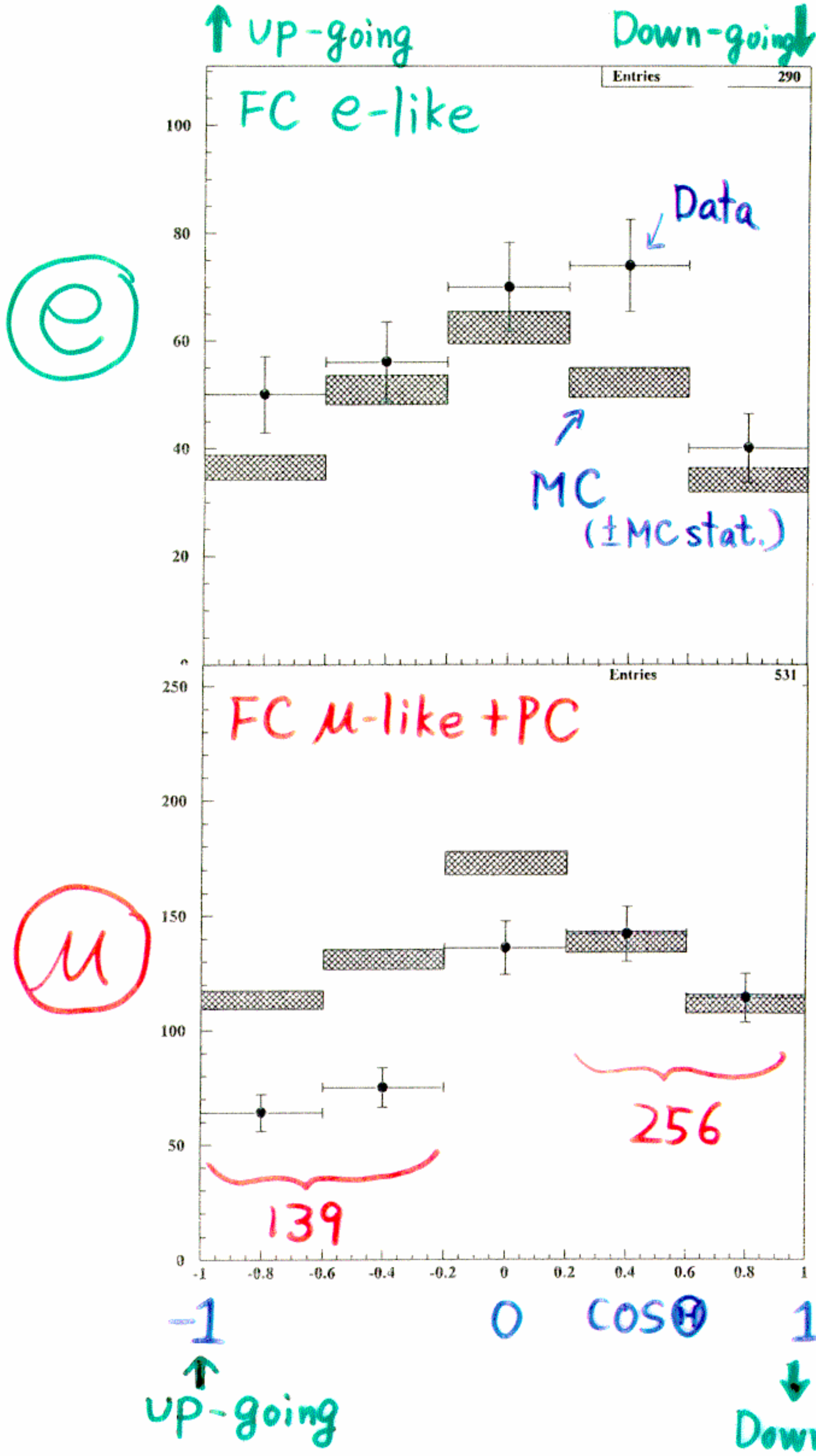
μ-like $\nu_\mu, \bar{\nu}_\mu$ CC: 98%

Q.E. : $\nu N \to \ell^{\pm} N'$

non-Q.E. : $\nu N \to \ell^{\pm} N' \pi \cdots$

Zenith angle dependence

(Multi-GeV)



χ^2 (shape) = 2.8/4 d.o.f. (59% C.L.)

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

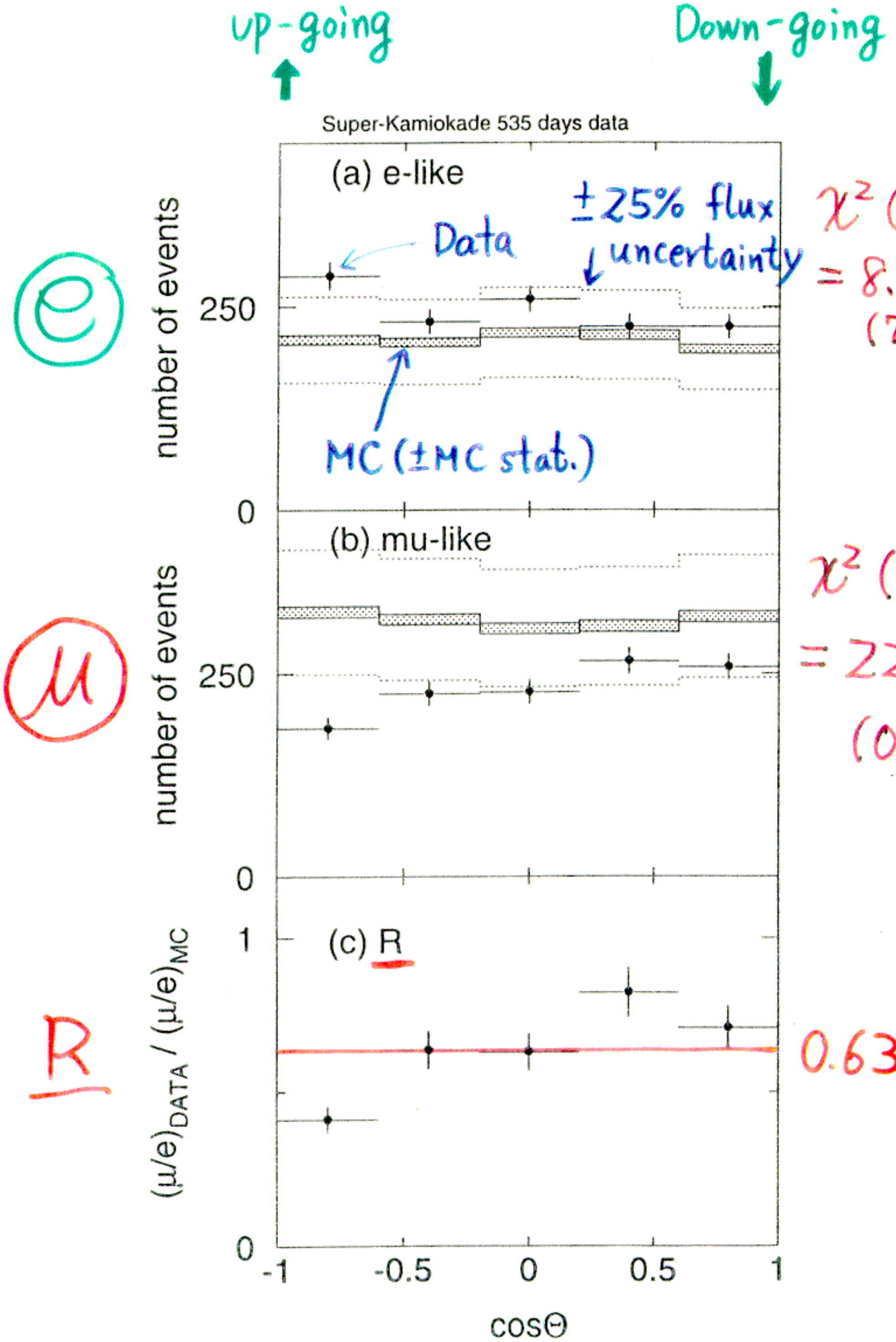
χ^2 (shape) = 30/4 d.o.f. (4.9×10^{-4}% C.L.)

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

* Up/Down systematic error
  - Prediction … 1.8% (flux calc. ≦ 1%, 1km rock … 1.5%)
  - Data … 2.1% (calib. … 0.7%, background < 2%)

Zenith angle dependence

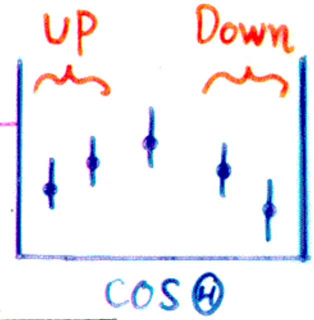
(Sub-GeV)



χ^2 (shape) = 8.5/4 d.o.f. (7.5% C.L.)

χ^2 (shape) = 22/4 d.o.f. (0.02% C.L.)

Up/Down vs. lepton momentum



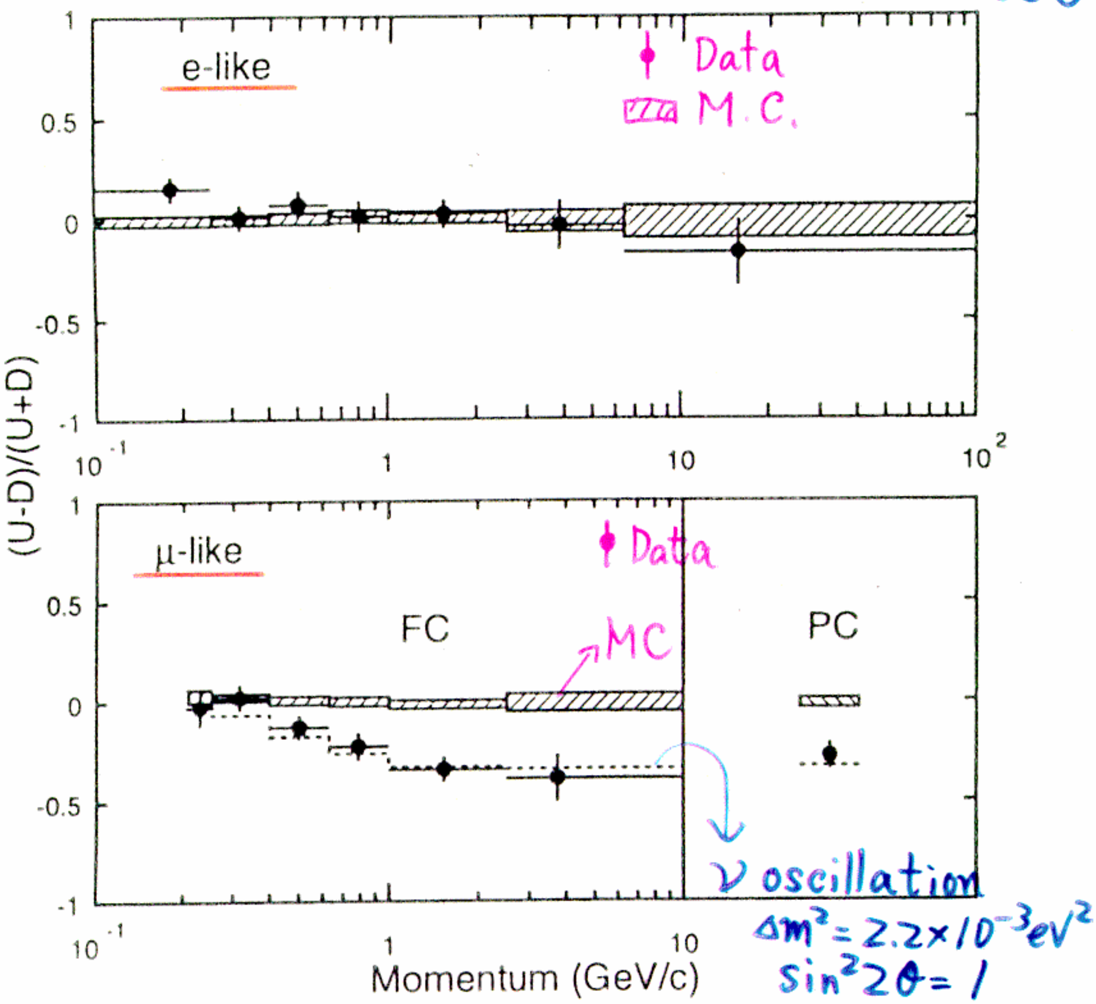
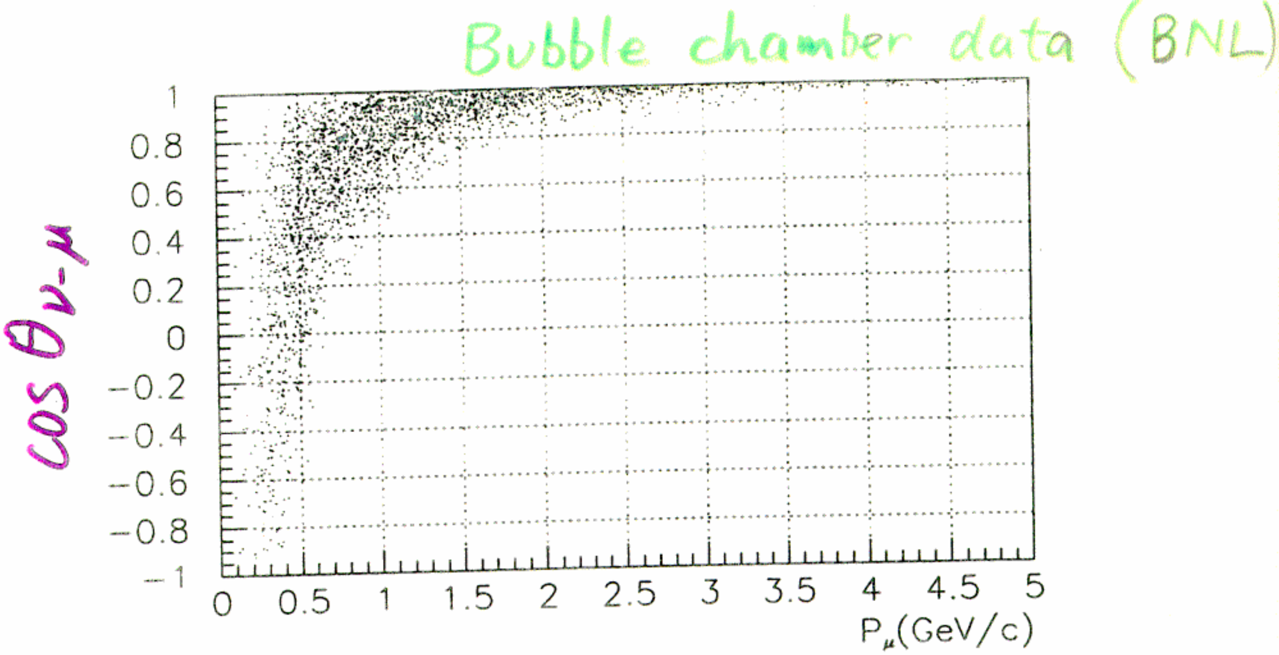
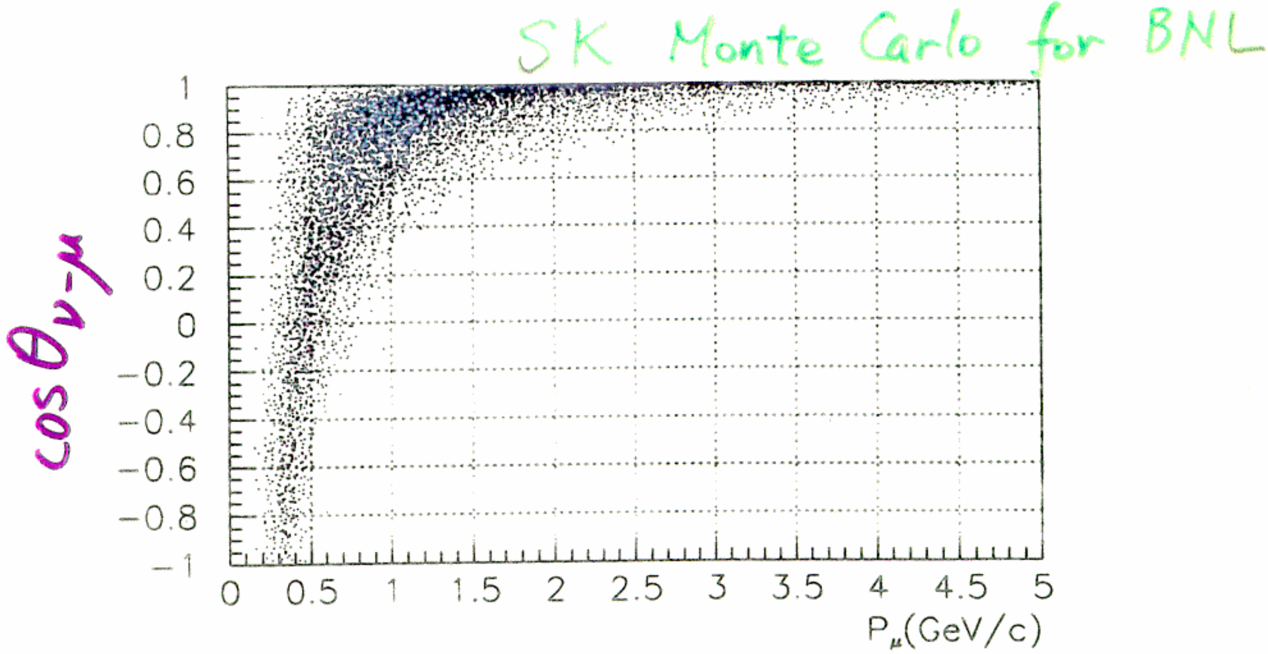


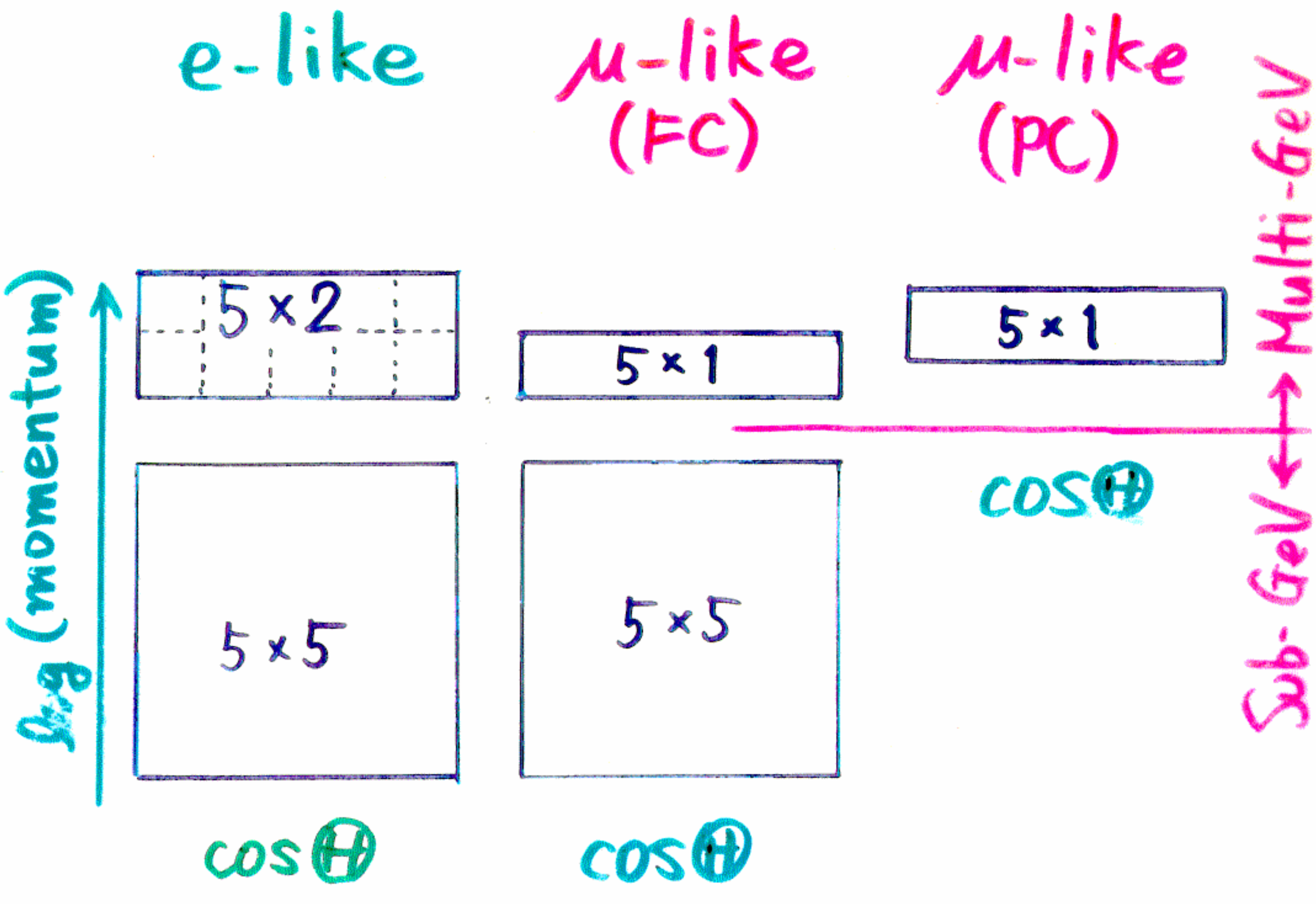
FIG. 1. The $(U - D)/(U + D)$ asymmetry as a function of momentum for FC e-like and μ-like events and PC events. While it is not possible to assign

ν- lepton angular correlation





Definition of χ^2 for $\begin{cases}\Delta m^2 \\ \sin^2 2\theta\end{cases}$



$$\chi^2(\sin^2 2\theta, \Delta m^2) = \sum \frac{(N_{data} - N_{exp'd})^2}{\sigma^2}$$

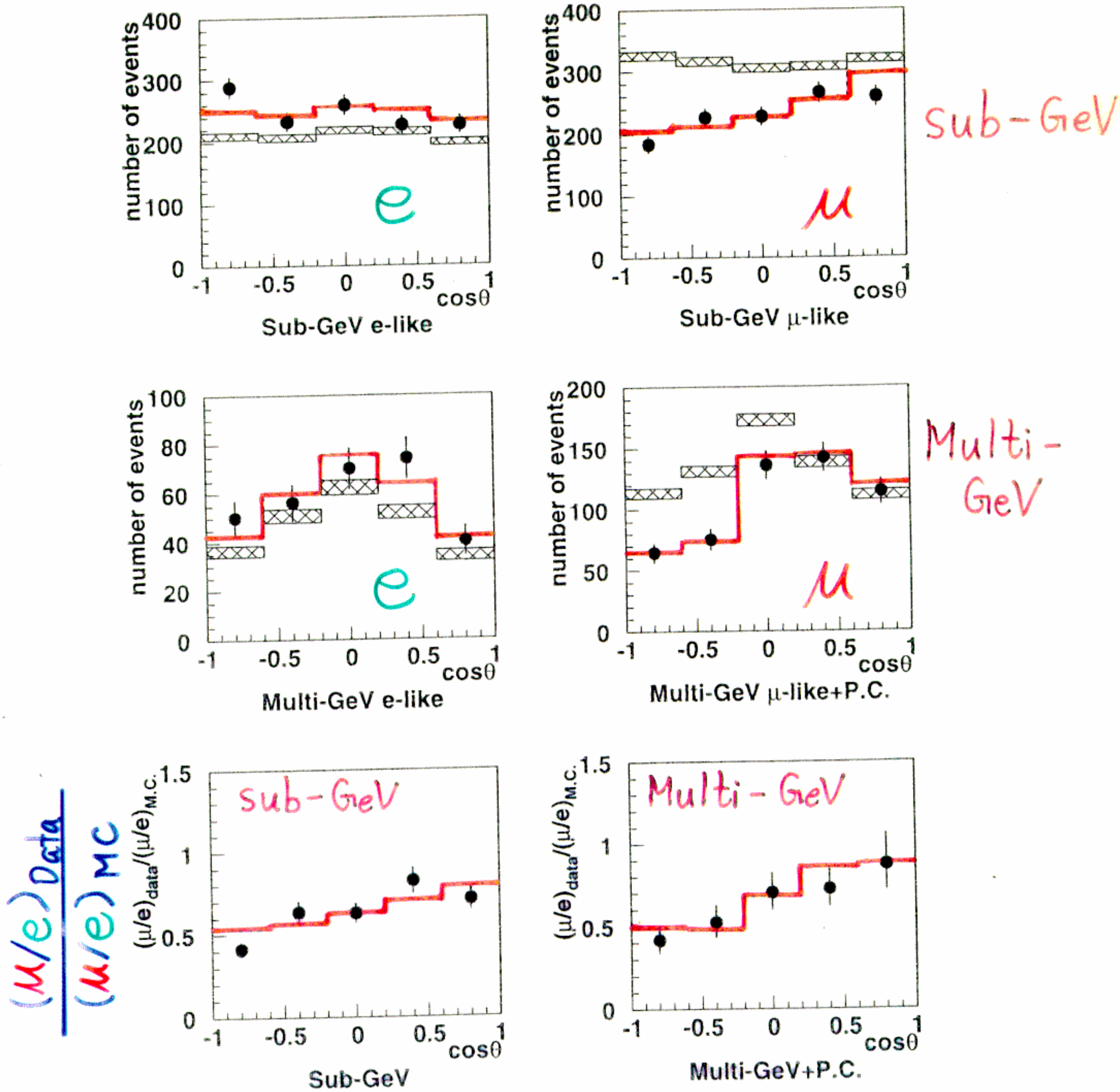
$$+ \sum_i \left(\frac{\alpha_i}{\sigma_i}\right)^2 \leftarrow \text{syst. error}$$

$$\downarrow$$

$$N_{exp'd} = N_{exp'd}(\sin^2 2\theta, \Delta m^2, \alpha_1, \alpha_2 \cdots)$$

Data vs. Oscillations

$\nu_\mu \to \nu_\tau$ ($\Delta m^2 = 2.2 \times 10^{-3}$ eV^2, $\sin^2 2\theta = 1$)

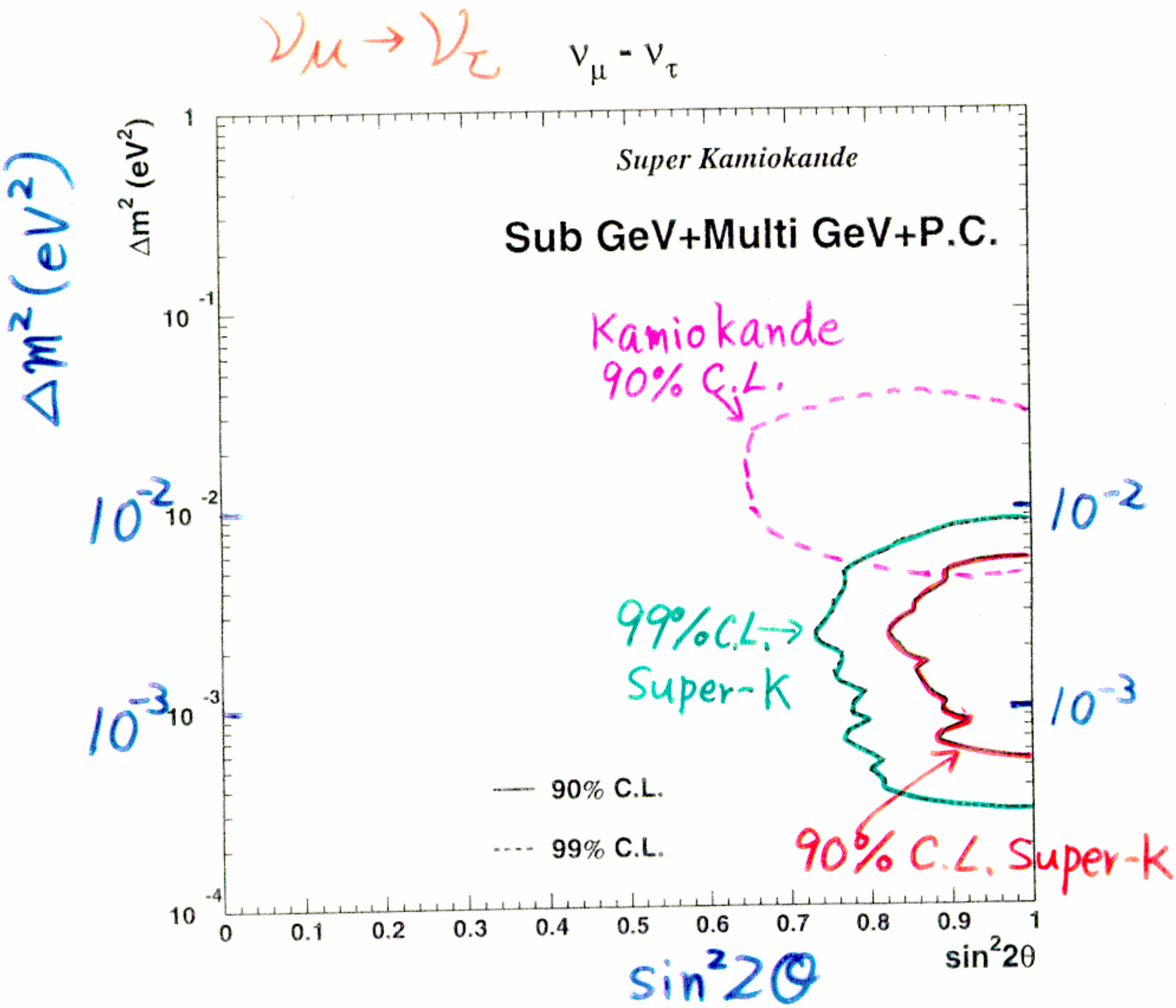


χ^2 (best fit) = 65/67 d.o.f.

χ^2 (No oscillation) = 135/67 d.o.f.

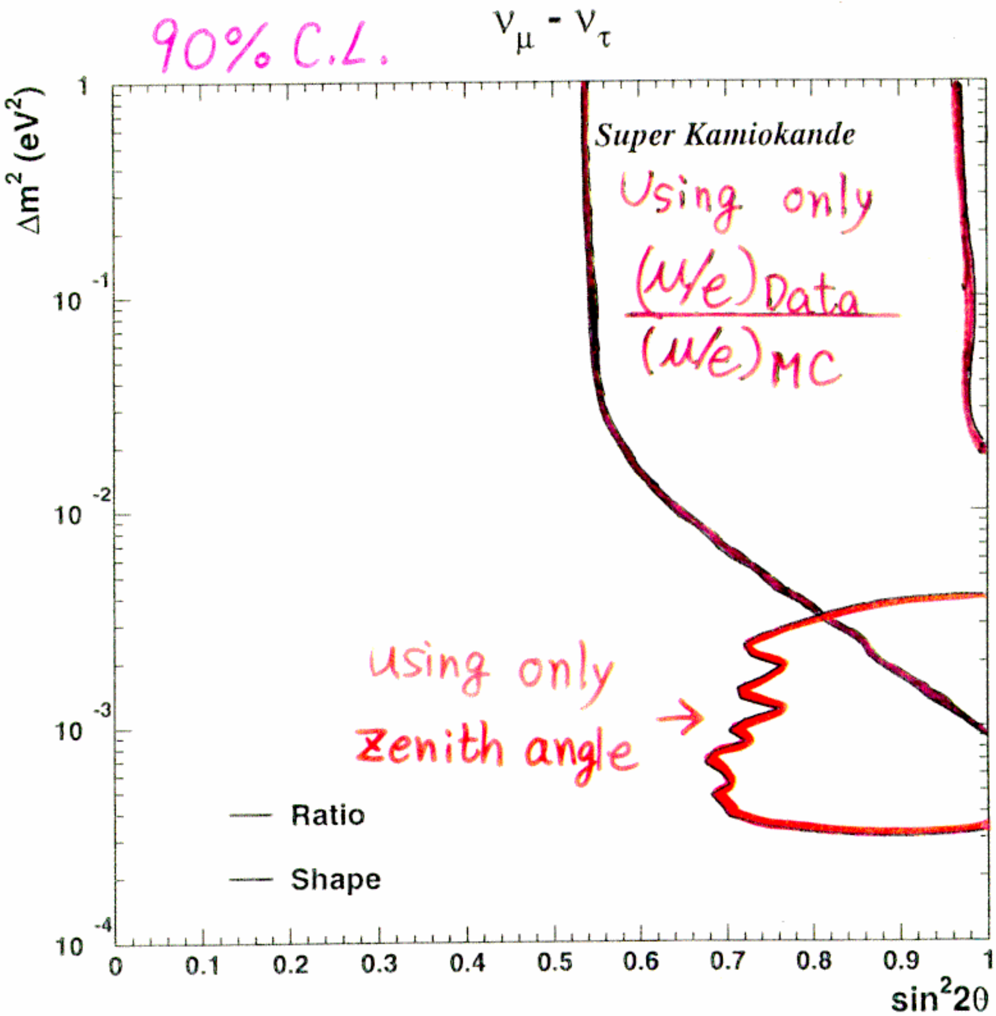
$\Delta\chi^2 = 70$!

Allowed region based on Contained events



Allowed region (Contained events)

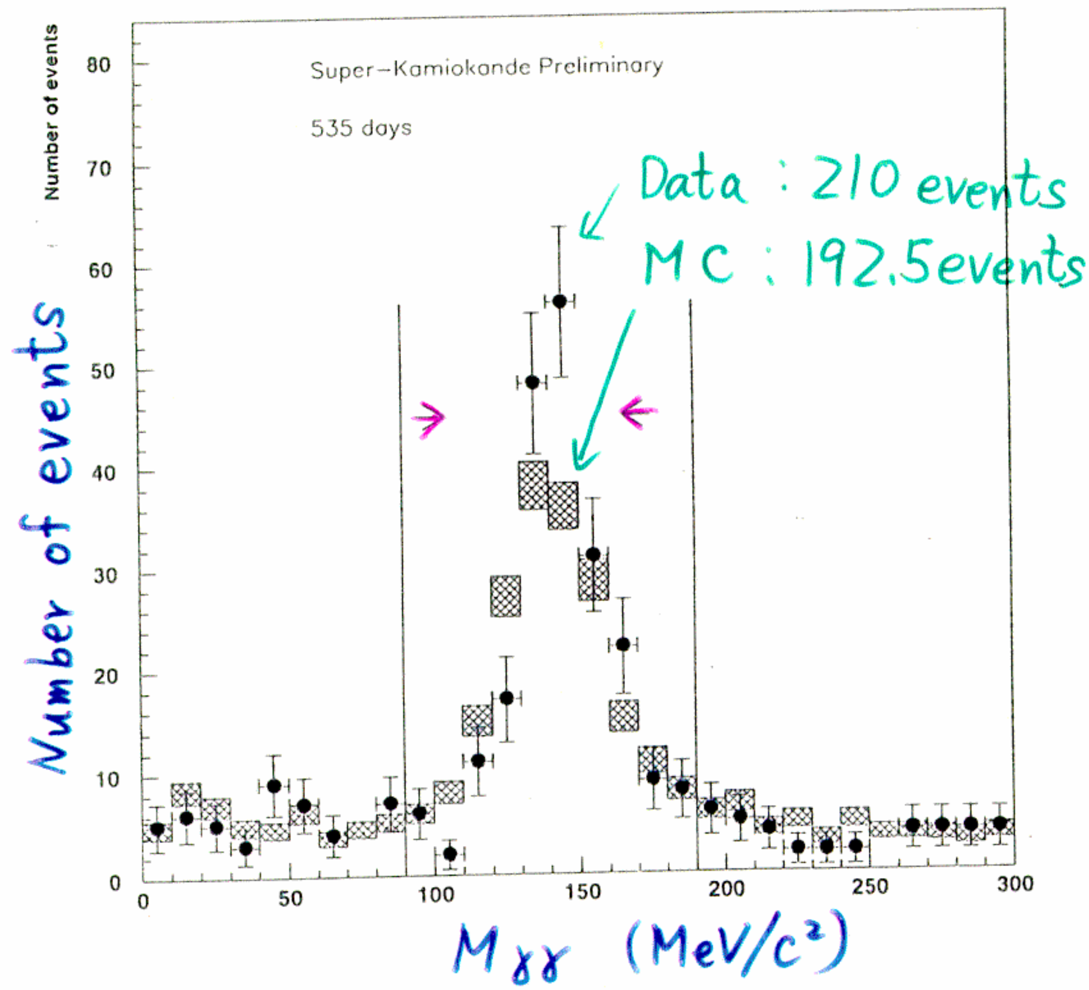
Consistency check



If $\nu_\mu \to \nu_\tau$ oscillations,

- NC (π^0-events) ···· no change
- ν_e (e-like events)··· no change

$$\Rightarrow \left(\pi^0/e\right)_{Data} = \left(\pi^0/e\right)_{MC}$$

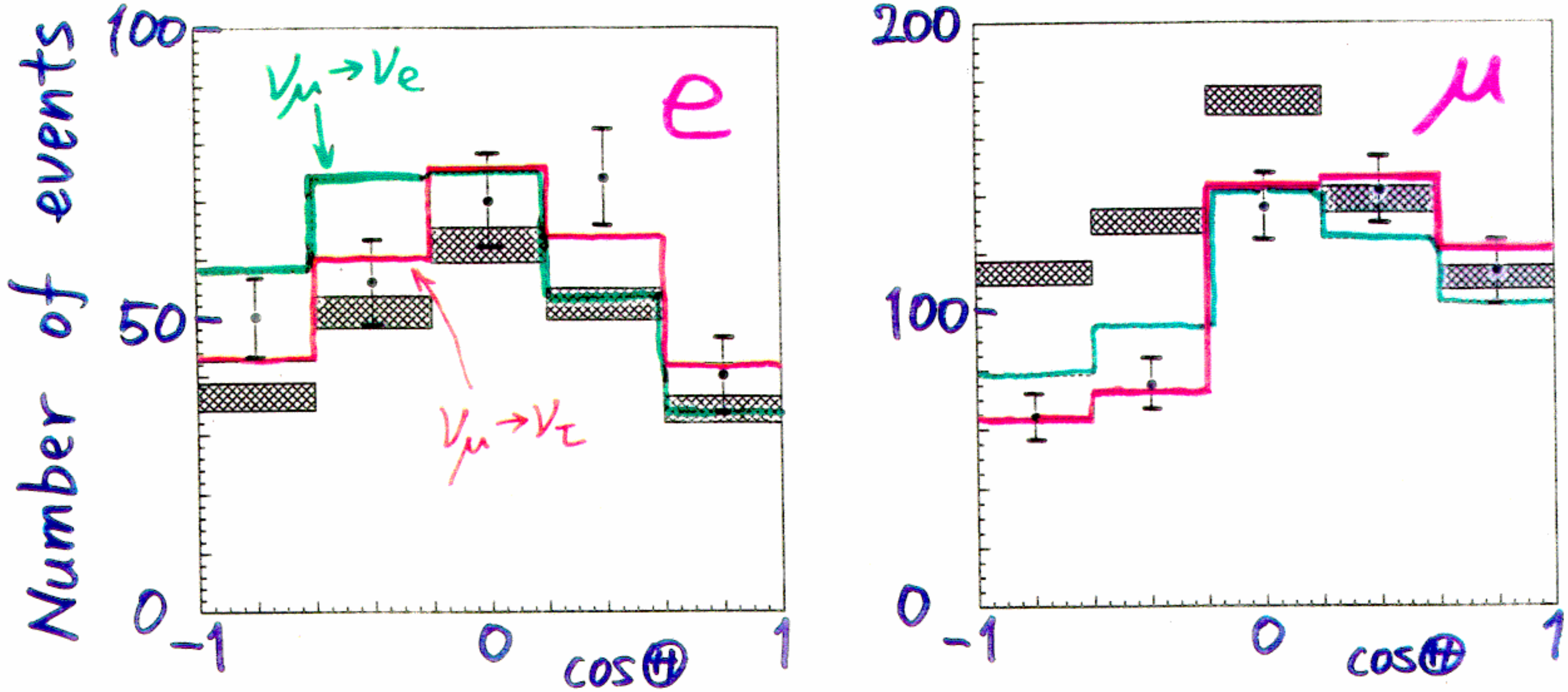


$$\frac{\left(\pi^0/e\right)_{Data}}{\left(\pi^0/e\right)_{MC}} = \frac{210/1231}{192.5/1049.1} = 0.93 \pm 0.07\,(stat.) \pm 0.19\,(sys.)$$

- Consistent with $\nu_\mu \to \nu_\tau$
- Need more study for reducing systematic error
  $\Rightarrow$ K2K long baseline experiment

$\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_e$?

Multi-GeV



$\chi^2(\nu_\mu \to \nu_\tau \text{ best fit}) = 65/_{67\,dof}$

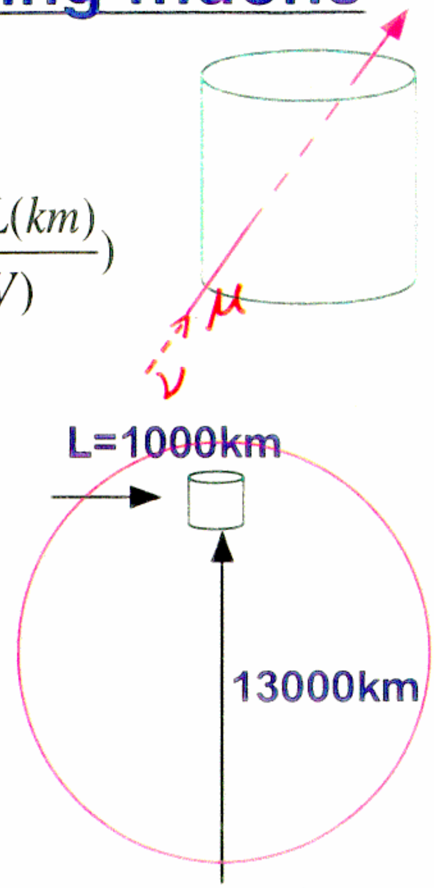
$\chi^2(\nu_\mu \to \nu_e \text{ best fit}) = 88/_{67}$

➡ SK data fit much better to $\nu_\mu \to \nu_\tau$.

Upward through-going muons

$<E_\nu> \sim 100$ GeV

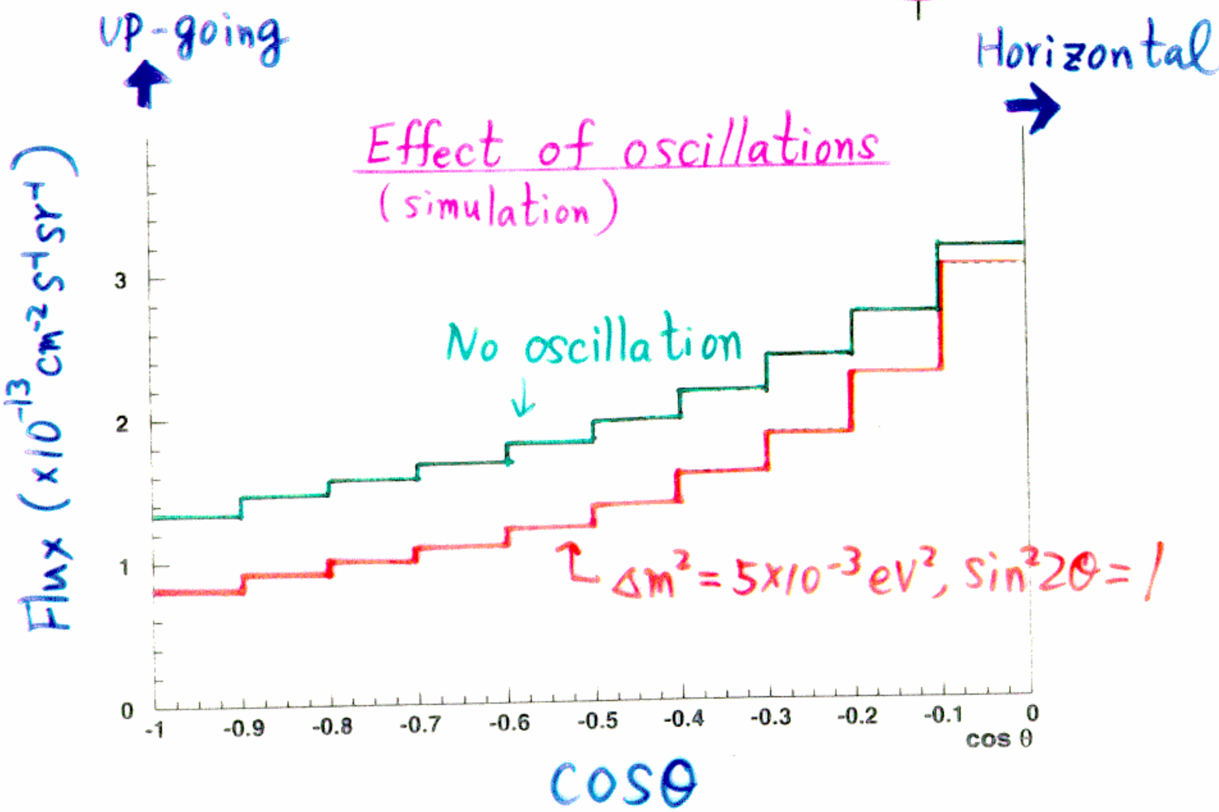
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \bullet \sin^2\left(\frac{1.27\Delta m^2 L(km)}{E(GeV)}\right)$$



e.g. if $\Delta m^2 = 5 \times 10^{-3}$ eV^2

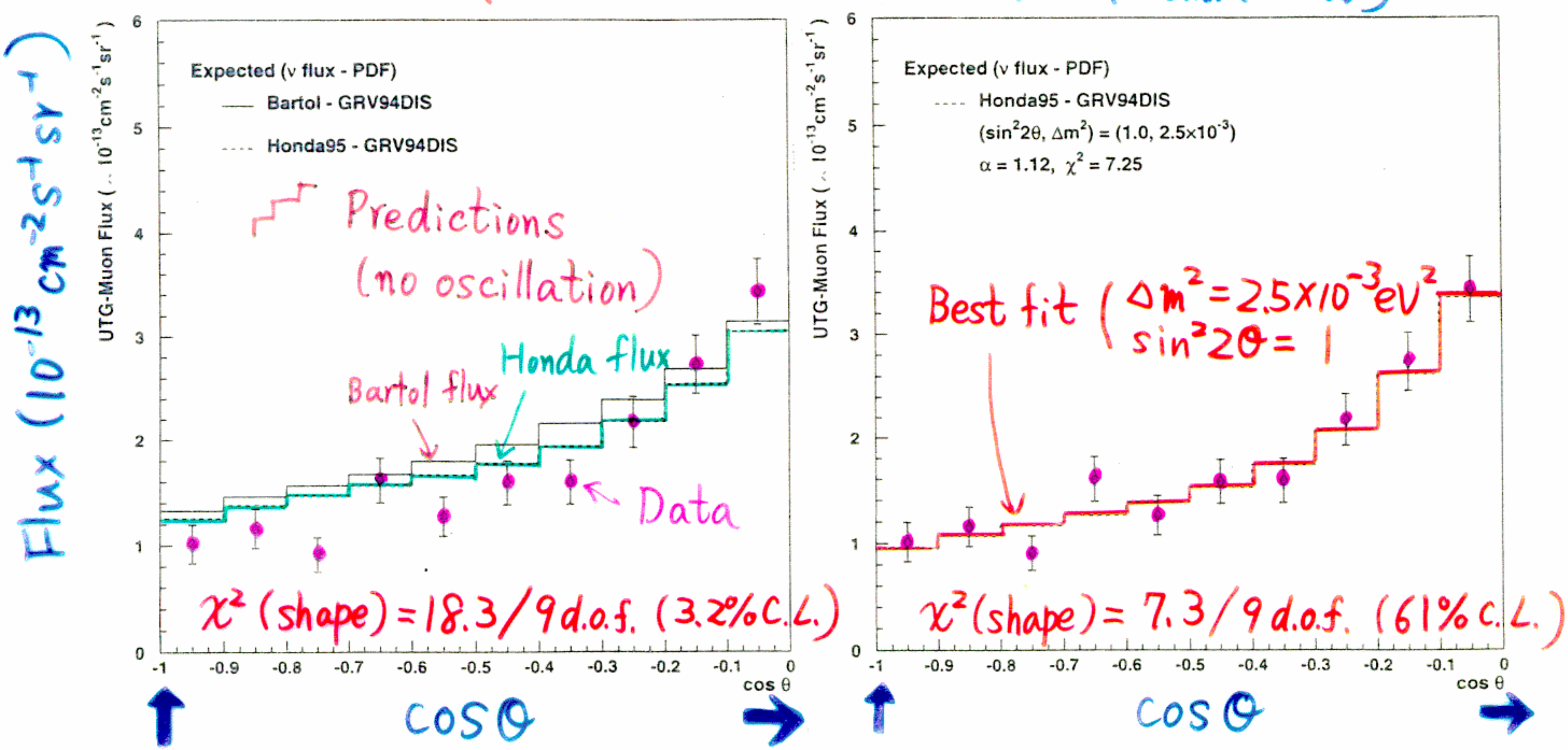
Horizontal muons
=> No oscillations

Vertical up-going muons
=> Oscillations



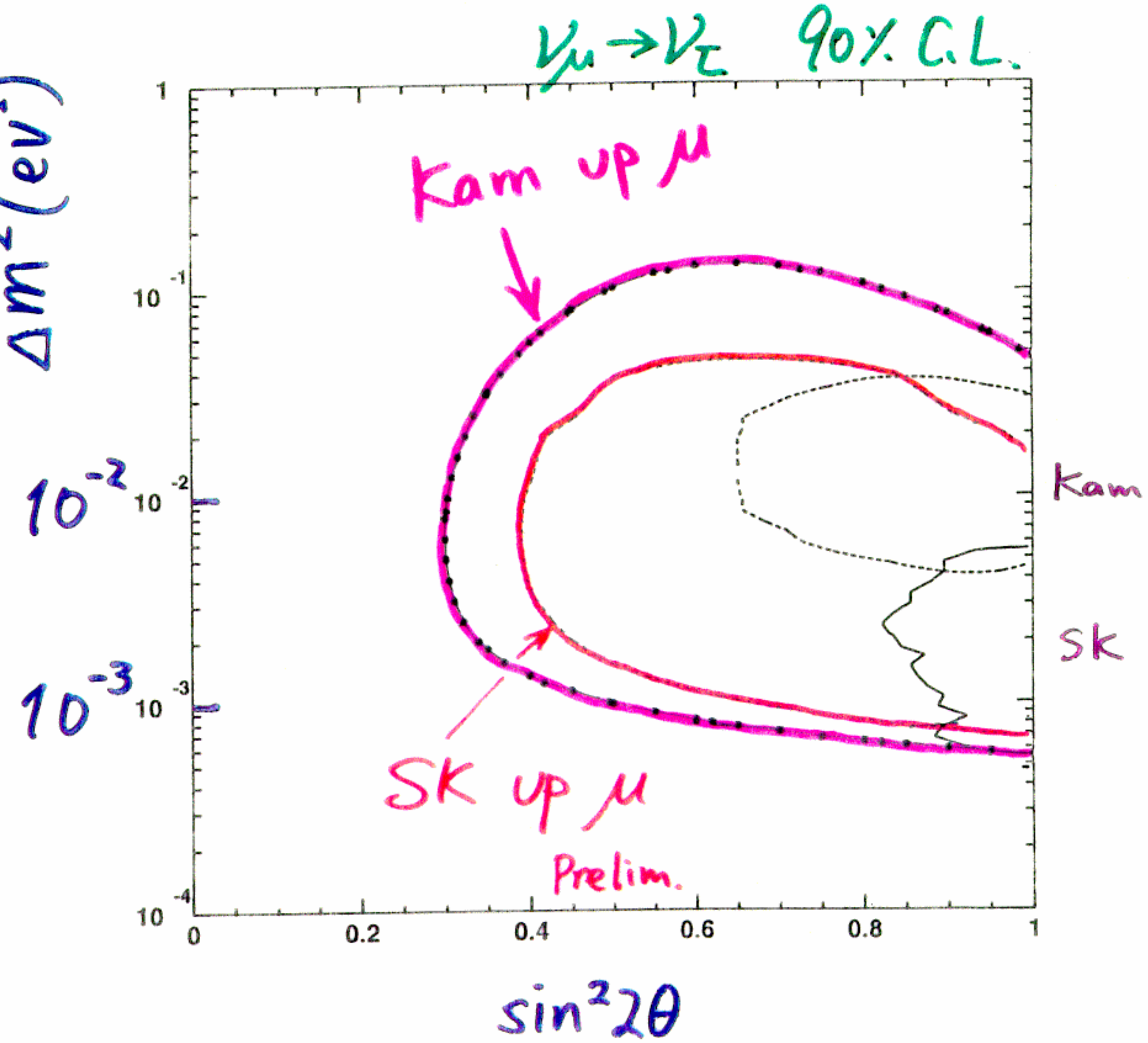
Upward through-going muon results

- 617 events / 534 days
- Flux
  - Data : $1.75 \pm 0.07 (stat.) \pm 0.09 (sys.)$ $(\times 10^{-13} cm^{-2} s^{-1} sr^{-1})$
  - Prediction : 2.02 ± 0.4 (Bartol flux)
  - 1.88 ± 0.4 (Honda flux)



Allowed region based on

↗ through muons



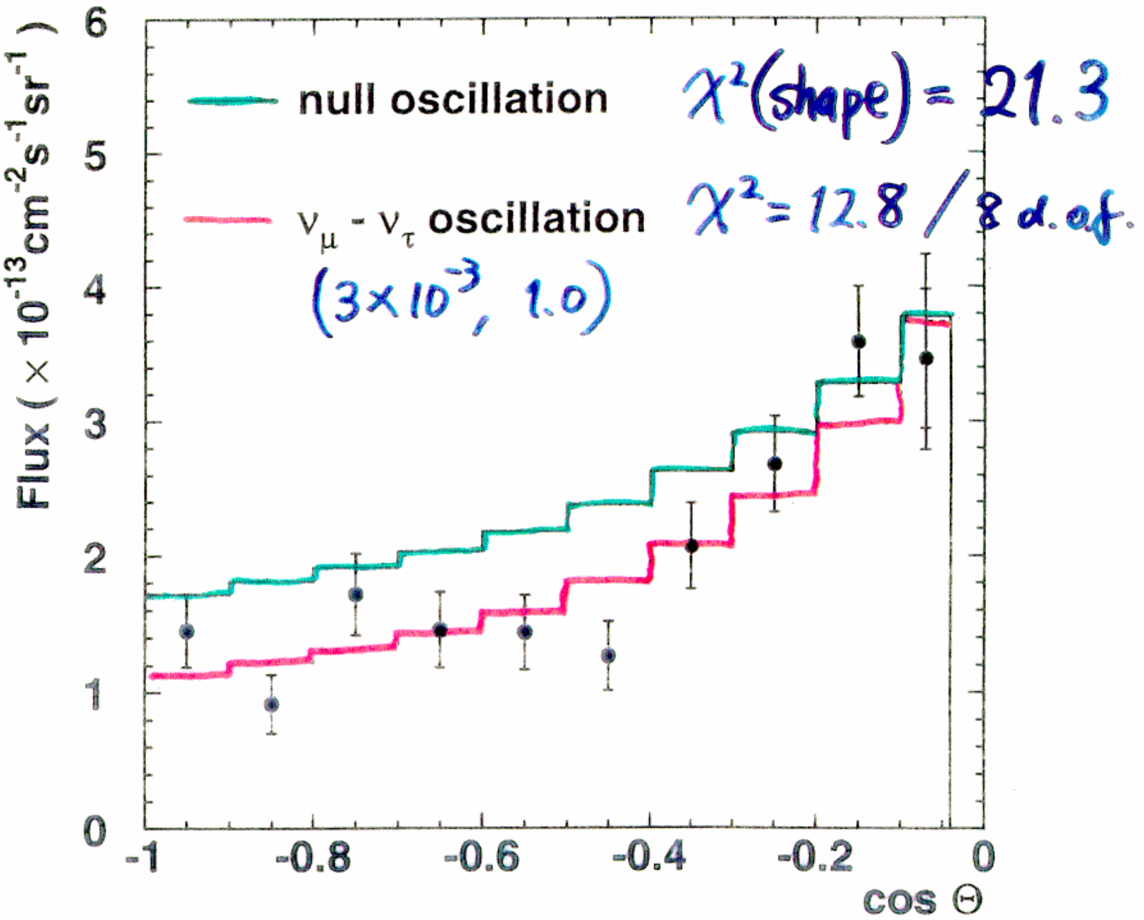
Final

Kamiokande up-going muon results

New

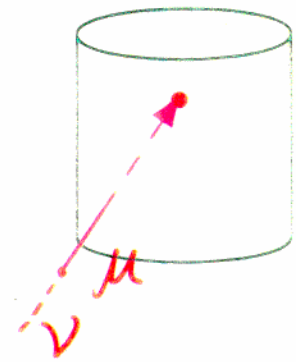
- 372 events / 6.7 yrs
- $\Phi_{obs} = (1.94 \pm 0.10 \pm^{0.07}_{0.06}) \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$

  $\Phi_{theo} = (2.46 \pm 0.54) \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$
- Zenith angle



Upward stopping muons

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \bullet \sin^2(\frac{1.27\Delta m^2 L(km)}{E(GeV)})$$

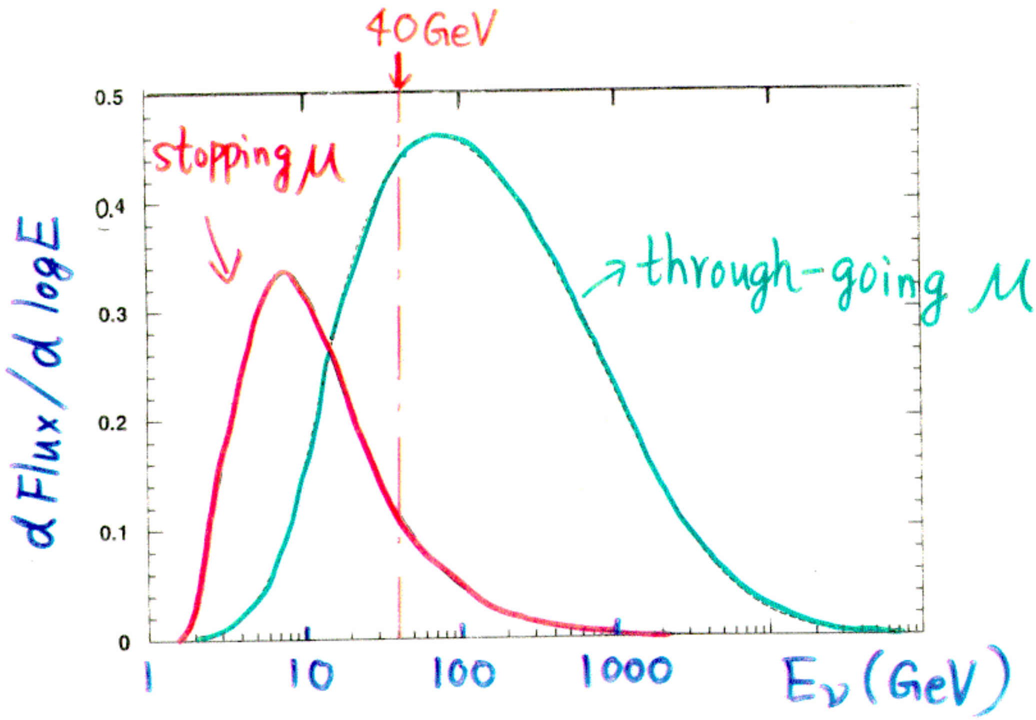


<L> ~ 6000 km

if $\Delta m^2 = 5 \times 10^{-3}$ eV^2

E_ν>> 40 GeV → No oscillations

E_ν< 40 GeV → Oscillations

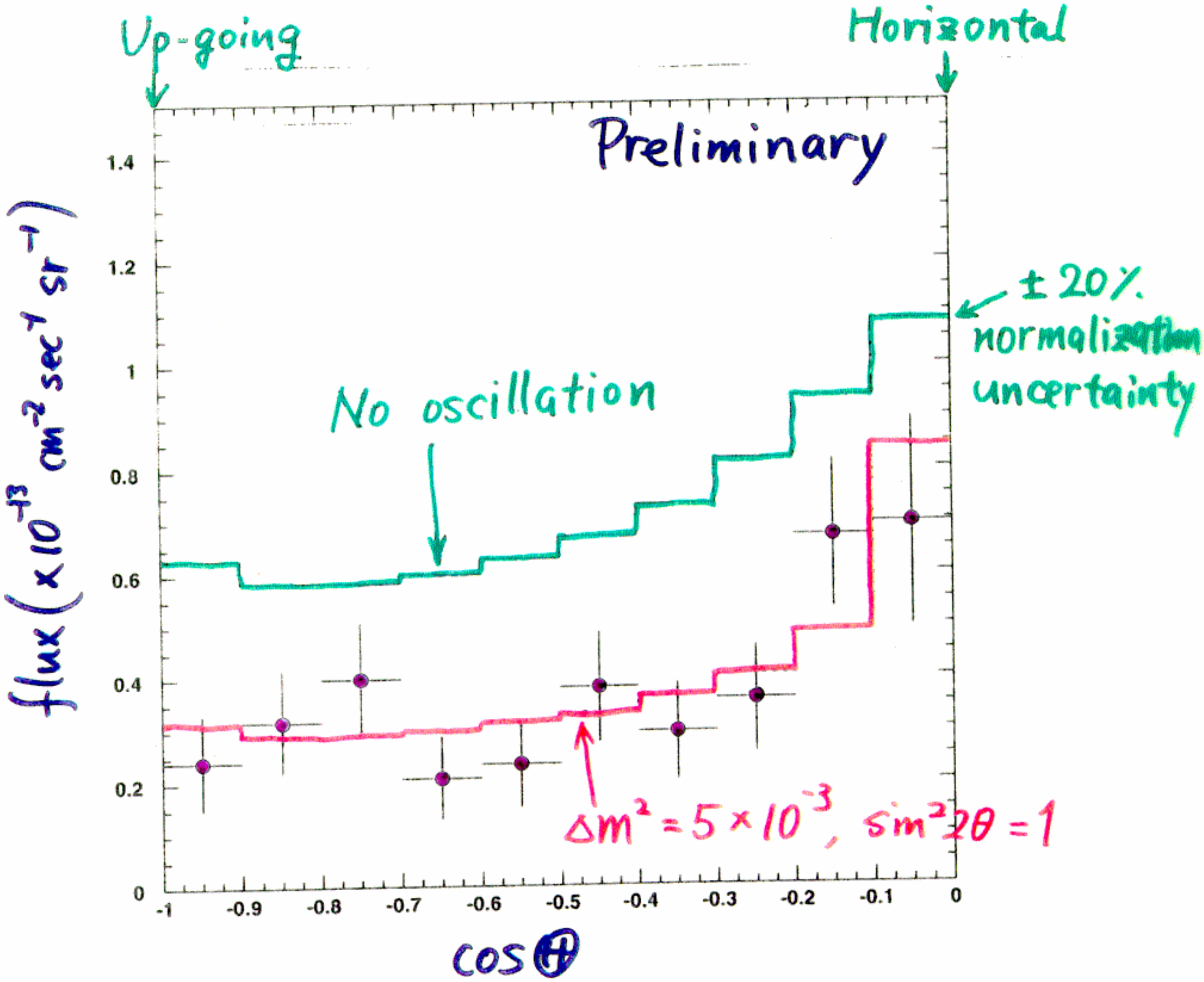


Oscillation →

$$\frac{(\uparrow \text{stopping } \mu / \uparrow \text{through } \mu)_{data}}{(\uparrow \text{stopping } \mu / \uparrow \text{through } \mu)_{calc}} < 1$$

↗ stopping muon data Super-Kamiokande

(137 events / 516 days)

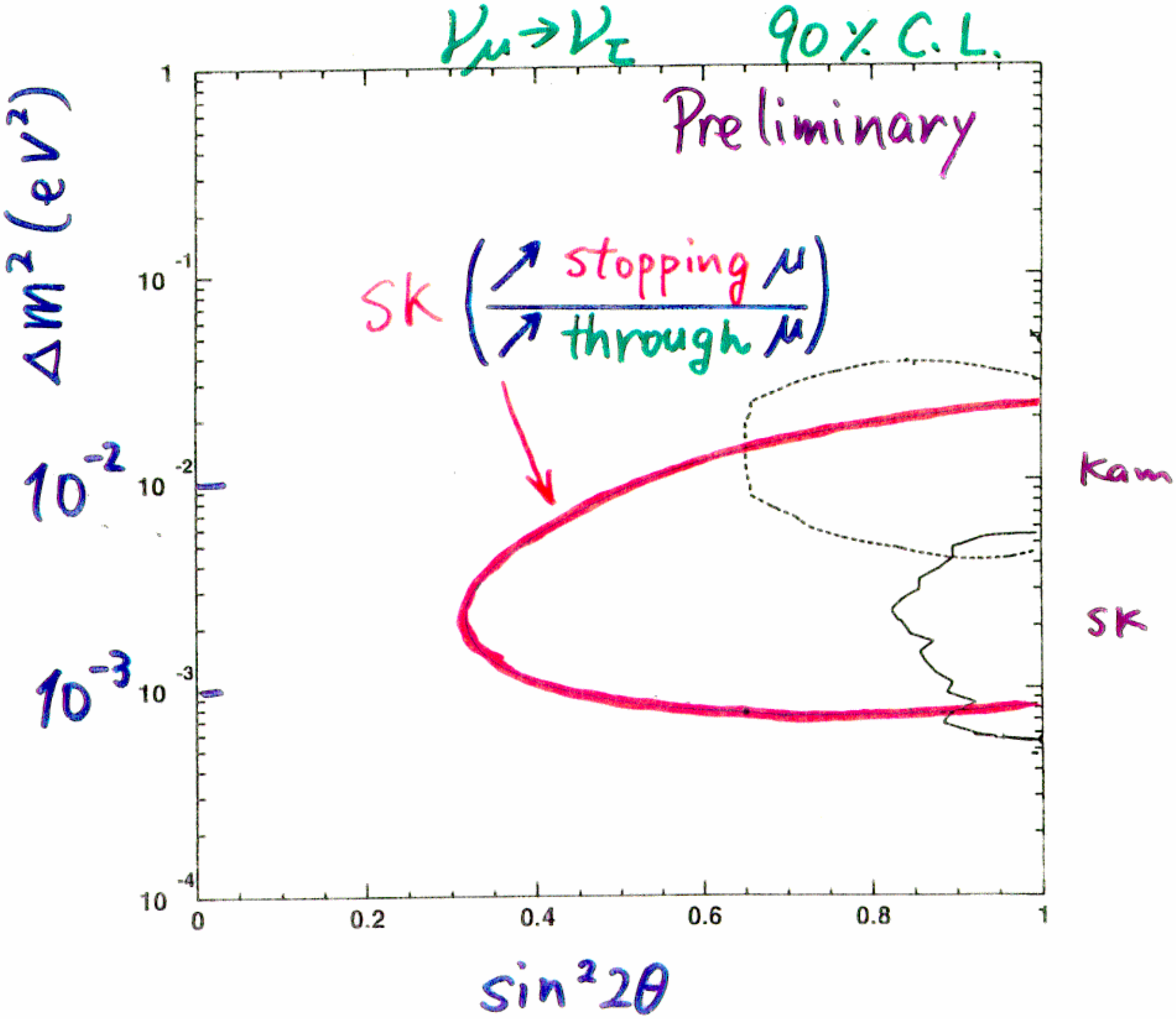


$$\frac{\left(\dfrac{\nearrow \text{stopping } \mu}{\nearrow \text{through } \mu}\right)_{\text{Data}}}{\left(\dfrac{\nearrow \text{stopping } \mu}{\nearrow \text{through } \mu}\right)_{\text{Prediction}}} = \frac{0.22 \pm 0.023 \pm 0.014}{0.39 \pm 0.05}$$

$$= 0.56 \pm 0.10 < 1$$

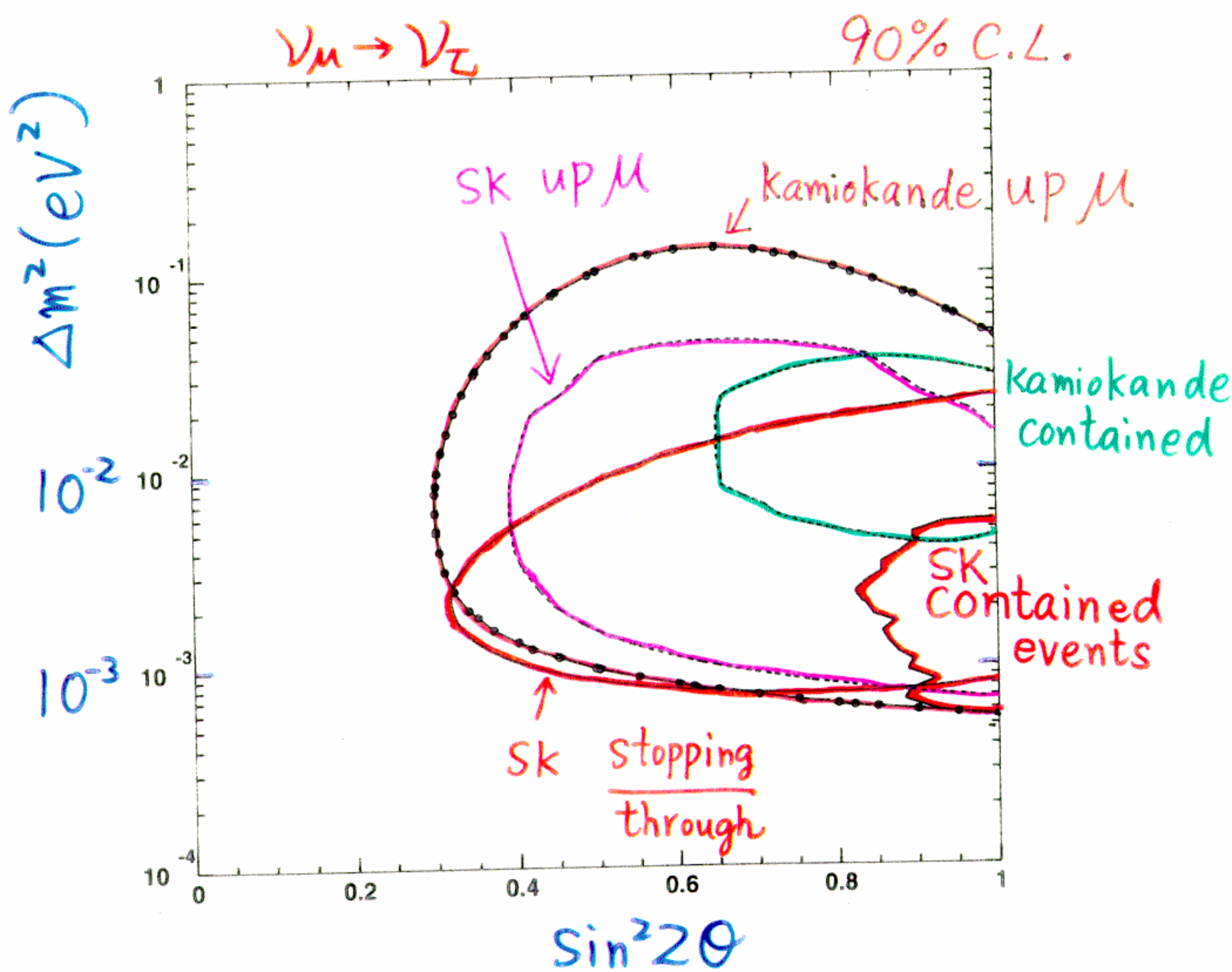
Allowed region based on

$\left(\frac{\nearrow \text{ stopping } \mu}{\nearrow \text{ through } \mu}\right)$



Summary for Atmospheric Neutrinos

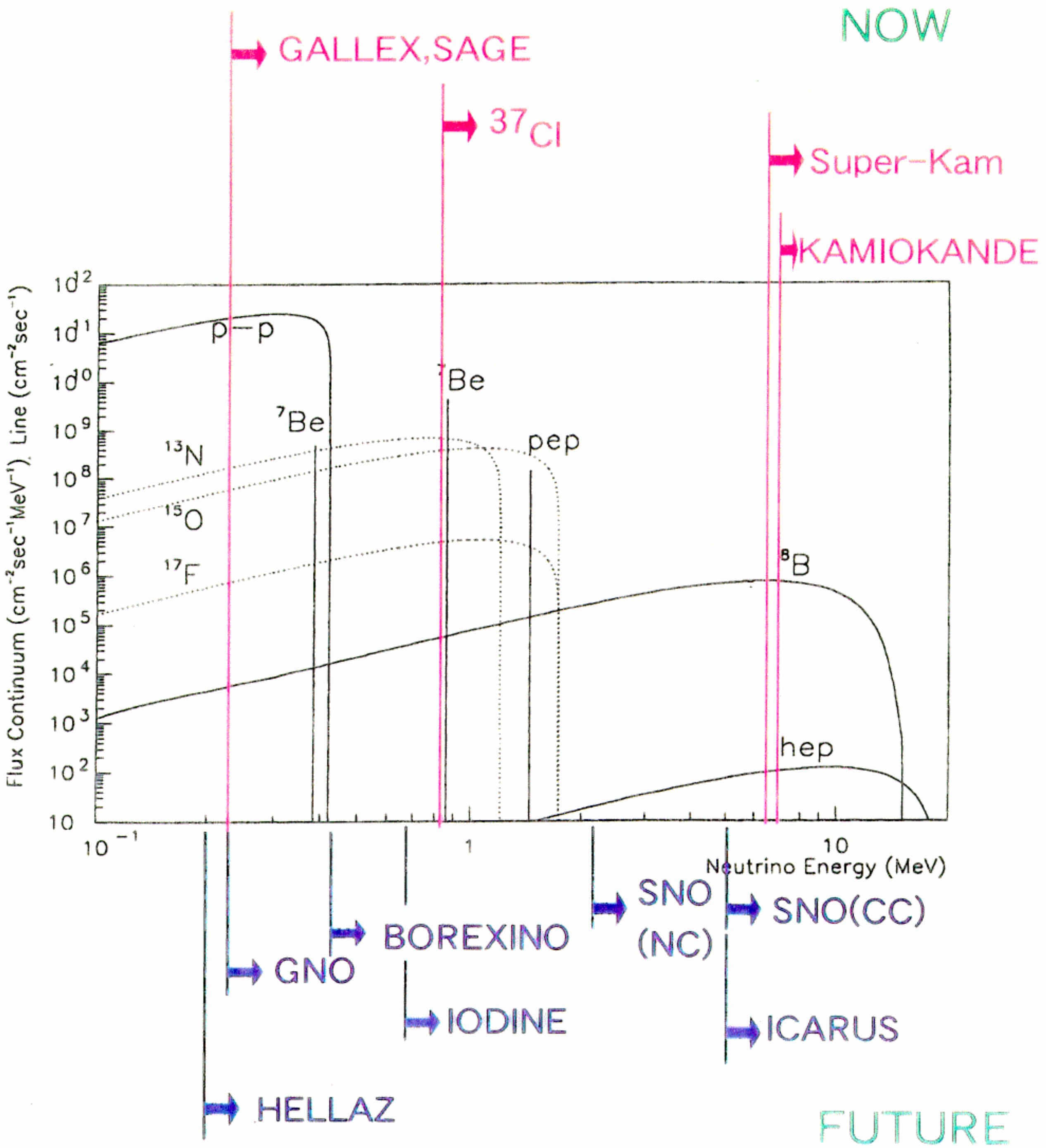
Evidence for ν_μ oscillations



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

$\sin^2 2\theta > 0.8$

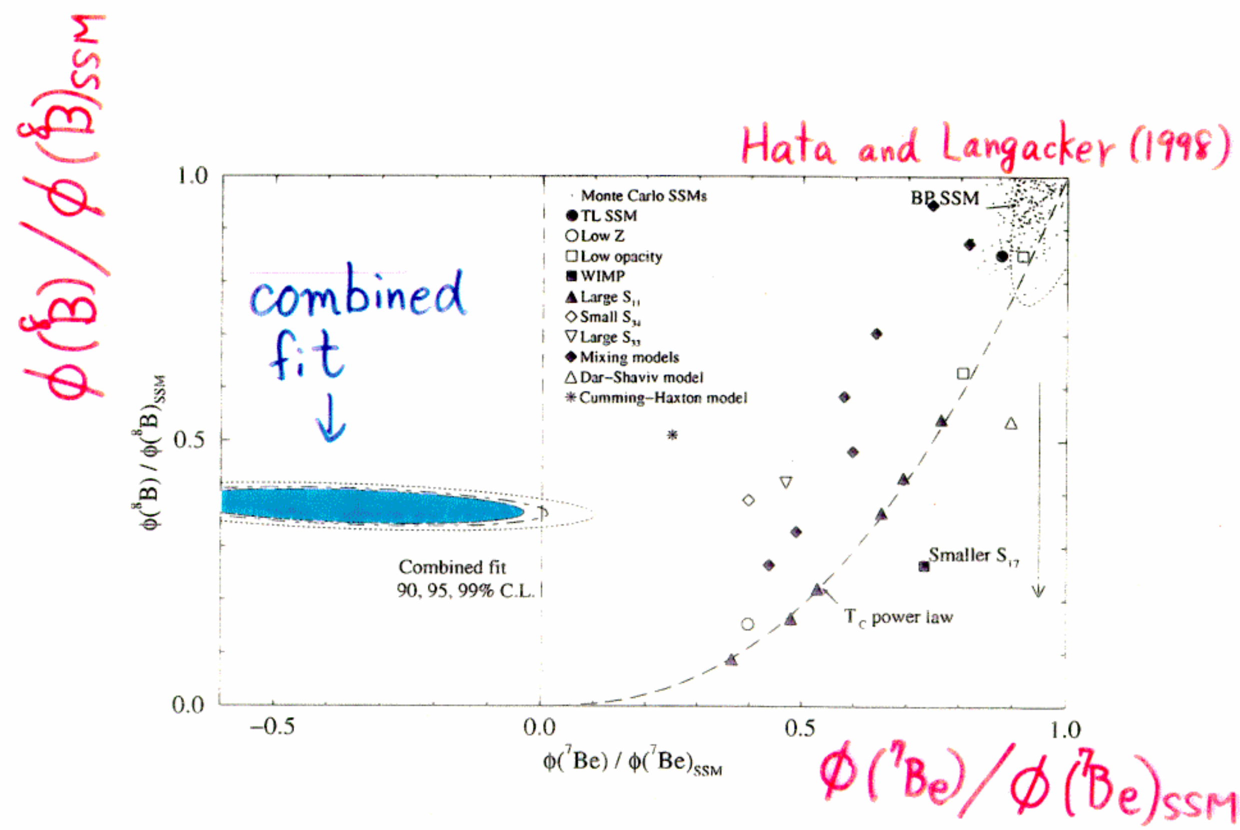
Solar Neutrinos



Solar Neutrino Experiments

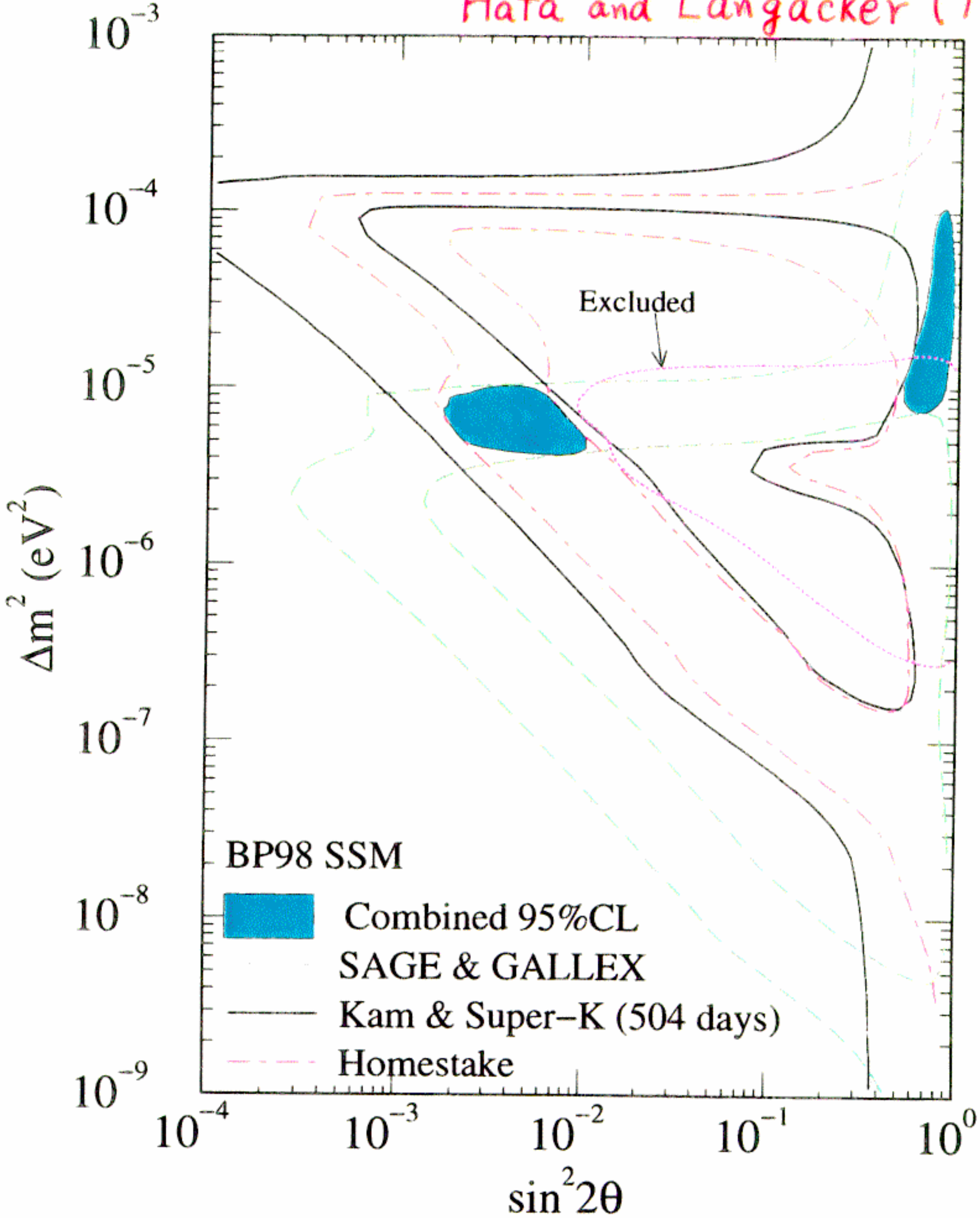
experiment	method	flux	Data/SSM (BP98)
^{37}Cl	$\nu_e{}^{37}$Cl	2.56 ± 0.23 SNU	0.33 ± 0.03
GALLEX	$\nu_e{}^{71}$Ga	78 ± 8 SNU	0.60 ± 0.06
SAGE	$\nu_e{}^{71}$Ga	67 ± 8 SNU	0.52 ± 0.06
Kamiokande	ν e scat.	$(2.80 \pm 0.19 \pm 0.33) \times 10^6$ /cm^2/sec	0.54 ± 0.07
Super-K.	ν e scat.	$(2.44 \pm 0.05$ $+0.09/-0.07) \times 10^6$ /cm^2/sec	0.47 ± 0.02

BP98: J.N.Bahcall et al., astro-ph/9805135.

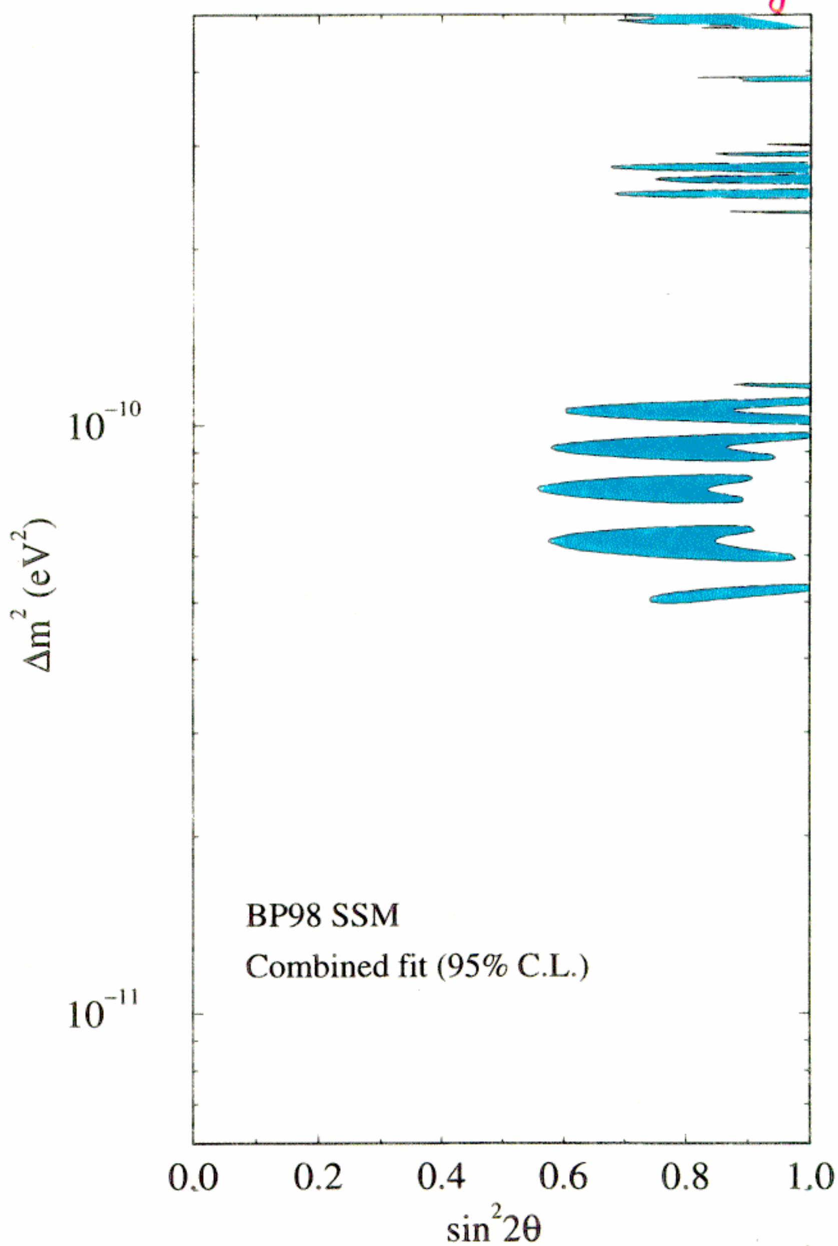


Astrophysical solutions have difficulty.

Hata and Langacker (1998)



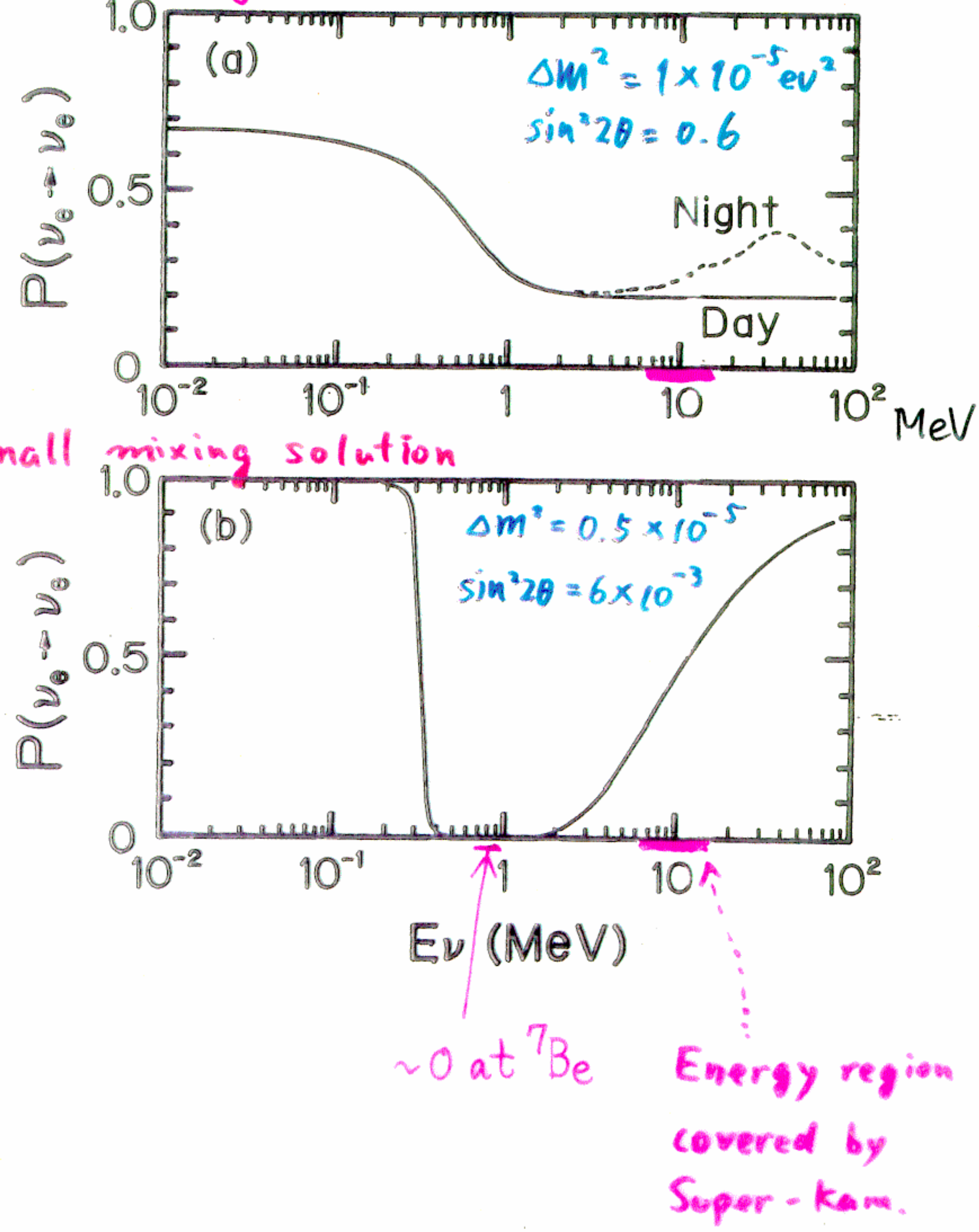
Hata and Langacker (1998)



To confirm the MSW, Vacuum solutions.....

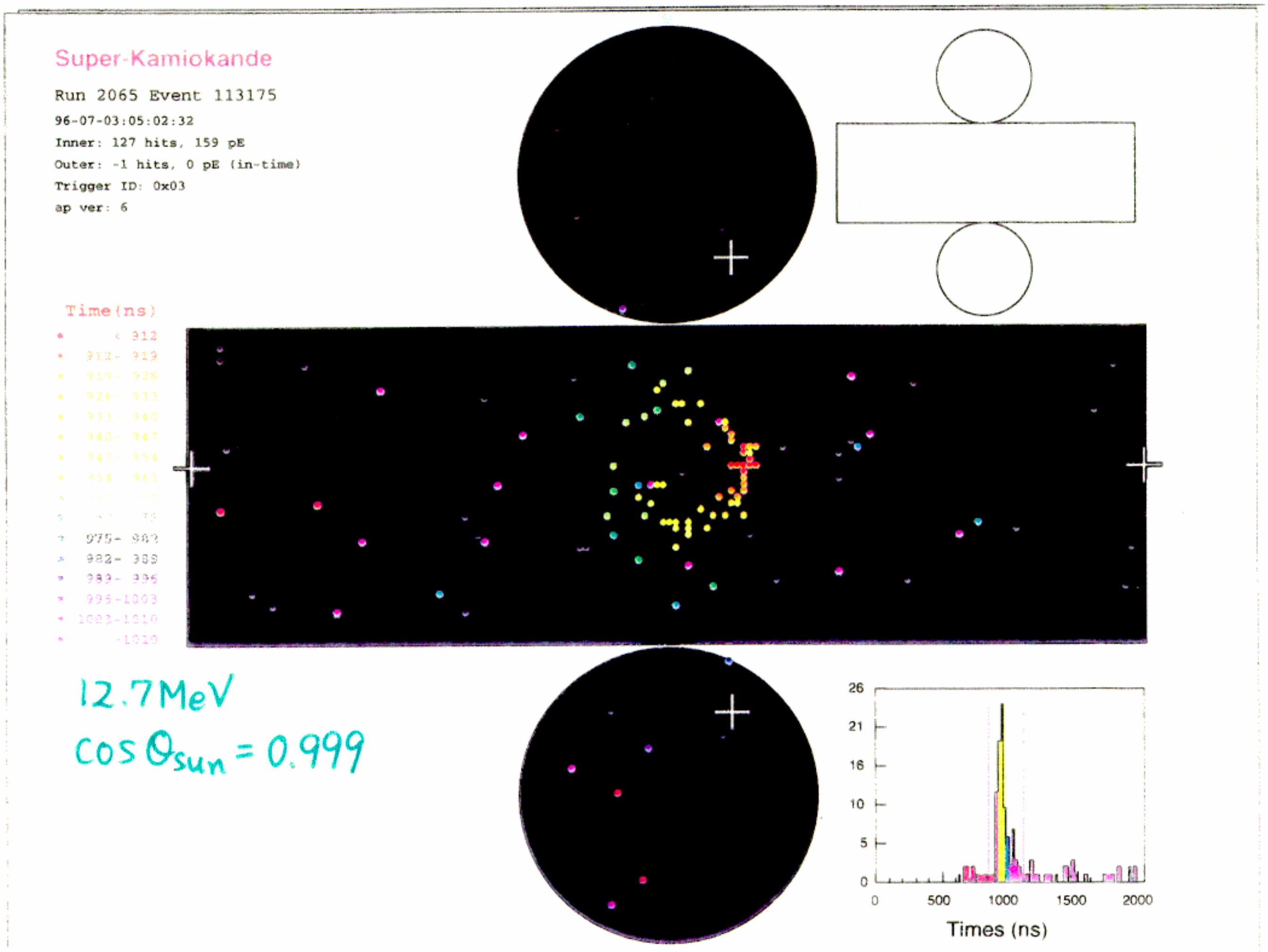
Large mixing solution

Small mixing solution



Typical low energy event

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



Detect solar neutrinos by

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

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

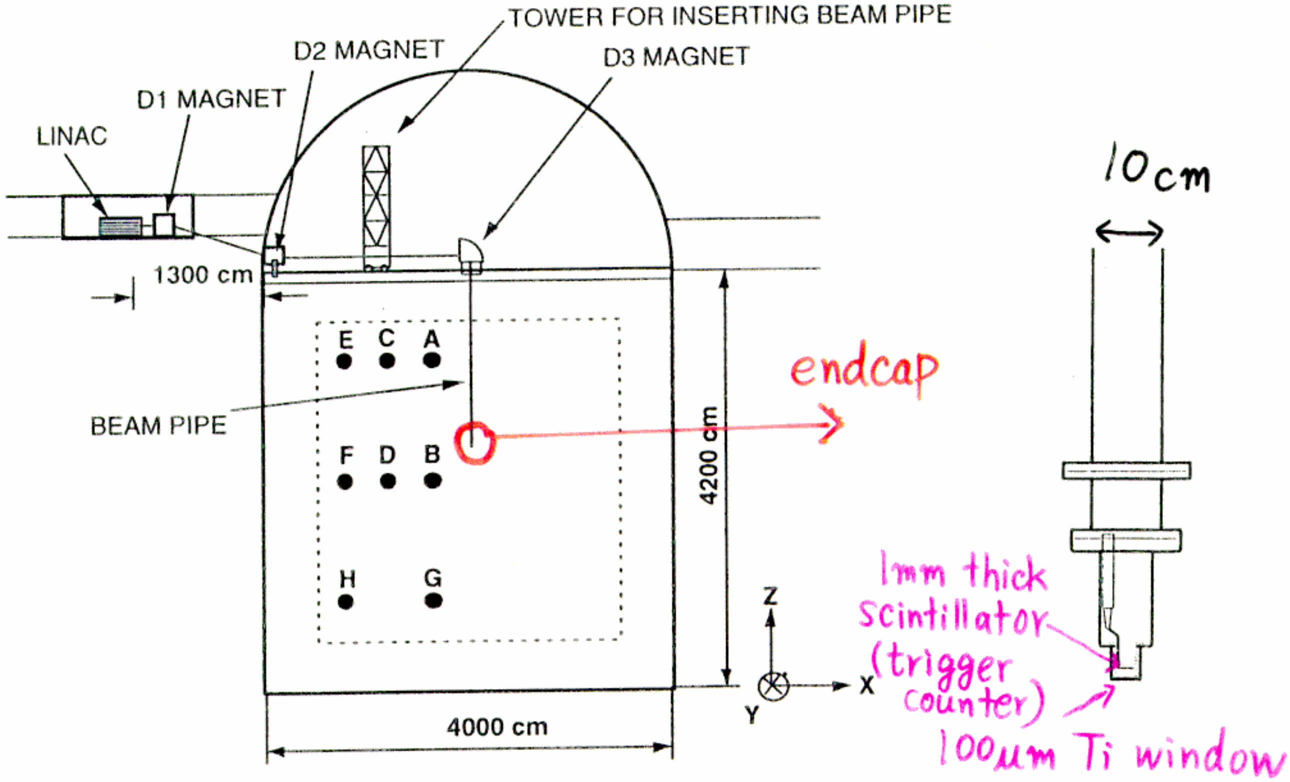
(5) Spallation products

~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).

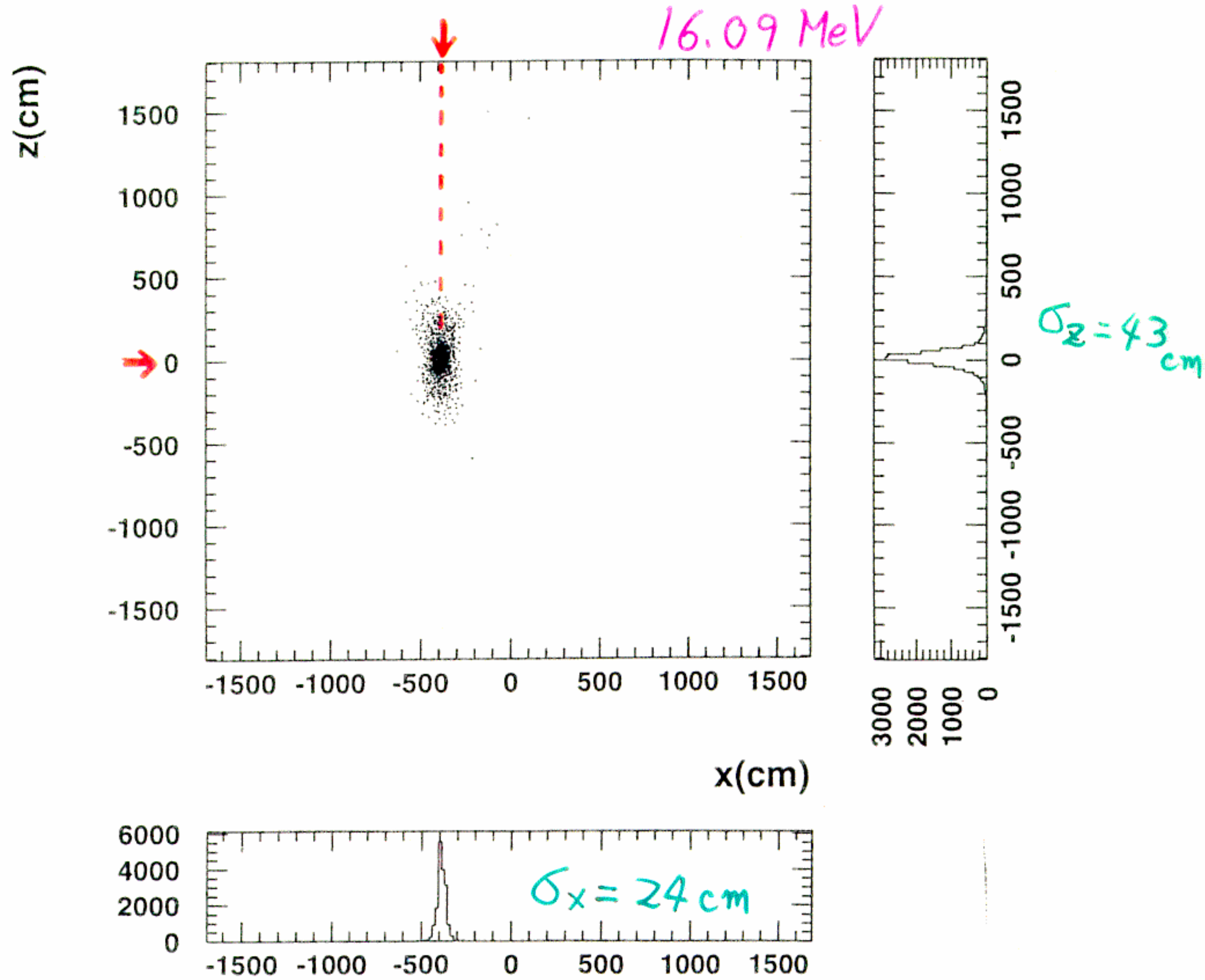
- Beam energy spread : < 0.5% FWHM.
- Event rate : ~ 0.1 e/pulse, pulse frequency : 66Hz

☆ Energy of the beam is measured by Ge detector.

Ge is calibrated by using γ sources and electrons from ^{207}Bi.

Reconstructed Vertex position

LINAC data @ X = −3.88 m, Z = 0.27 m

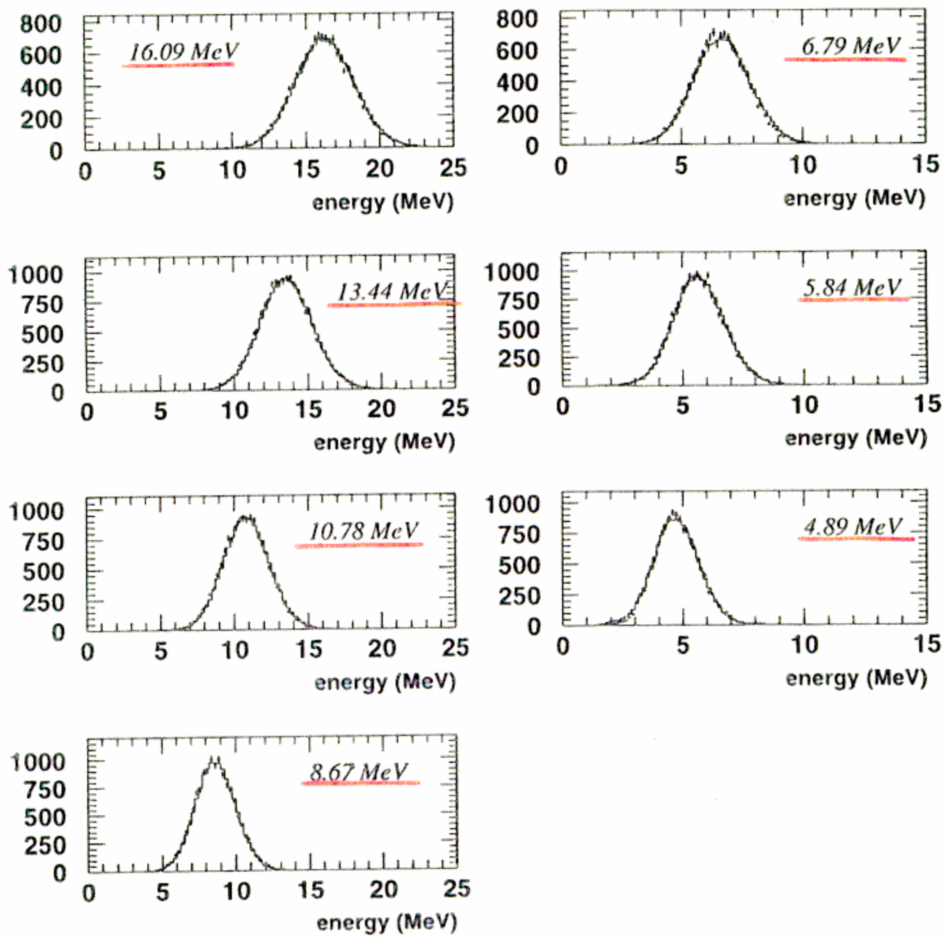


Energy Distributions

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

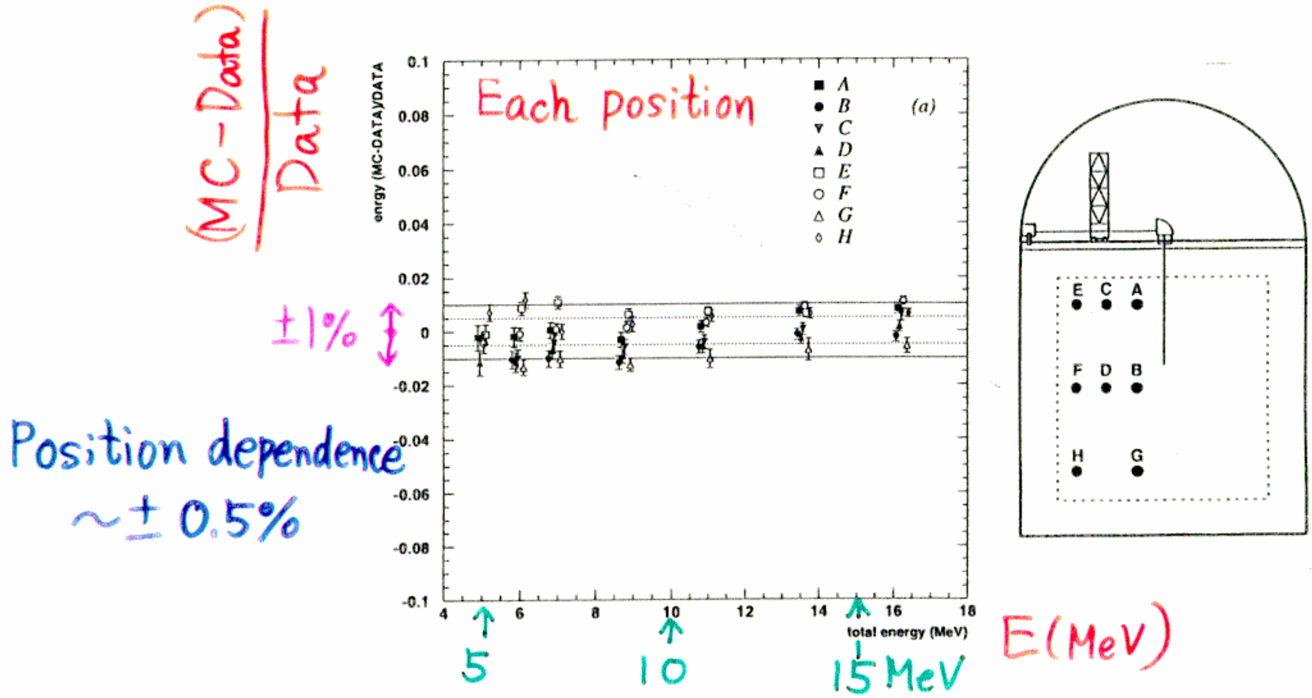
+ Data

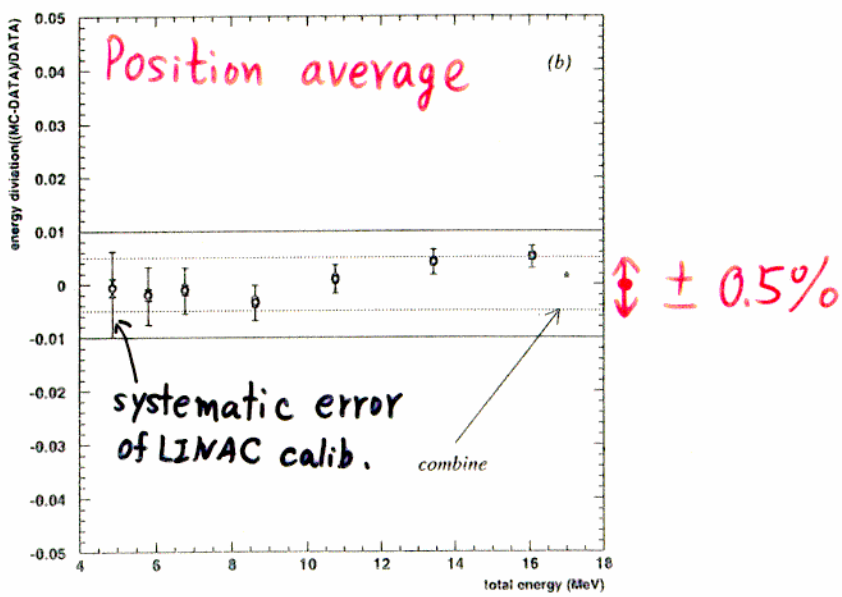
Monte Carlo



Energy scale difference

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

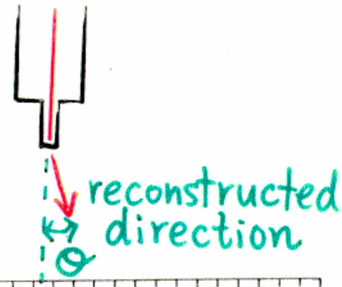




Energy dependence of absolute energy scale is less than 0.5%.

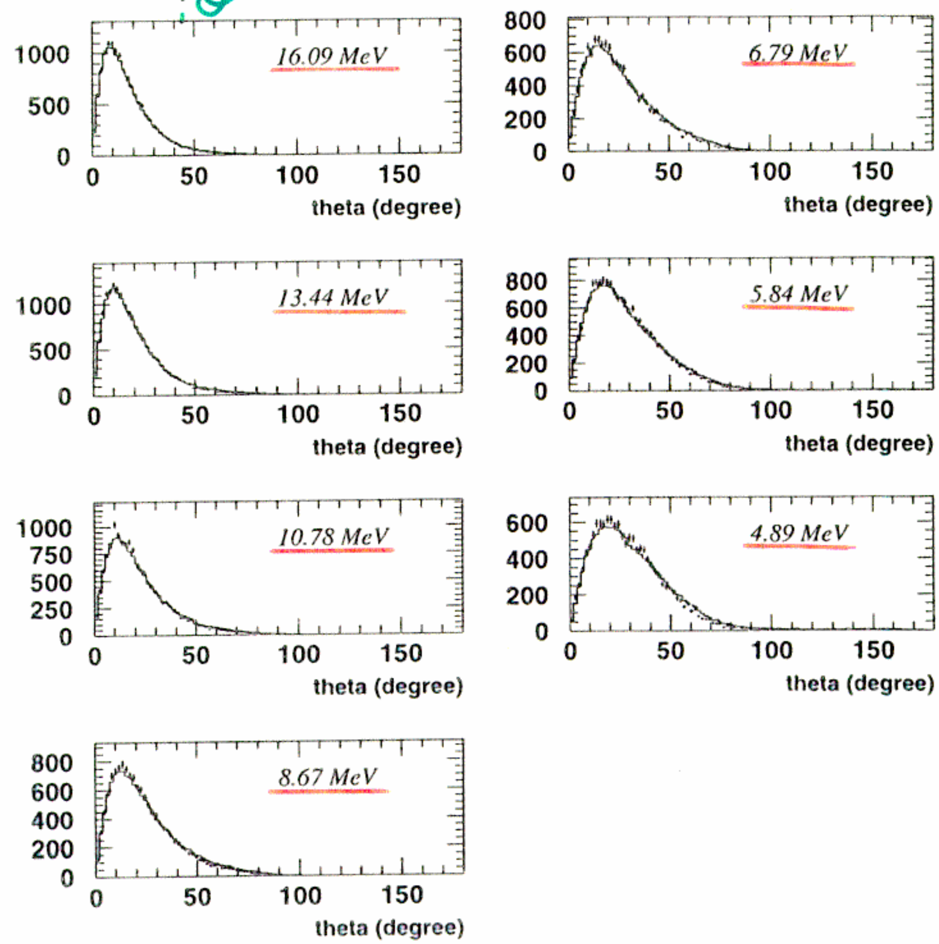
Angular distributions

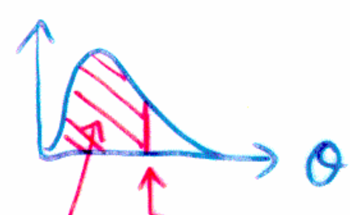
LINAC data @ X = -12m, Z = +12m



+ Data

Monte Carlo





SPALLATION

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

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

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

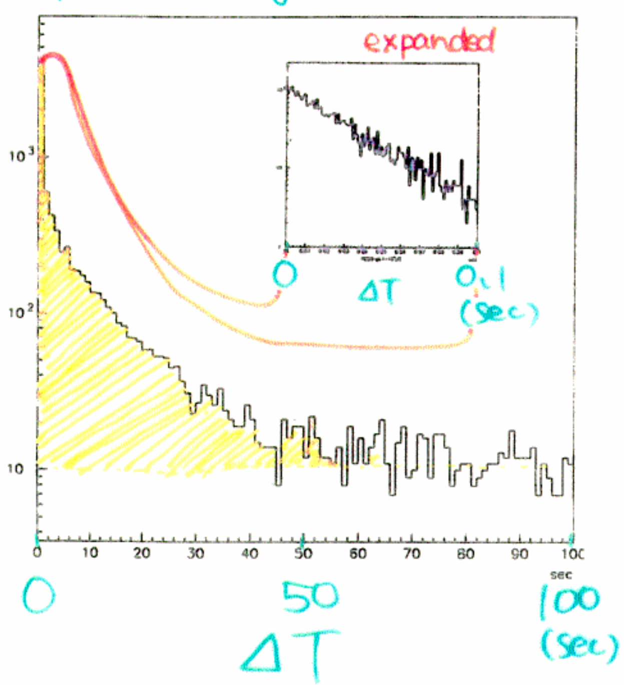
$${}^{16}N \quad (\beta @ 10 MeV, \tau_{1/2} = 7 s)$$

.....

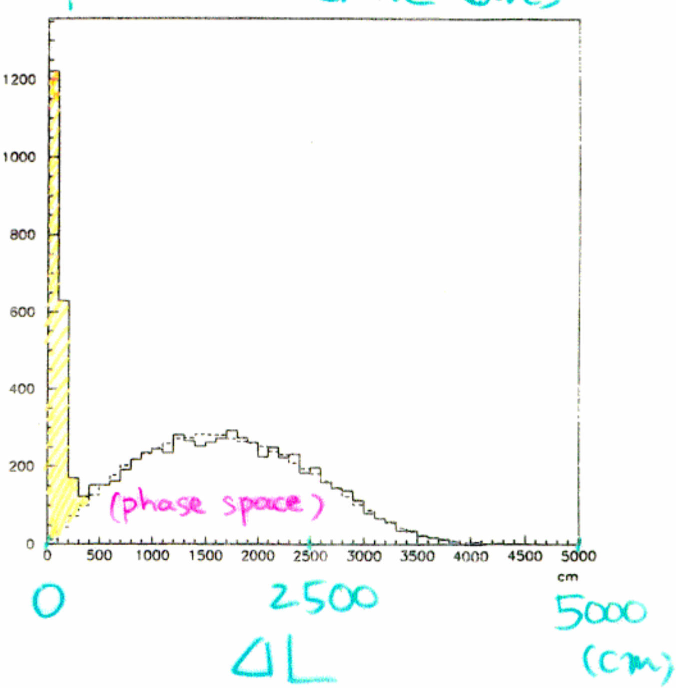
- Residual Q of muons
- ΔT, and ΔL with muons

→ **SPALLATION CUT**

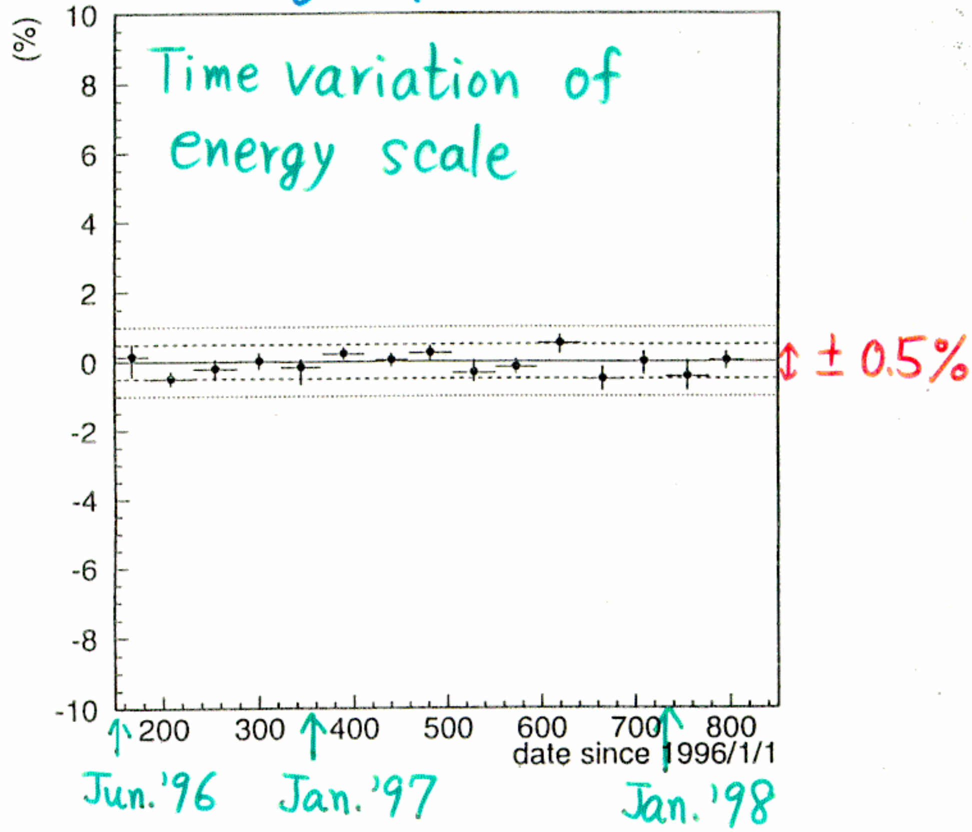
FAST DECAYS following μ with high Qres

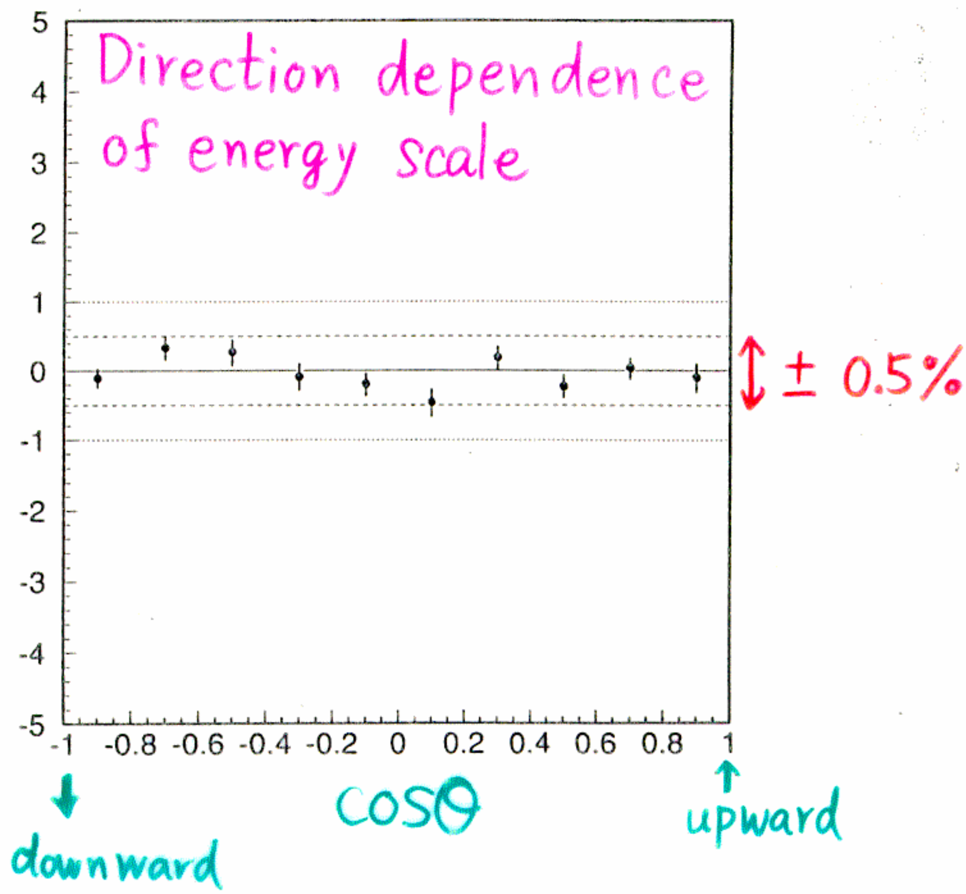


Clustered vertices after μ with moderate Qres



Calibration using Spallation events





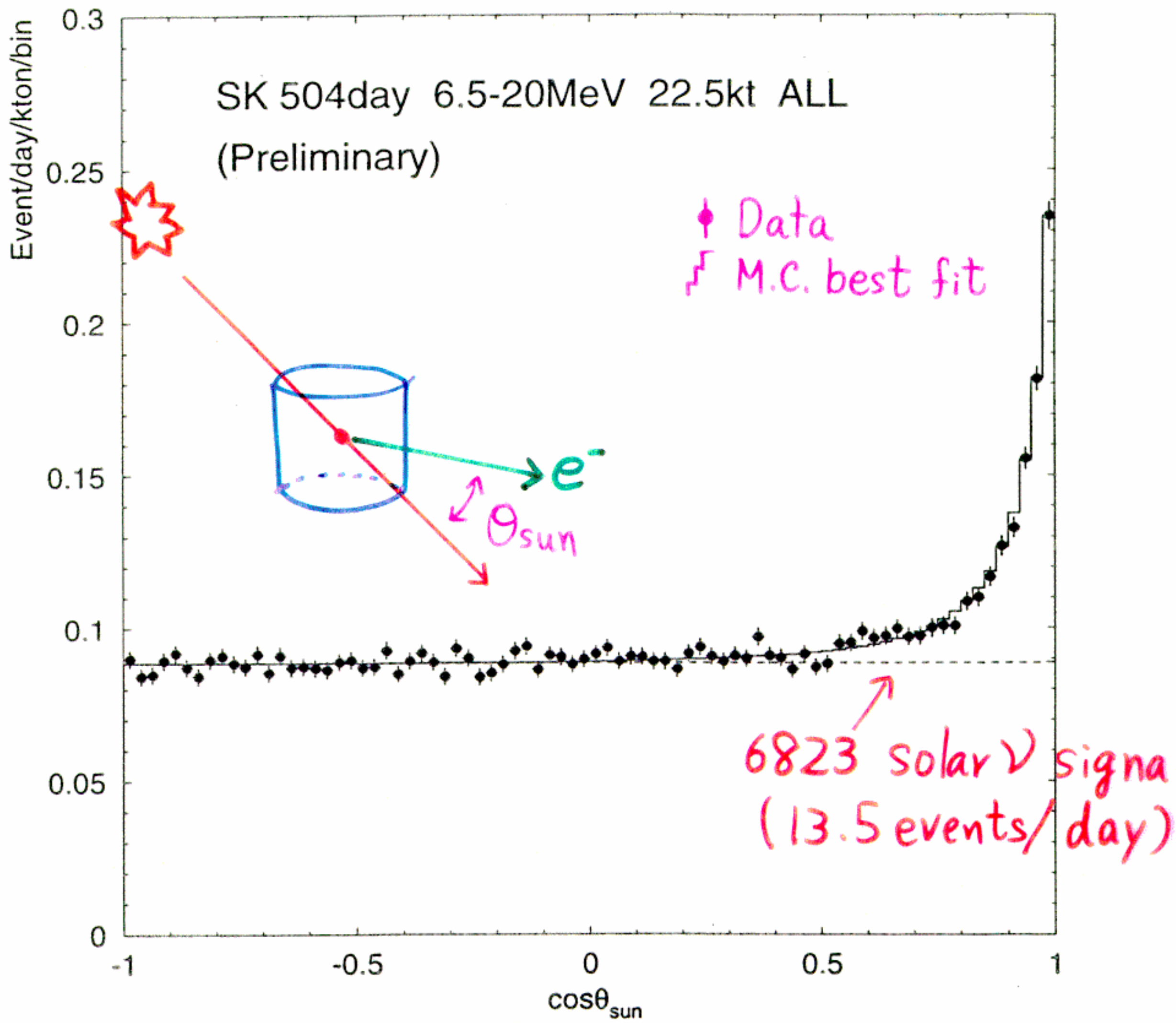
LOW-ENERGY DATA REDUCTION

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

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

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

Direction to the Sun

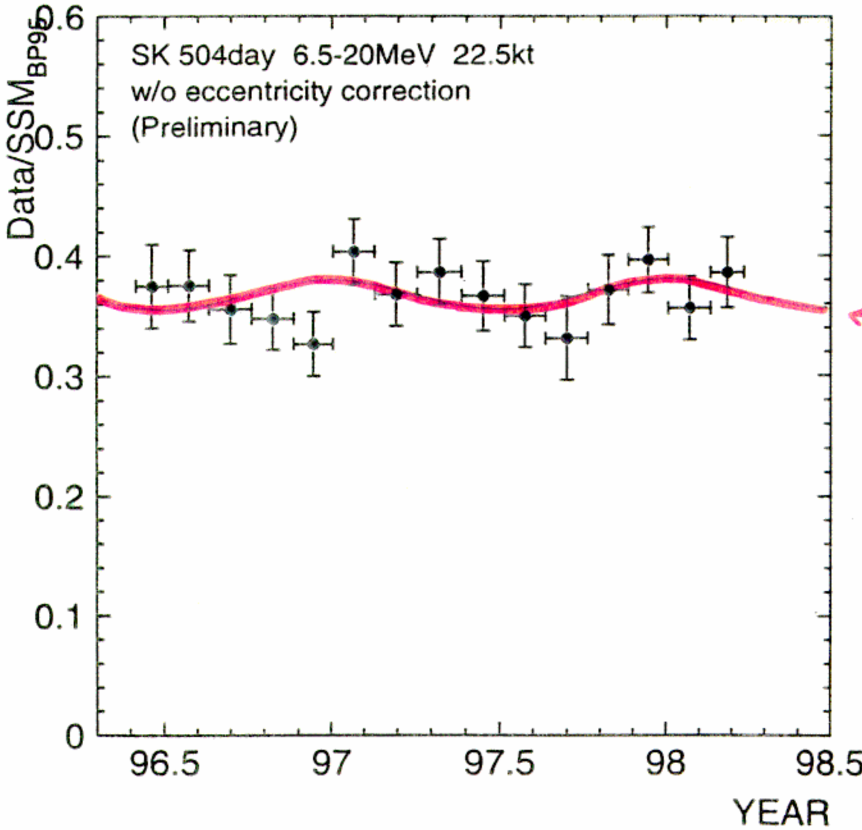


^8B flux : $2.44 \pm 0.05 {}^{+0.09}_{-0.07}$ [$\times 10^6$ /cm²/sec]

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

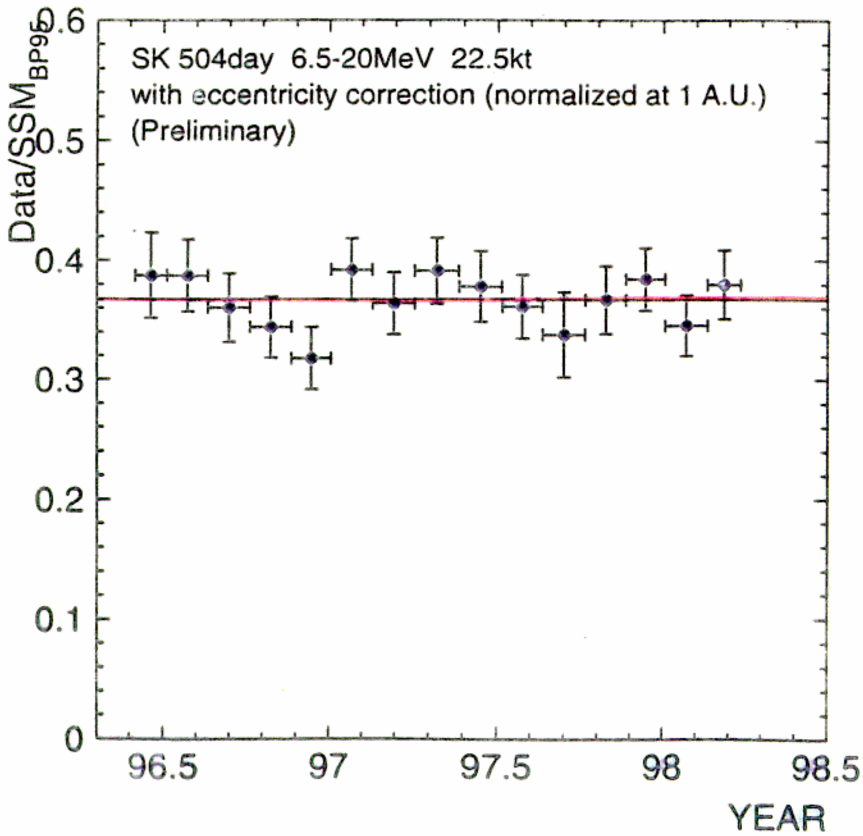
Data/SSM (BP98) : $0.474 {}^{+0.010}_{-0.009} {}^{+0.017}_{-0.014}$

Flux in every ~1.5 month period



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

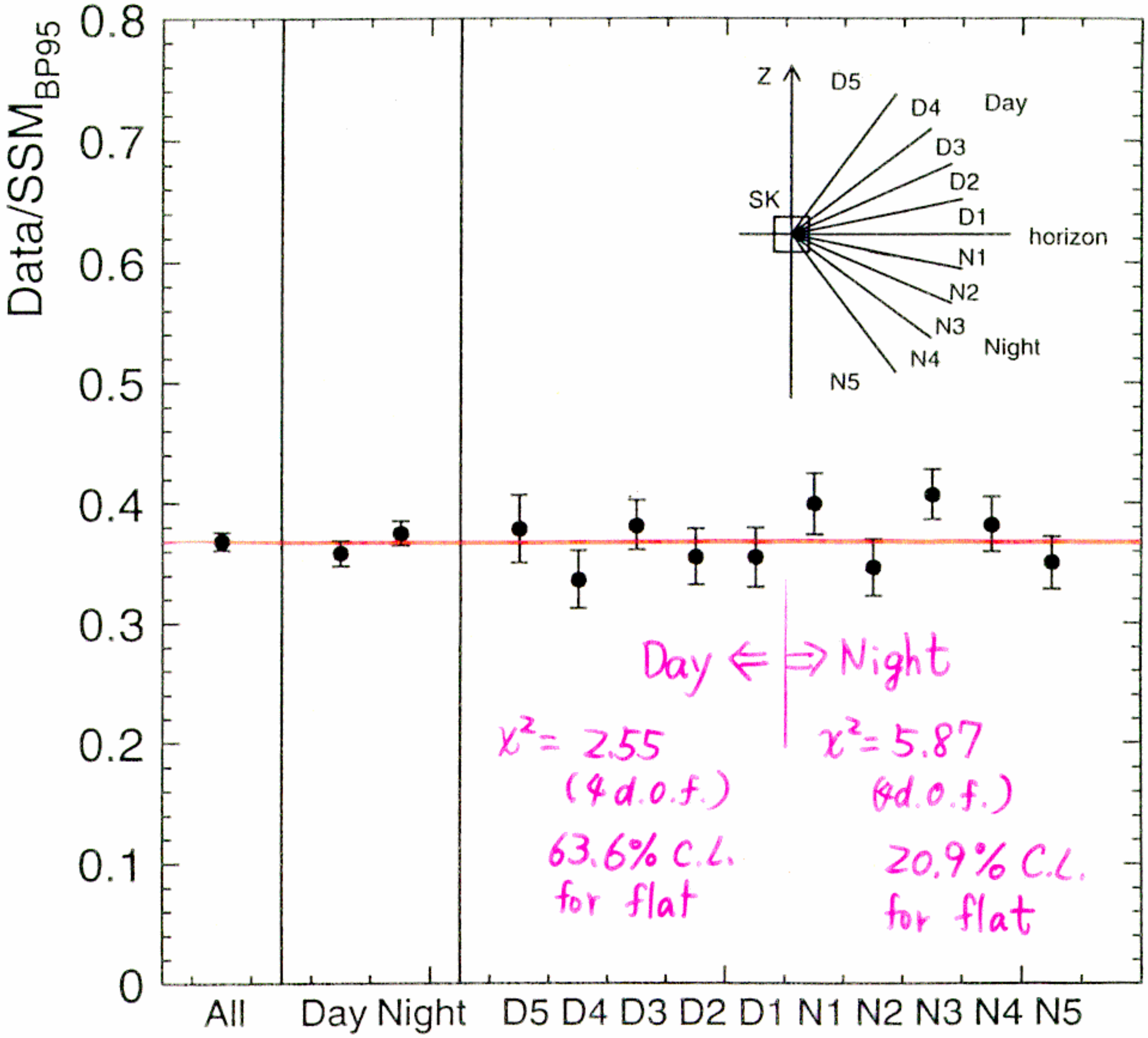
$\chi^2 = 8.78/14$
(84.4% C.L.)



Day / Night Results

SK 504day 6.5-20MeV 22.5kton

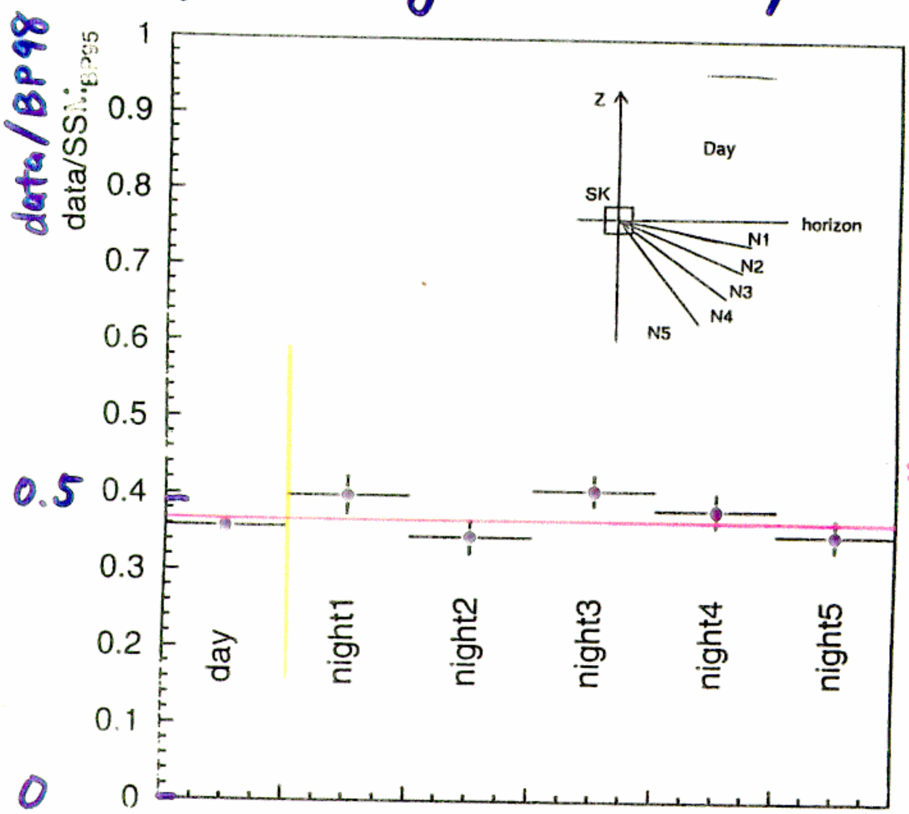
(Preliminary)



$$\frac{\text{Day} - \text{Night}}{\text{Day} + \text{Night}} = -0.023 \pm 0.020\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$

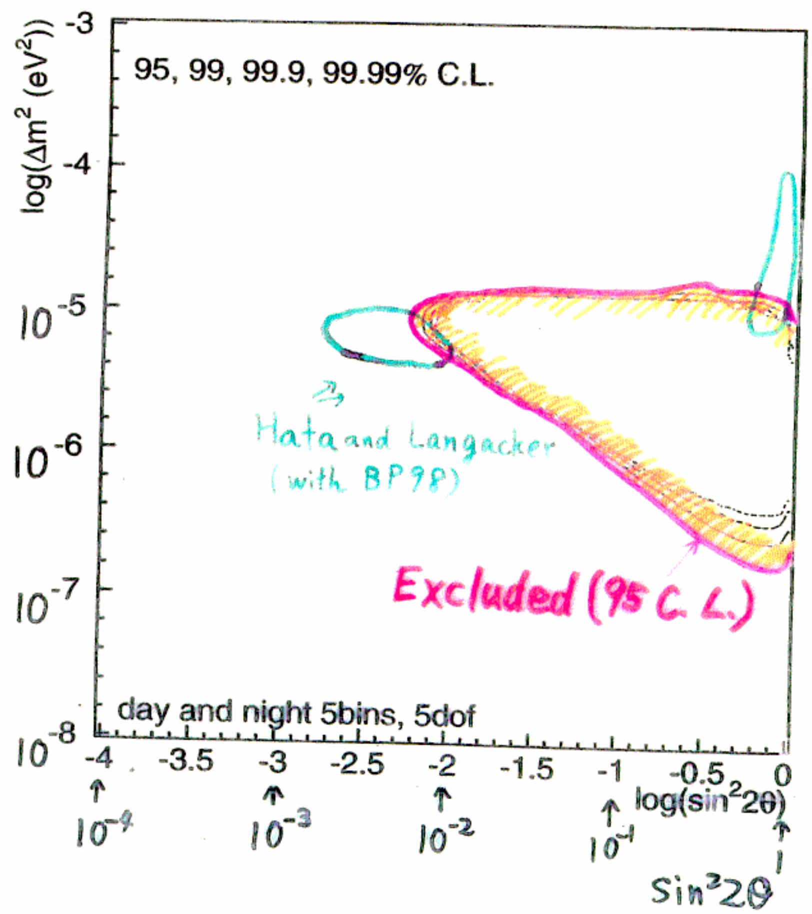
Day / Night analysis

Super-Kamiokande



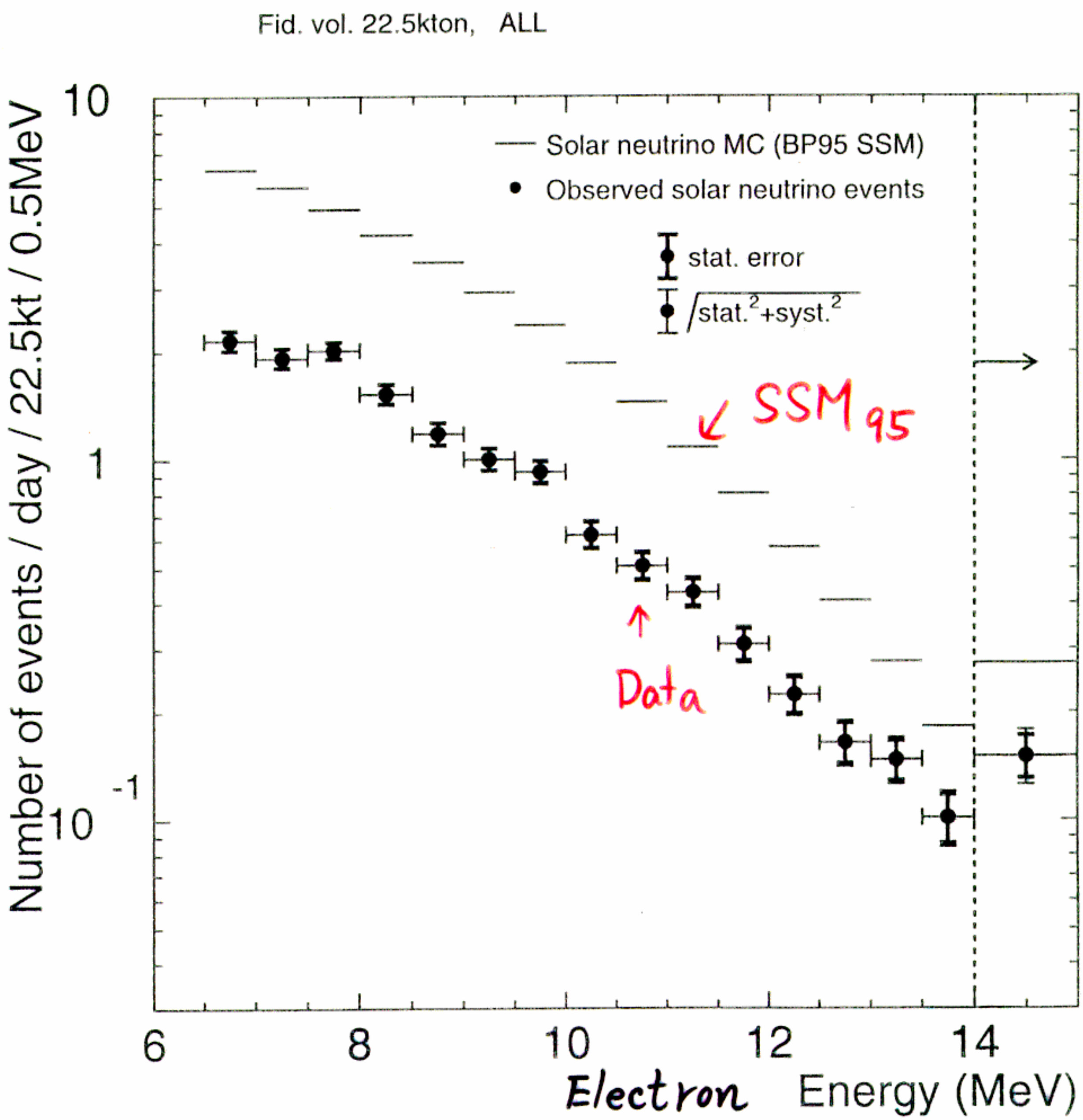
$$\frac{\text{Day} - \text{Night}}{\text{Day} + \text{Night}} = -0.023 \pm 0.020\ (\text{stat}) \pm 0.014\ (\text{syst})$$

Excluded region



Energy spectrum of solar ν events (Preliminary)

Super-Kamiokande 504day

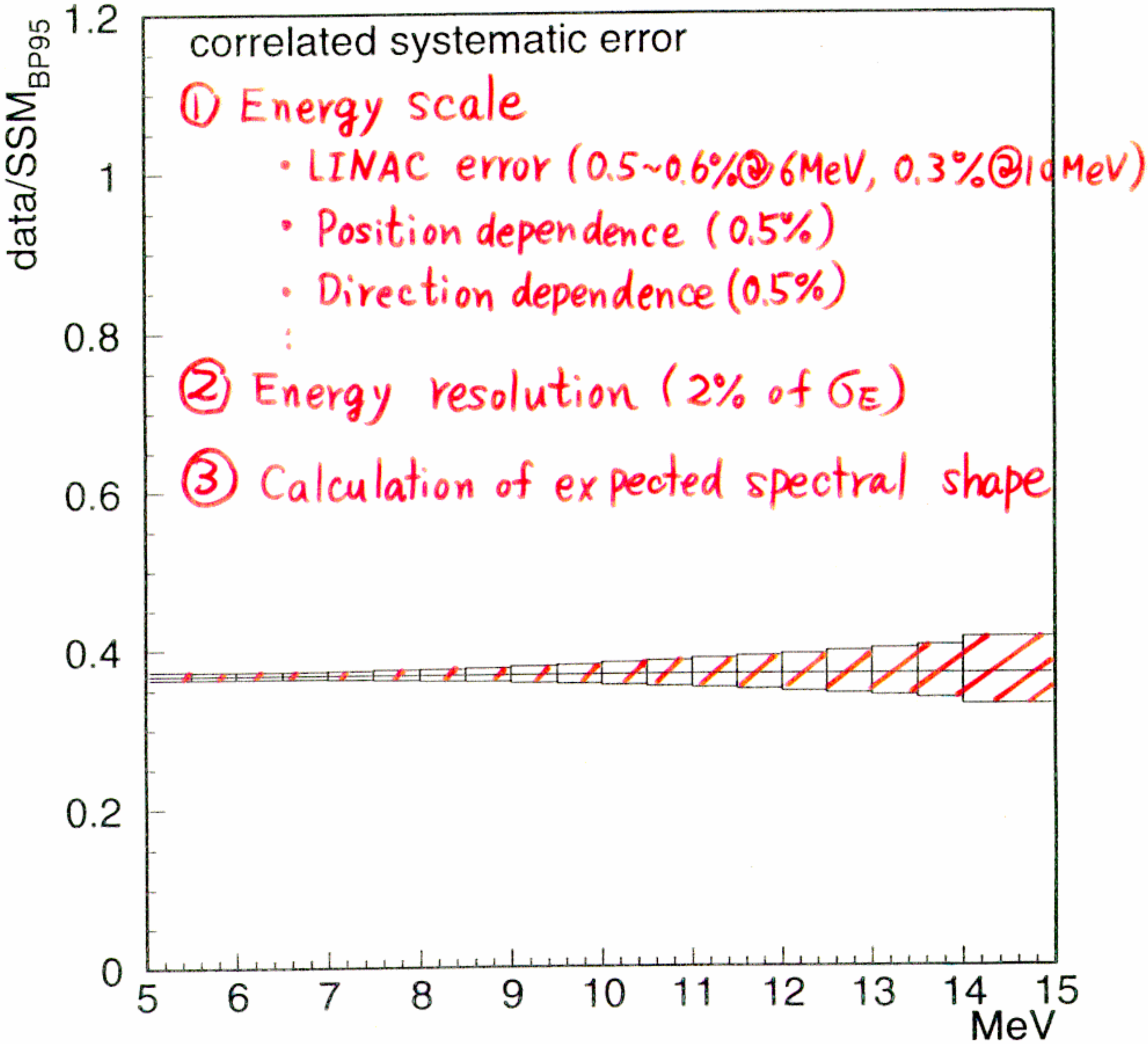


BP95: Bahcall and Pinsonneault, Rev. Mod. Phys. 67 (1995) 781.

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

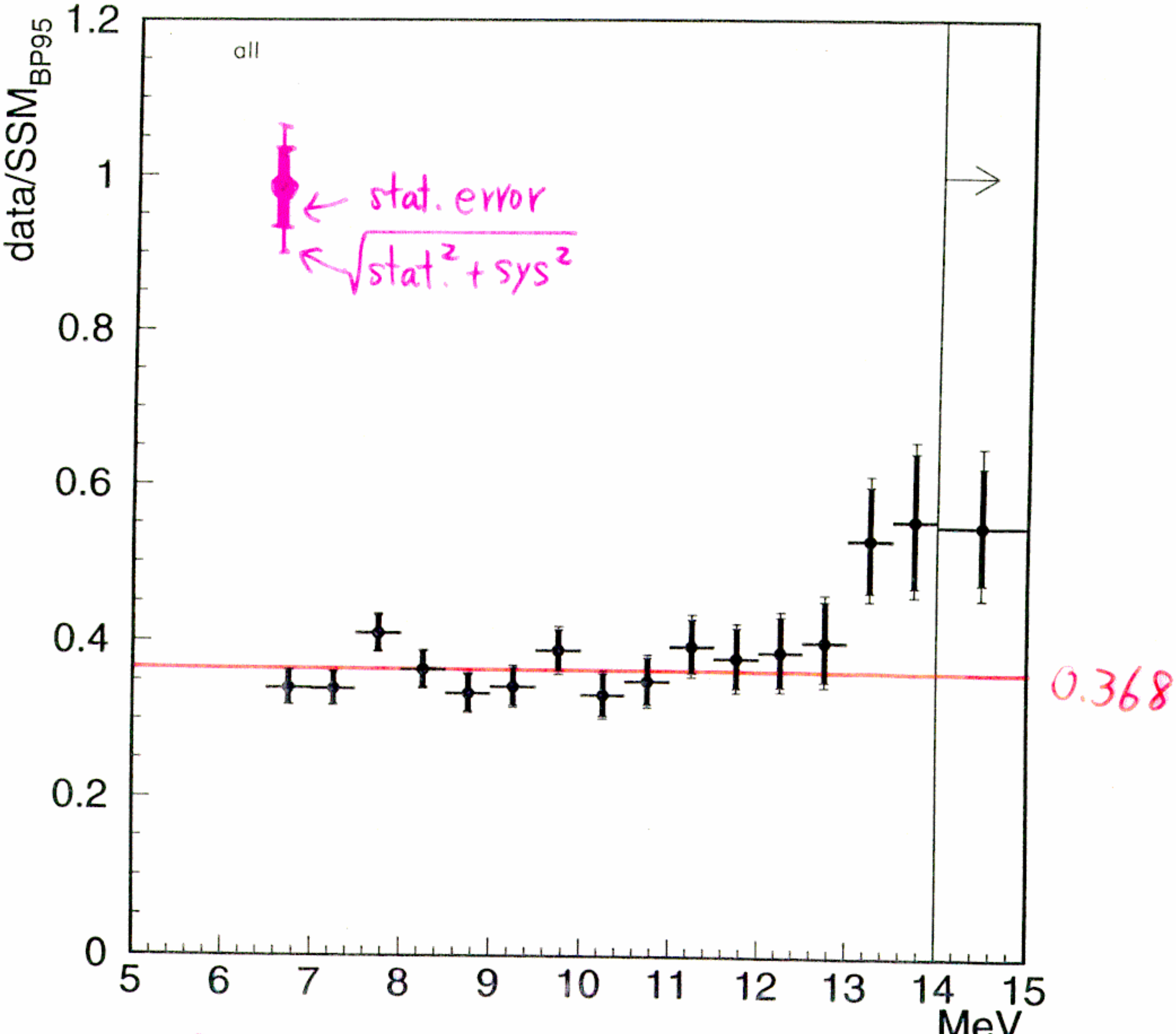
νe cross section: Bahcall et al., Phys. Rev. D51 (1995) 6146.

Correlated systematic error for energy spectrum



1

Energy Spectrum $\left(\frac{\text{Data}}{\text{SSM}}\right)$



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

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

Definitions of χ^2

Day/Night

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

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

Energy spectrum (flux independent)

Day, Night

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

16 Energy bins

$$+ \left(\frac{\varepsilon_s}{\sigma_s}\right)^2 + \left(\frac{\varepsilon_r}{\sigma_r}\right)^2 + \ldots$$

31 d.o.f.

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

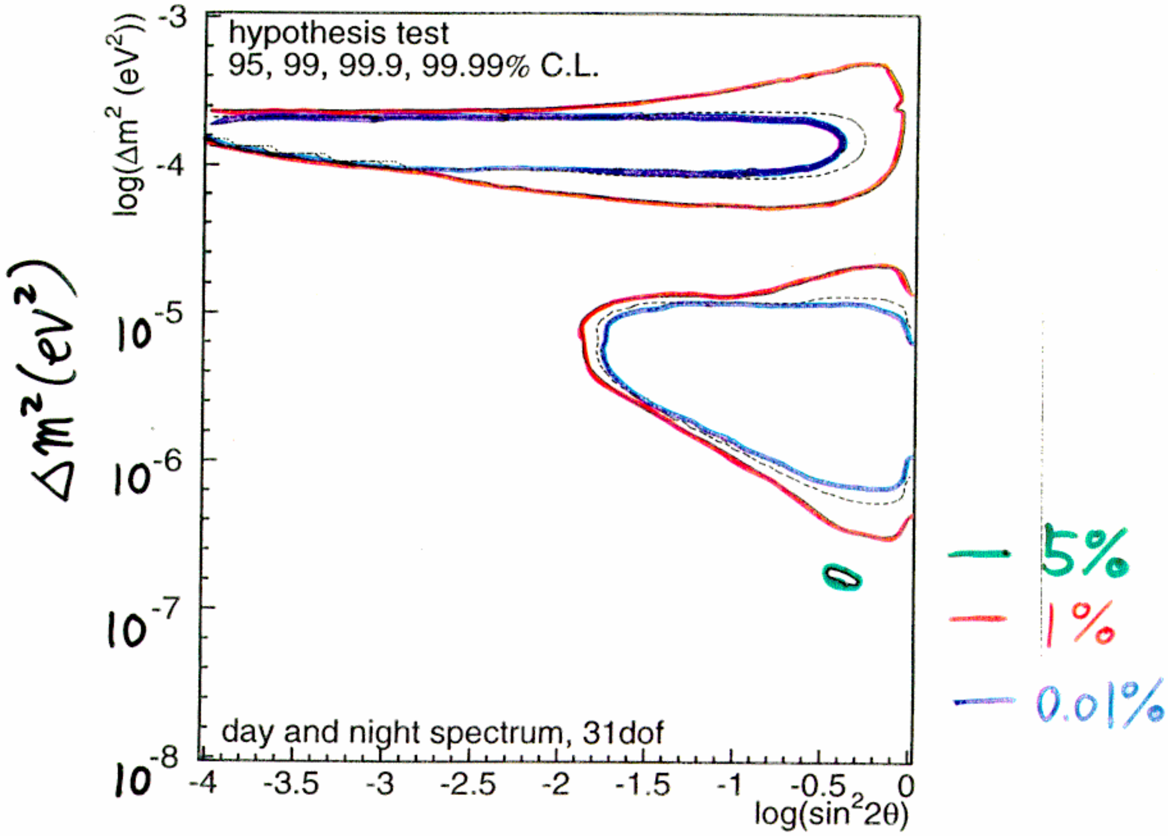
$F_i(\varepsilon_s, \varepsilon_r, \ldots)$: response function of correlated errors

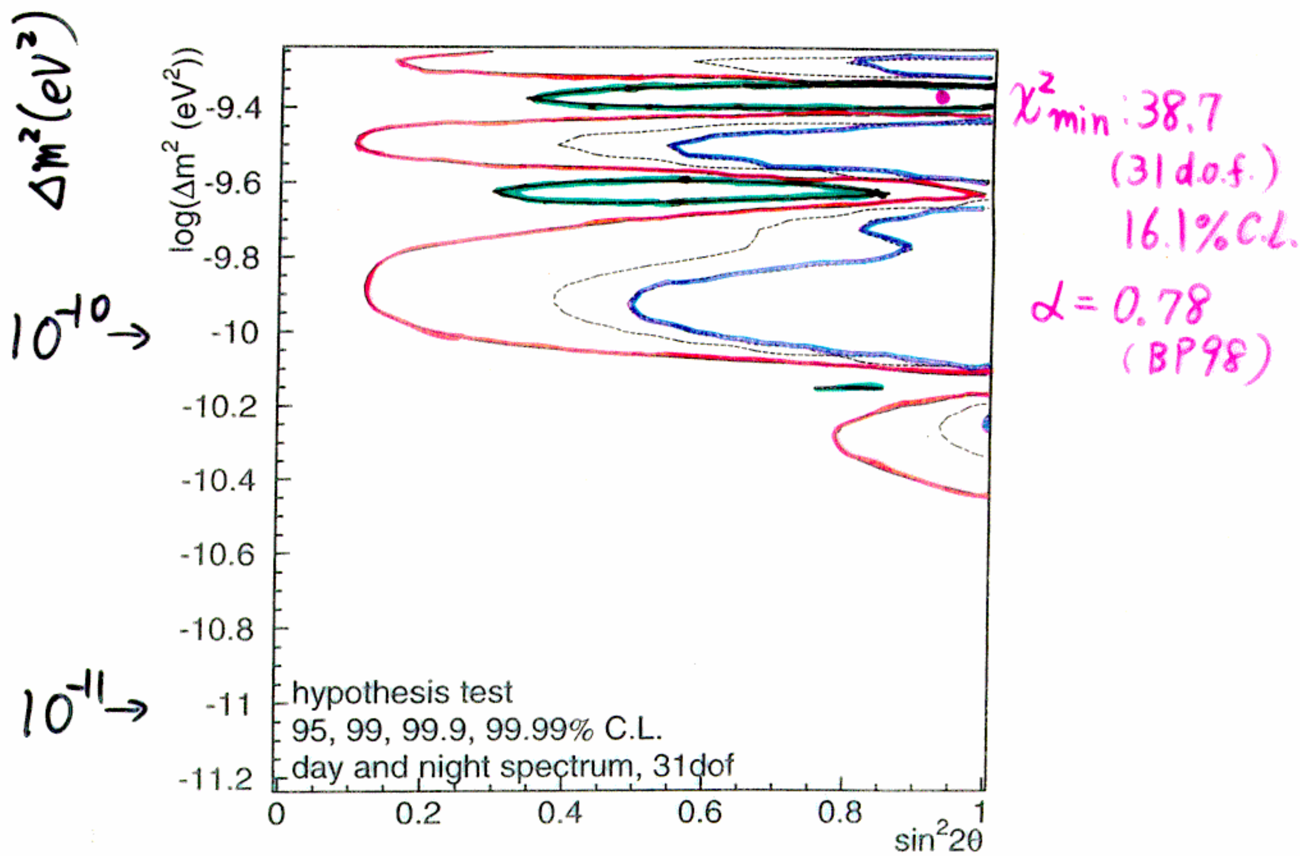
σ_s : scale error

σ_r : resolution error

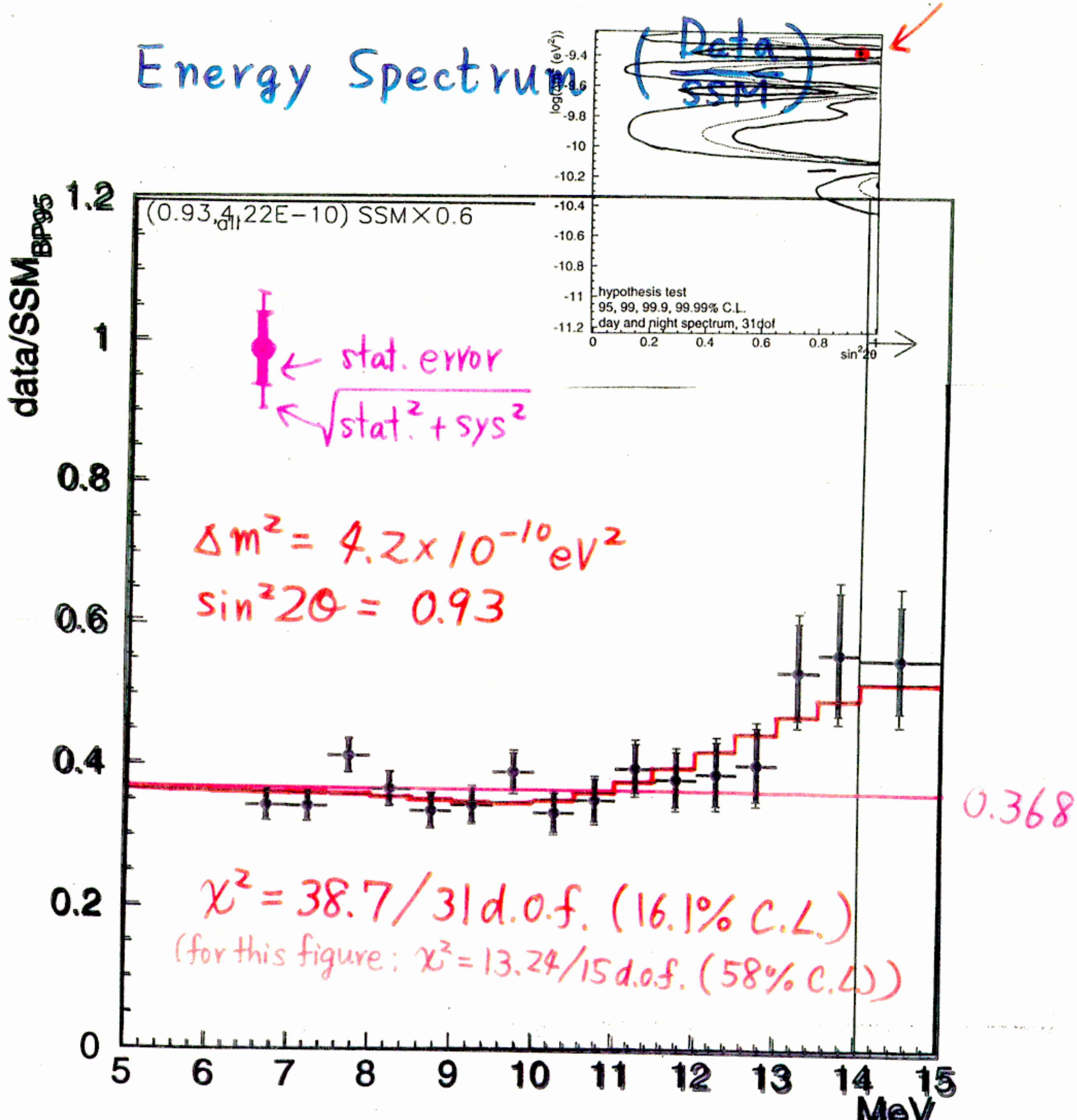
.....

χ^2- contour (Spectrum ⊕ Day/Night)





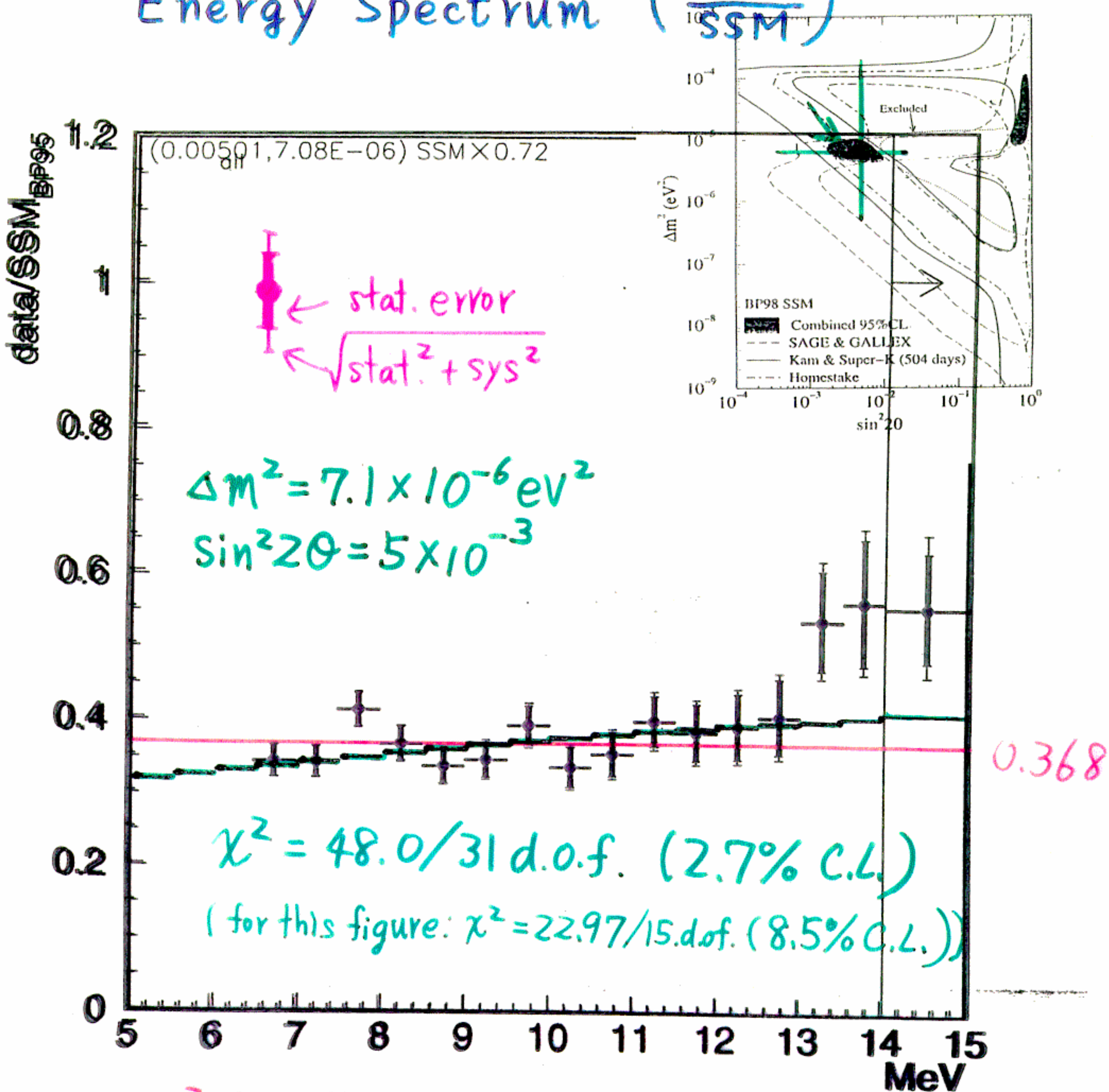
Energy Spectrum (Data / SSM)



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

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

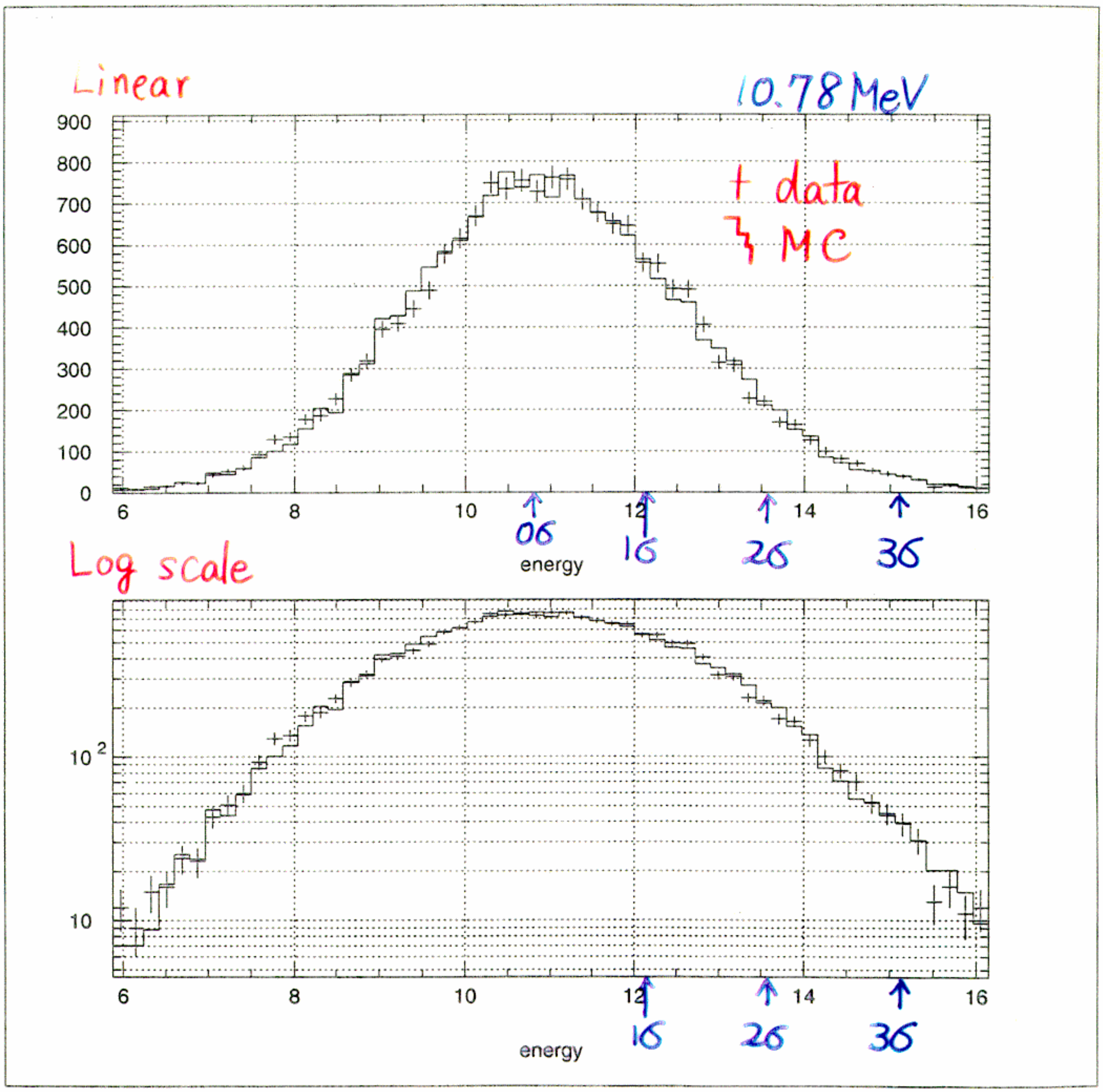
Energy Spectrum ($\frac{Data}{SSM}$)



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

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

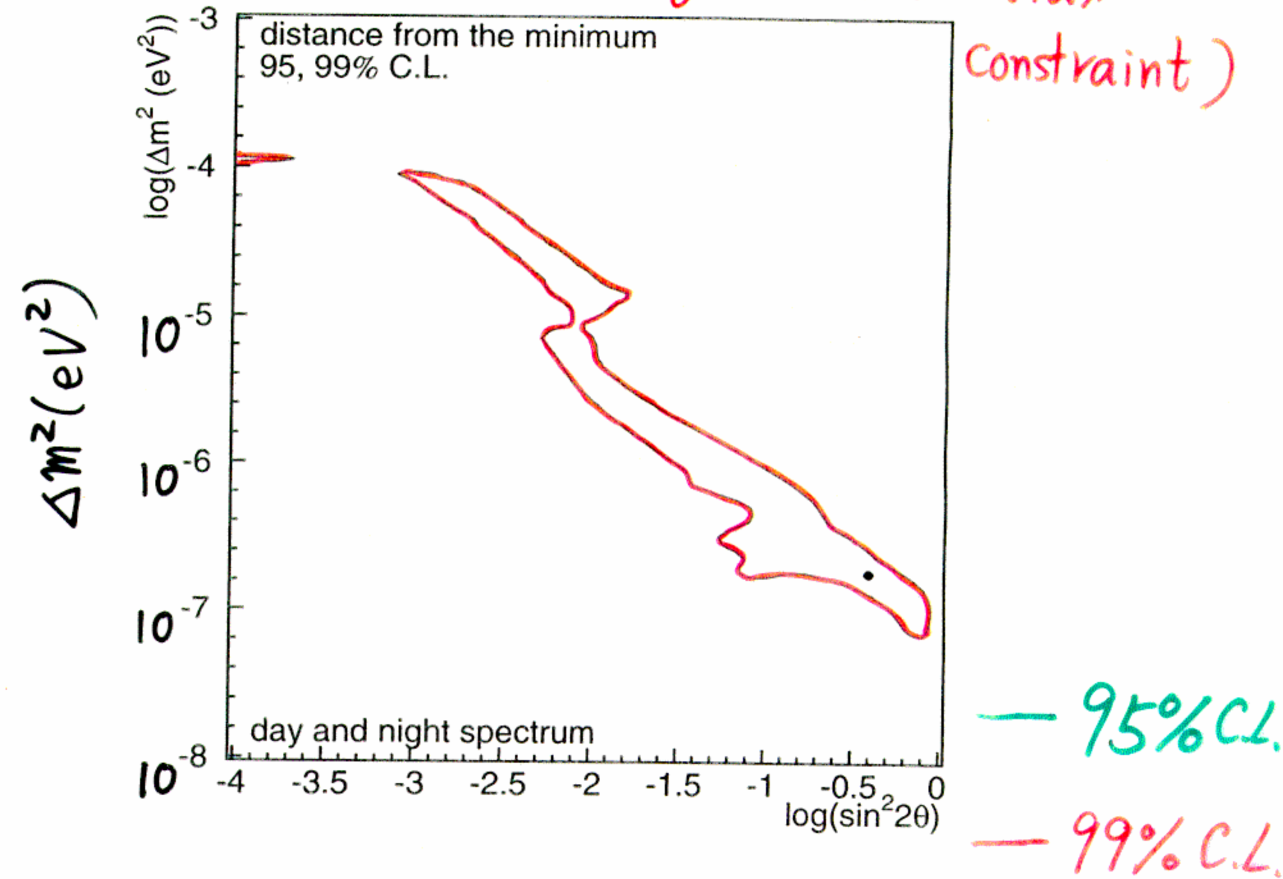
LINAC energy spectrum

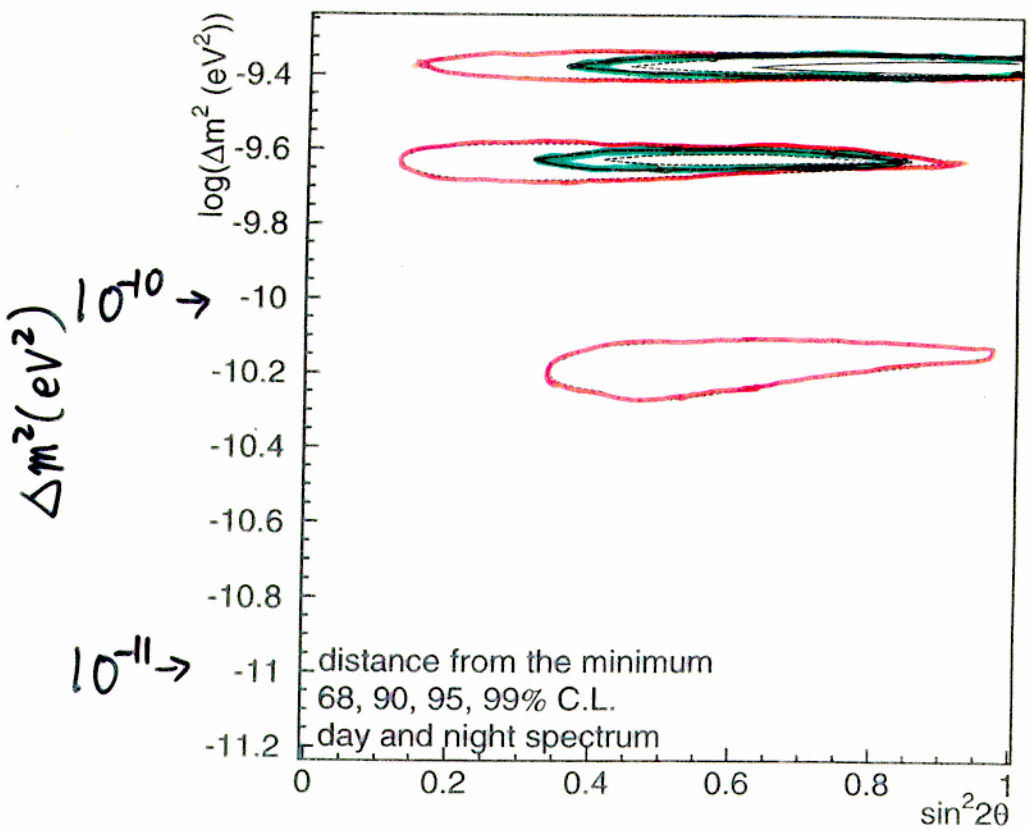


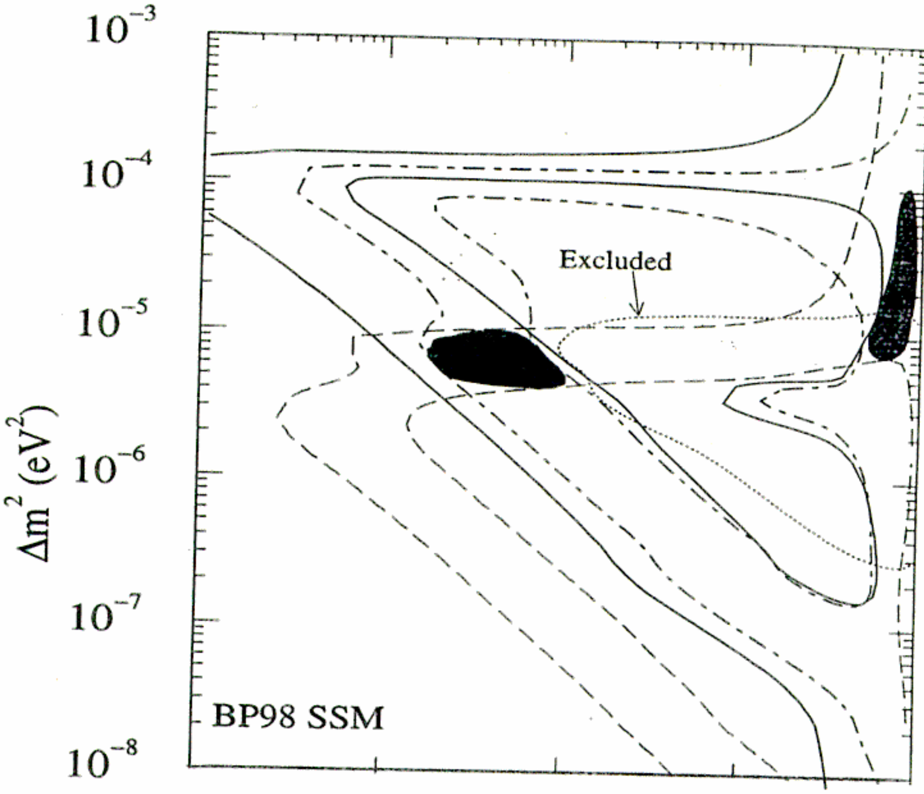
Data and MC agree to each other.

Resolution tail is well understood.

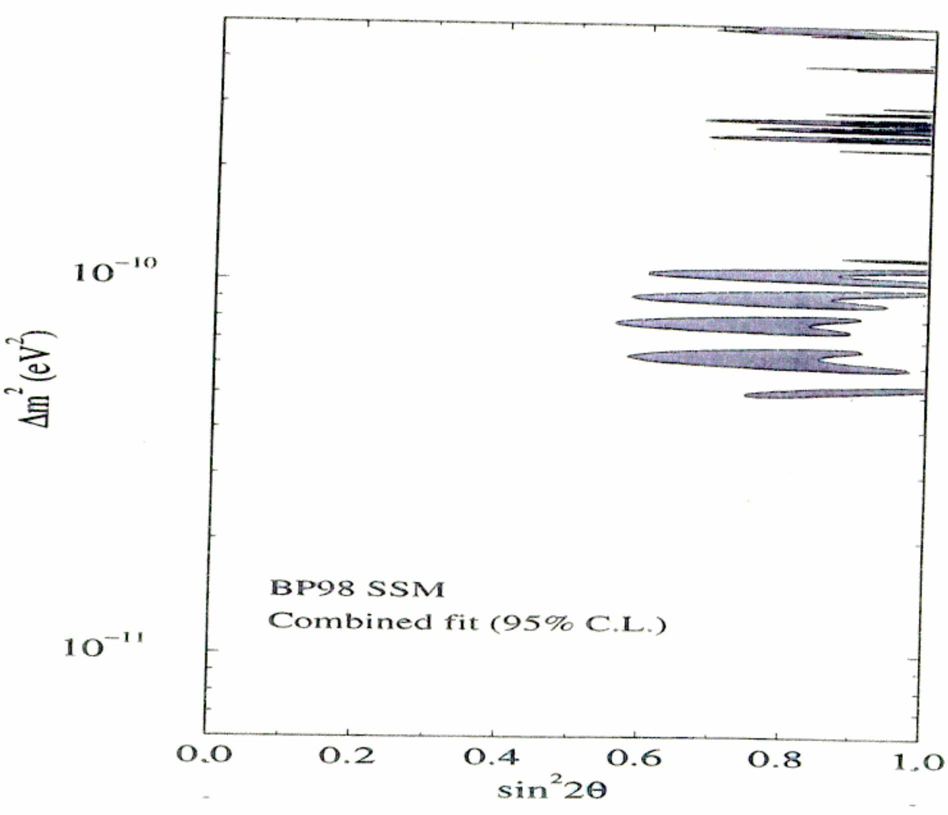
Allowed region (w/o flux constraint)



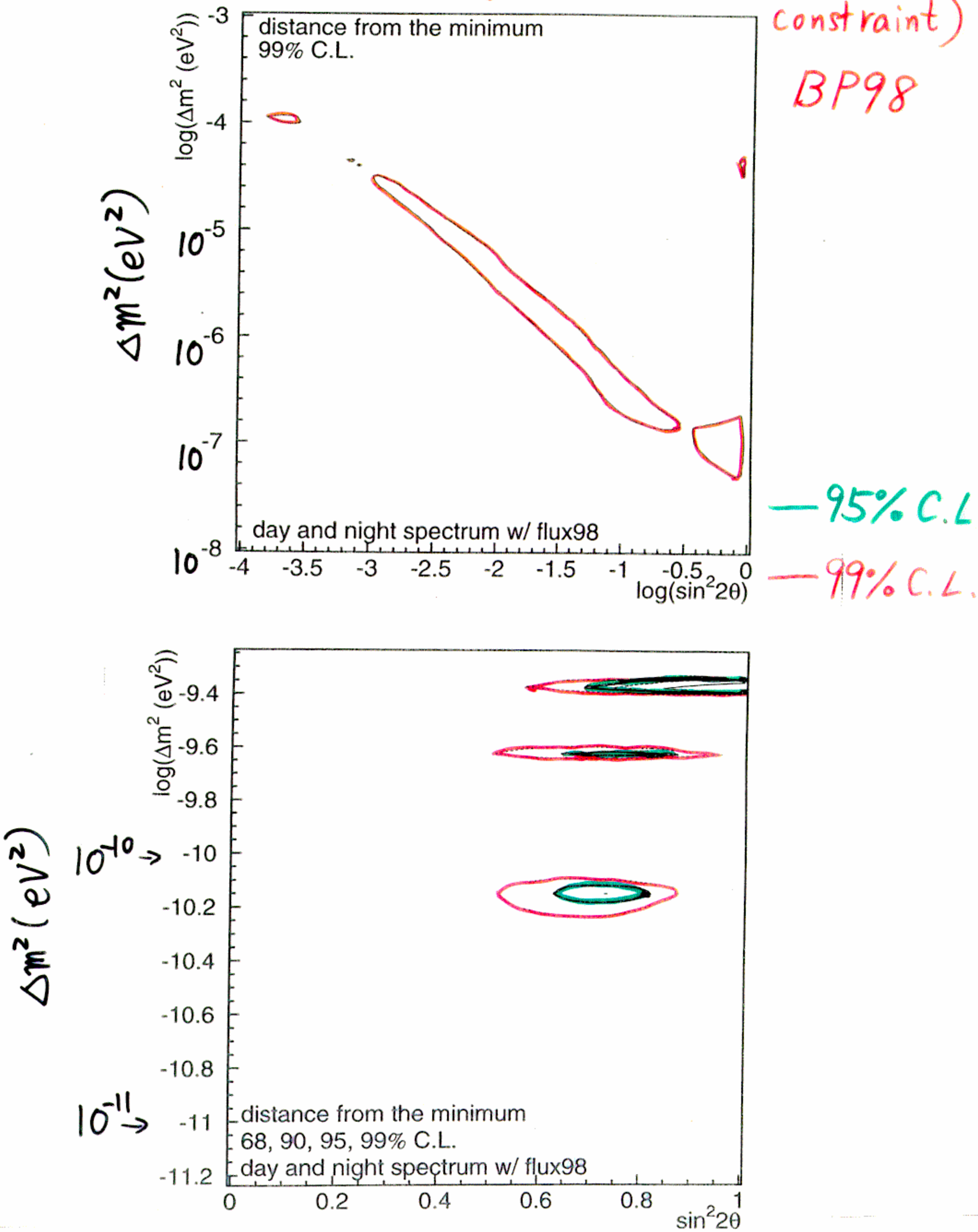




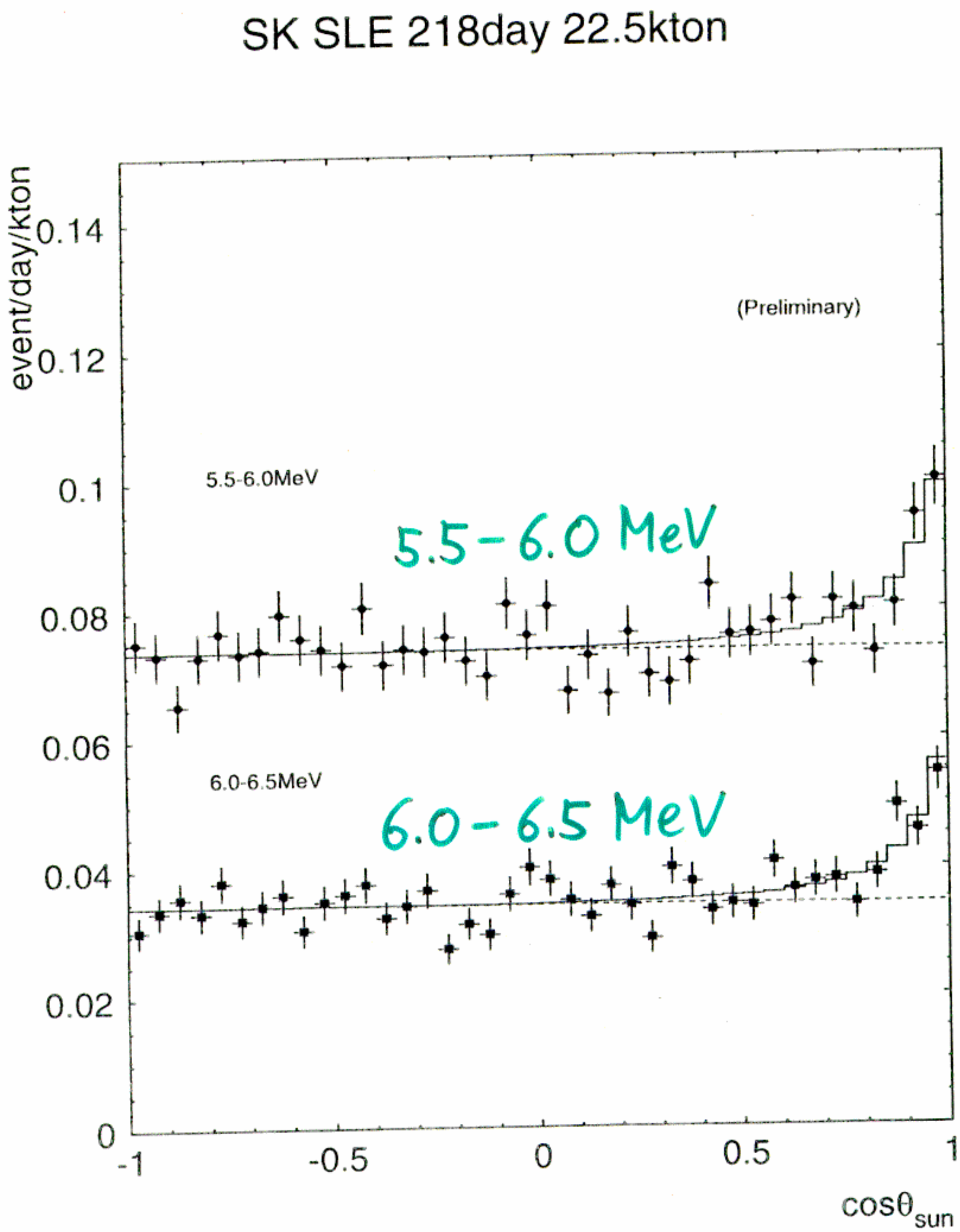
Hata & Langacker (BP98)



Allowed region (with flux constraint) BP98

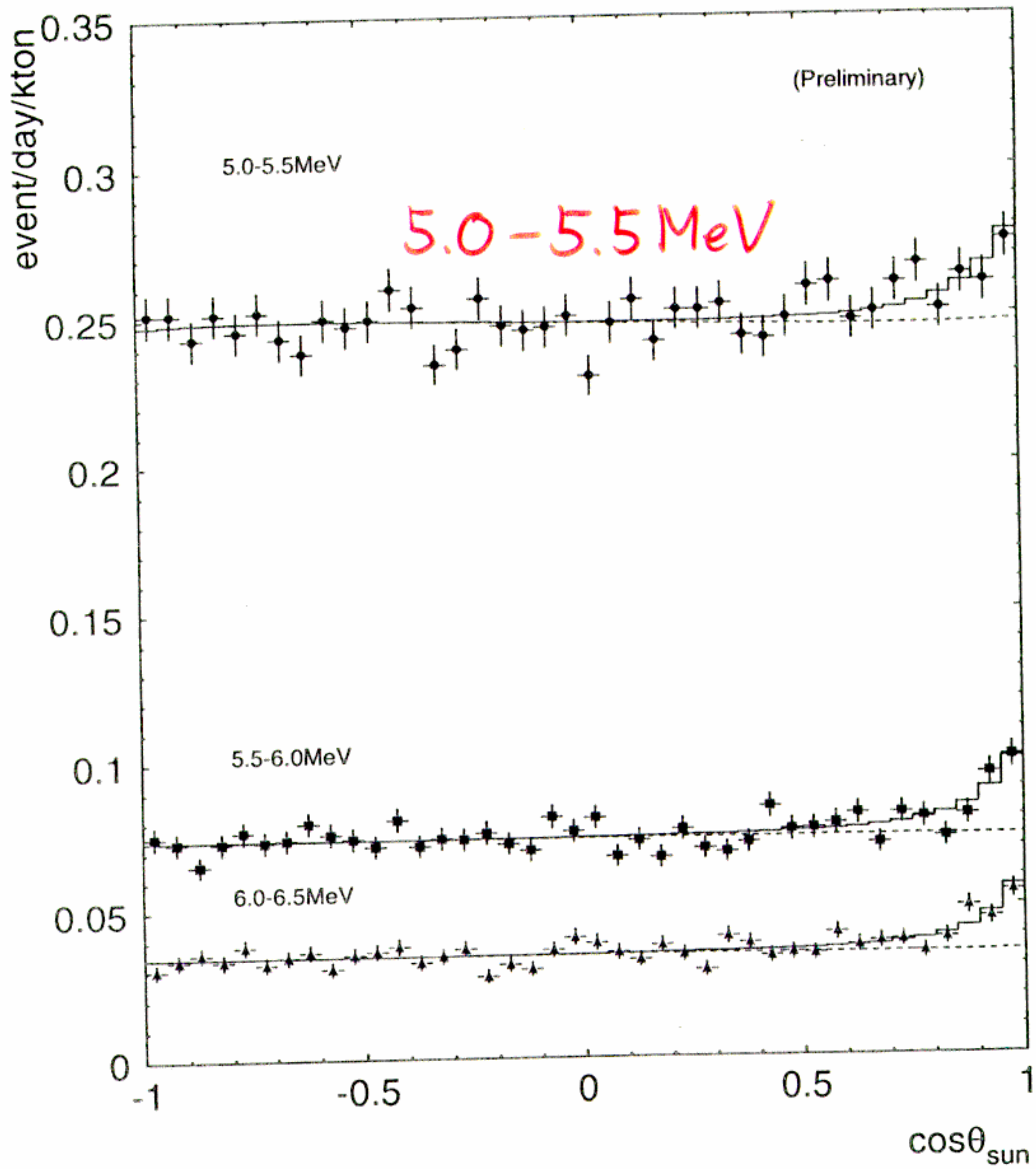


Cos θsun for SLE data



Solar ν signal is clearly seen!

SK SLE 218day 22.5kton



Conclusions

☆ Atmospheric Neutrinos

Evidence for ν_μ oscillations in

contained events, upward-through-going muons and upward-stopping-muons.

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

$\sin^2 2\theta \sim 1$

☆ Solar Neutrinos

- Precise energy calibration by LINAC.
- Flux of ^8B (504 days' data)

  $2.44 \pm 0.05(stat)\ +0.09/-0.07(sys)\ [10^6\ /cm^2/sec]$
  (47.4% of BP98)
- No seasonal variations are observed.
- No Day/Night difference.

  $(D-N)/(D+N) = -0.023 \pm 0.020 \pm 0.014$
- Energy spectrum analysis.
  - "No Oscillation" is disfavored at ~5 % C.L.
  - Need more statistics for discussing ν oscillations.
- Progress in lower energy (5.0-6.5 MeV) range.