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Atmospheric neutrino observation in Super-Kamiokande

—Evidence for ν_μ oscillations—

T. Kajita

Kamioka Observatory, U of Tokyo

for the Super-Kamiokande collab.
(& Kamiokande)

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Super-Kamiokande collaboration

(~120 people)

Y.Fukuda[a], T.Hayakawa[a], E.Ichihara[a], K.Inoue[a], K.Ishihara[a], H.Ishino[a], Y.Itow[a], T.Kajita[a], J.Kameda[a], S.Kasuga[a], K.Kobayashi[a], Y.Kobayashi[a], Y.Koshio[a], K.Martens[a], M.Miura[a], M.Nakahata[a], S.Nakayama[a], A.Okada[a], M.Oketa[a], K.Okumura[a], M.Ota[a], N.Sakurai[a], M.Shiozawa[a], Y.Suzuki[a], Y.Takeuchi[a], Y.Totsuka[a], S.Yamada[a], M.Earl[b], A.Habig[b], E.Kearns[b], S.B.Kim[b], M.D.Messier[b], K.Scholberg[b], J.L.Stone[b], L.R.Sulak[b], C.W.Walter[b], M.Goldhaber[c], T.Barszczak[d], W.Gajewski[d], P.G.Halverson[d], J.Hsu[d], W.R.Kropp[d], L.R. Price[d], F.Reines[d], H.W.Sobel[d], M.R.Vagins[d], K.S.Ganezer[e], W.E.Keig[e], R.W.Ellsworth[f], S.Tasaka[g], J.W.Flanagan[h], A.Kibayashi[h], J.G.Learned[h], S.Matsuno[h], V.Stenger[h], D.Takemori[h], T.Ishii[i], J.Kanzaki[i], T.Kobayashi[i], K.Nakamura[i], K.Nishikawa[i], Y.Oyama[i], A.Sakai[i], M.Sakuda[i], O.Sasaki[i], S.Echigo[j], M.Kohama[j], A.T.Suzuki[j], T.J.Haines[k], E.Blaufuss[l], R.Sanford[l], R.Svoboda[l], M.L.Chen[m], Z.Conner[m], J.A.Goodman[m], G.W.Sullivan[m], M.Mori[n], J.Hill[o], C.K.Jung[o], C.Mauger[o], C.McGrew[o], E.Sharkey[o], B.Viren[o], C.Yanagisawa[o], W.Doki[p], T.Ishizuka[p], Y.Kitaguchi[p], H.Koga[p], K.Miyano[p], H.Okazawa[p], C.Saji[p], M.Takahata[p], A.Kusano[q], Y.Nagashima[q], M.Takita[q], T.Yamaguchi[q], M.Yoshida[q], M.Etoh[r], K.Fujita[r], A.Hasegawa[r], T.Hasegawa[r], S.Hatakeyama[r], T.Iwamoto[r], T.Kinebuchi[r], M.Koga[r], T.Maruyama[r], H.Ogawa[r], A.Suzuki[r], F.Tsushima[r], M.Koshiba[s], M.Nemoto[t], K.Nishijima[t], T.Futagami[u], Y.Hayato[u], Y.Kanaya[u], K.Kaneyuki[u], Y.Watanabe[u], D.Kielczewska[v], R.Doyle[w], J.George[w], A.Stachyra[w], L.Wai[w], J.Wilkes[w], K.Young[w]

[a] Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188-8502, Japan

[b] Department of Physics, Boston University, Boston, MA 02215, USA

[c] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

[d] Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697-4575, USA

[e] Department of Physics, California State University, Dominguez Hills, Carson, CA 90747, USA

[f] Department of Physics, George Mason University, Fairfax, VA 22030, USA

[g] Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan

[h] Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA

[i] Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

[j] Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

[k] Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, NM 87544, USA

[l] Physics Department, Louisiana State University, Baton Rouge, LA 70803, USA

[m] Department of Physics, University of Maryland, College Park, MD 20742, USA

[n] Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan

[o] Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794-3800, USA

[p] Department of Physics, Niigata University, Niigata, Niigata 950-2181, Japan

[q] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan

[r] Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan

[s] The University of Tokyo, Tokyo 113-0033, Japan

[t] Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan

[u] Department of Physics, Tokyo Institute for Technology, Meguro, Tokyo 152-8551, Japan

[v] Institute of Experimental Physics, Warsaw University, 00-681 Warsaw, Poland

[w] Department of Physics, University of Washington, Seattle, WA 98195-1560, USA

[1] Present address: Department of Physics and Astronomy, State University of New York, Stony Brook

[2] Present address: Department of Physics, Seoul National University, Seoul 151-742, Korea

[3] Present address: NASA, JPL, Pasadena, CA 91109, USA

[4] Present address: Accelerator Laboratory, High Energy Accelerator Research Organization (KEK)

[5] Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637 USA

[6] Present address: Institute for Cosmic Ray Research, University of Tokyo

[7] Present address: Dept. of System Engineering, Shizuoka University Hamamatsu, Shizuoka 432-8561, Japan

[8] Present address: Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK)

[9] Supported by the Polish Committee for Scientific Research

Kamiokande III collaboration

(~50 people)

S. Hatakeyama[1], T. Hara[2], Y. Fukuda[3], T. Hayakawa[3], K. Inoue[3], K. Ishihara[3], H. Ishino[3], S. Joukou[3], T. Kajita[3], S. Kasuga[3], Y. Koshio[3], T. Kumita[3†], K. Matsumoto[3], M. Nakahata[3], K. Nakamura[3*], K. Okumura[3], A. Sakai[3*], M. Shiozawa[3], J. Suzuki[3], Y. Suzuki[3], T. Tomoeda[3], Y. Totsuka[3], K. S. Hirata[4], K. Kihara[4], Y. Oyama[4*], M. Koshiba[5], K. Nishijima[6], T. Horiuchi[6], K. Fujita[1], M. Koga[1], T. Maruyama[1], A. Suzuki[1], M. Mori[7‡], T. Suda[8§], A. T. Suzuki[8], T. Ishizuka[9], K. Miyano[9], H. Okazawa[9], Y. Nagashima[2], M. Takita[2], T. Yamaguchi[2], Y. Hayato[a*], K. Kaneyuki[a], T. Suzuki[a] Y. Takeuchi[a¶], T. Tanimori[a], S. Tasaka[b], E. Ichihara[c], S. Miyamoto[c], and K. Nishikawa[c*]

[1] *Physics Department, Graduate School of Science, Tohoku University, Sendai, Miyagi 980-8578, Japan*

[2] *High Energy Physics Division, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*

[3] *Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188-8502, Japan*

[4] *National Laboratory for High Energy Physics, Tsukuba, Ibaraki 305-0801, Japan*

[5] *Institute of Research and Development, Tokai University, Shibuya, Tokyo 151-0063, Japan*

[6] *Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan*

[7] *Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan*

[8] *Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan*

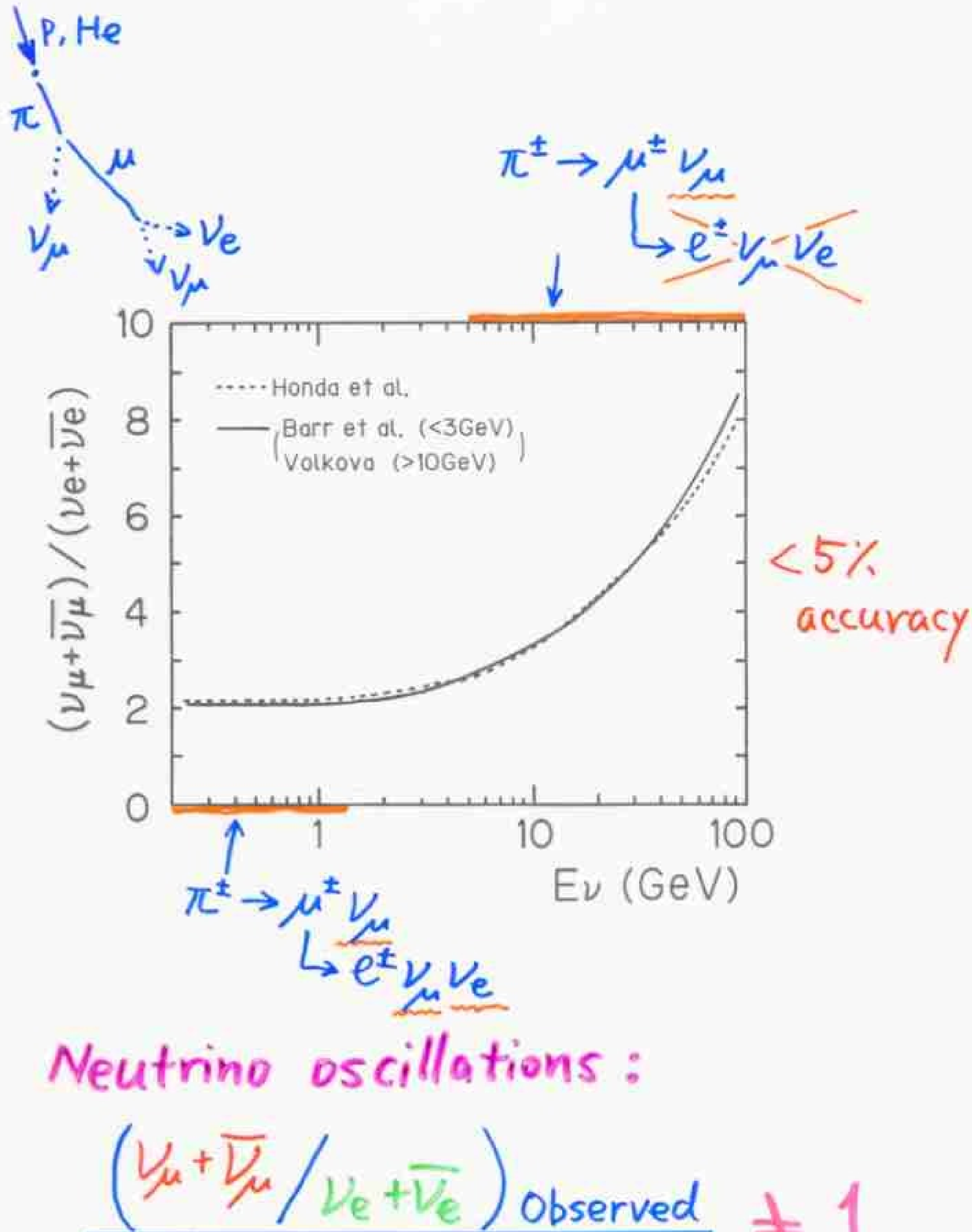
[9] *Niigata University, Niigata 950-2181, Japan*

[a] *Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan*

[b] *Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan*

[c] *Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188-8501, Japan*

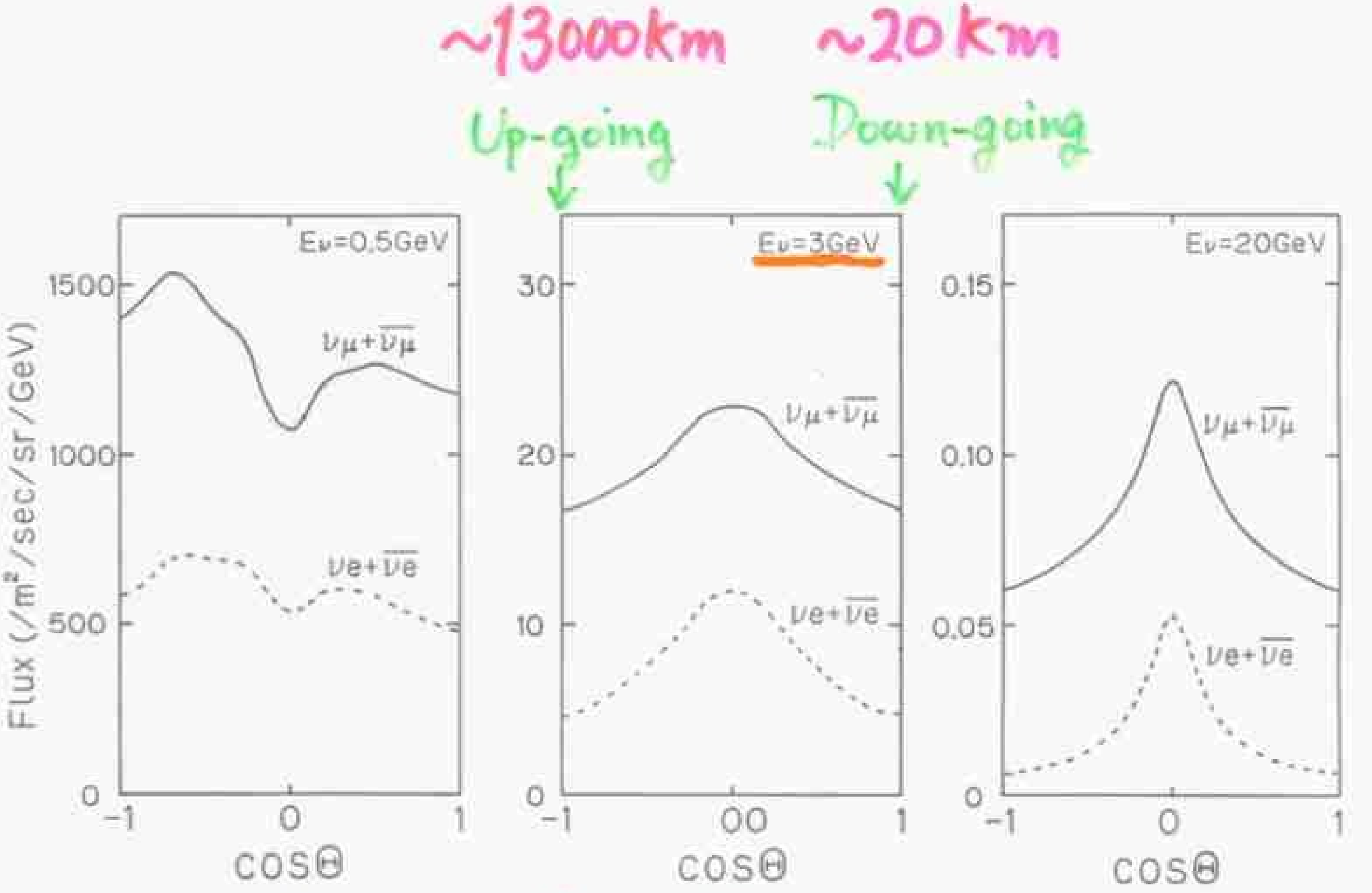
Atmospheric neutrinos



Neutrino oscillations :

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

Zenith angle



For E_ν > a few GeV;

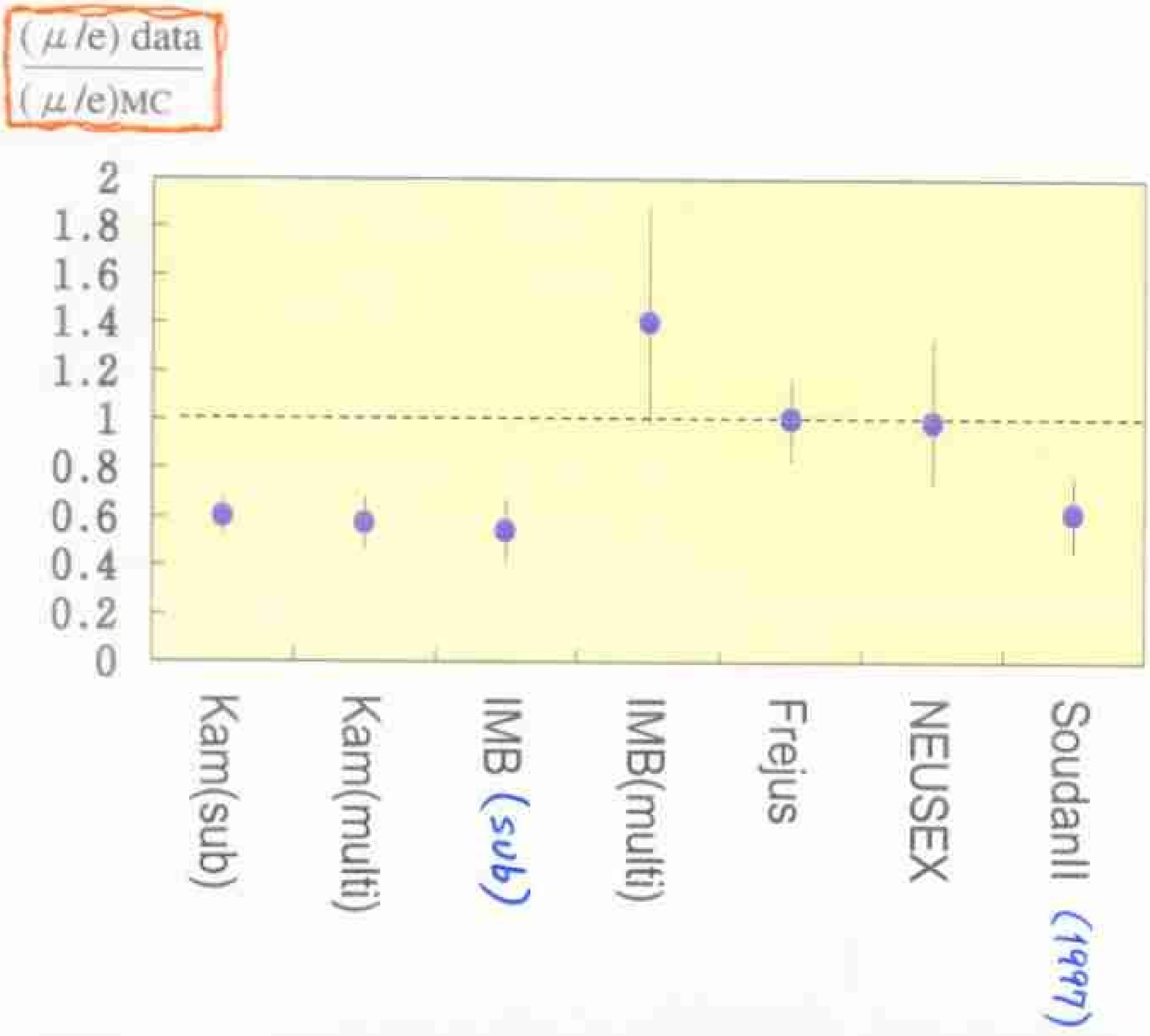
$$\frac{\text{Calculated flux (Up)}}{\text{(Down)}} = 1 \ (\pm < \text{a few } \%$$

⇓

Zenith angle dependence
(Up/Down asymmetry)

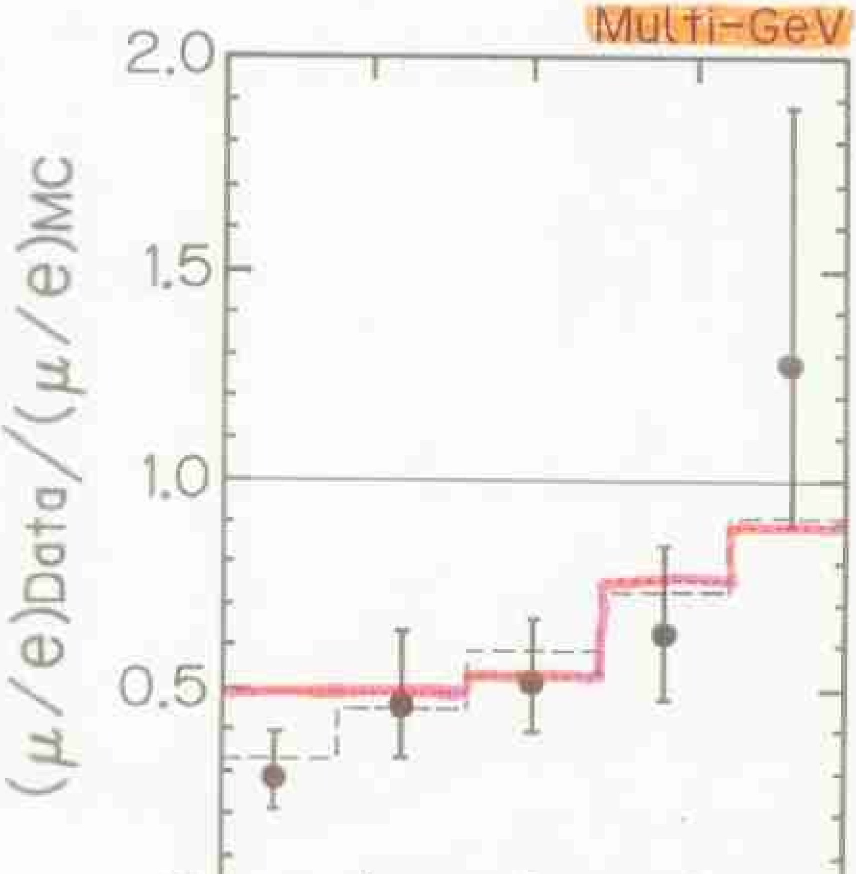
Atmospheric ν History

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



Zenith angle dependence

(KAMIOKANDE)



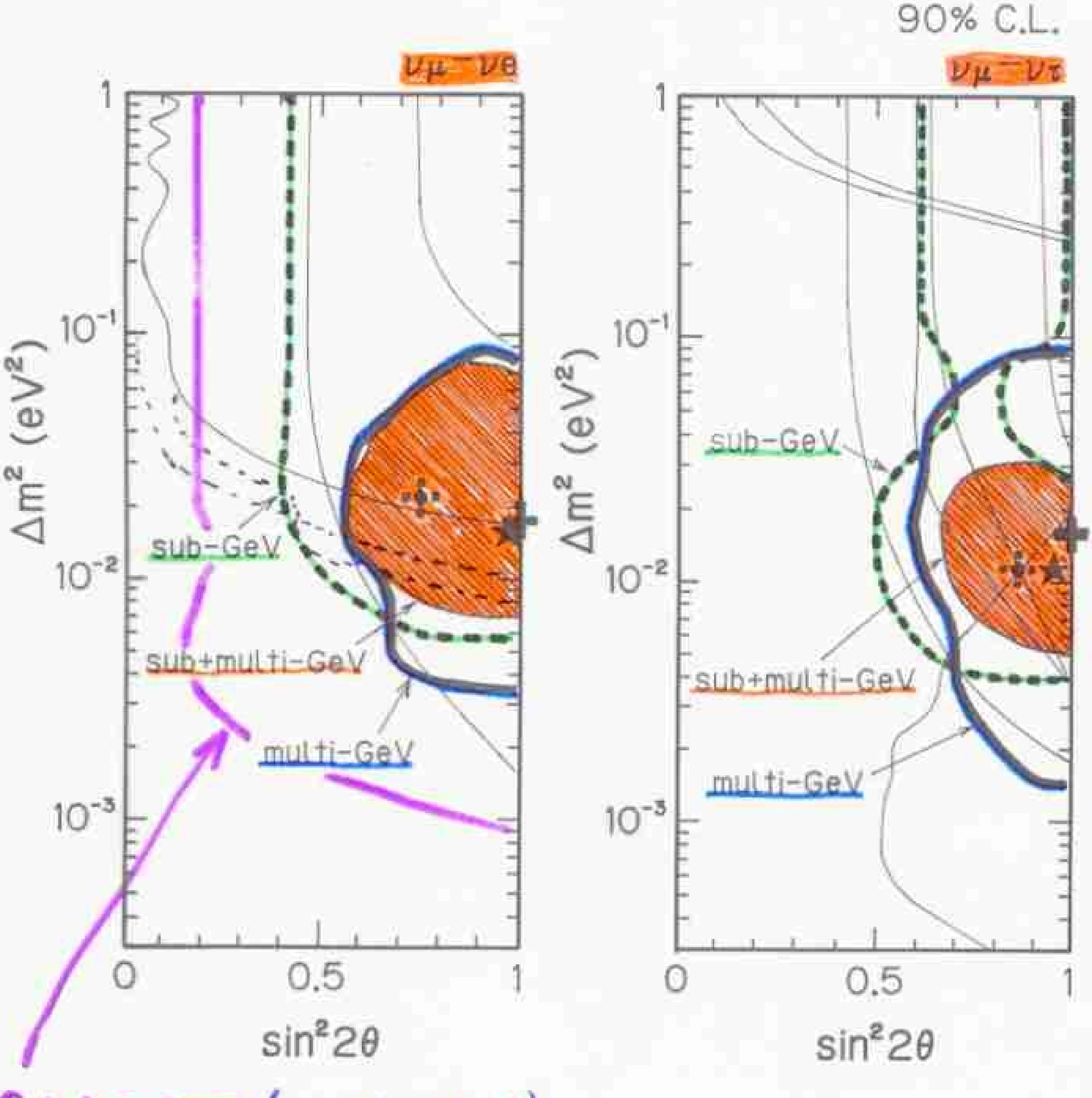
($E_{vis} > 1.33$ GeV) ⊕ Partially contained

Zenith-angle dependence! (seen)

— $\nu_\mu \to \nu_\tau$ (1.6×10^{-2} eV^2, 1.0)

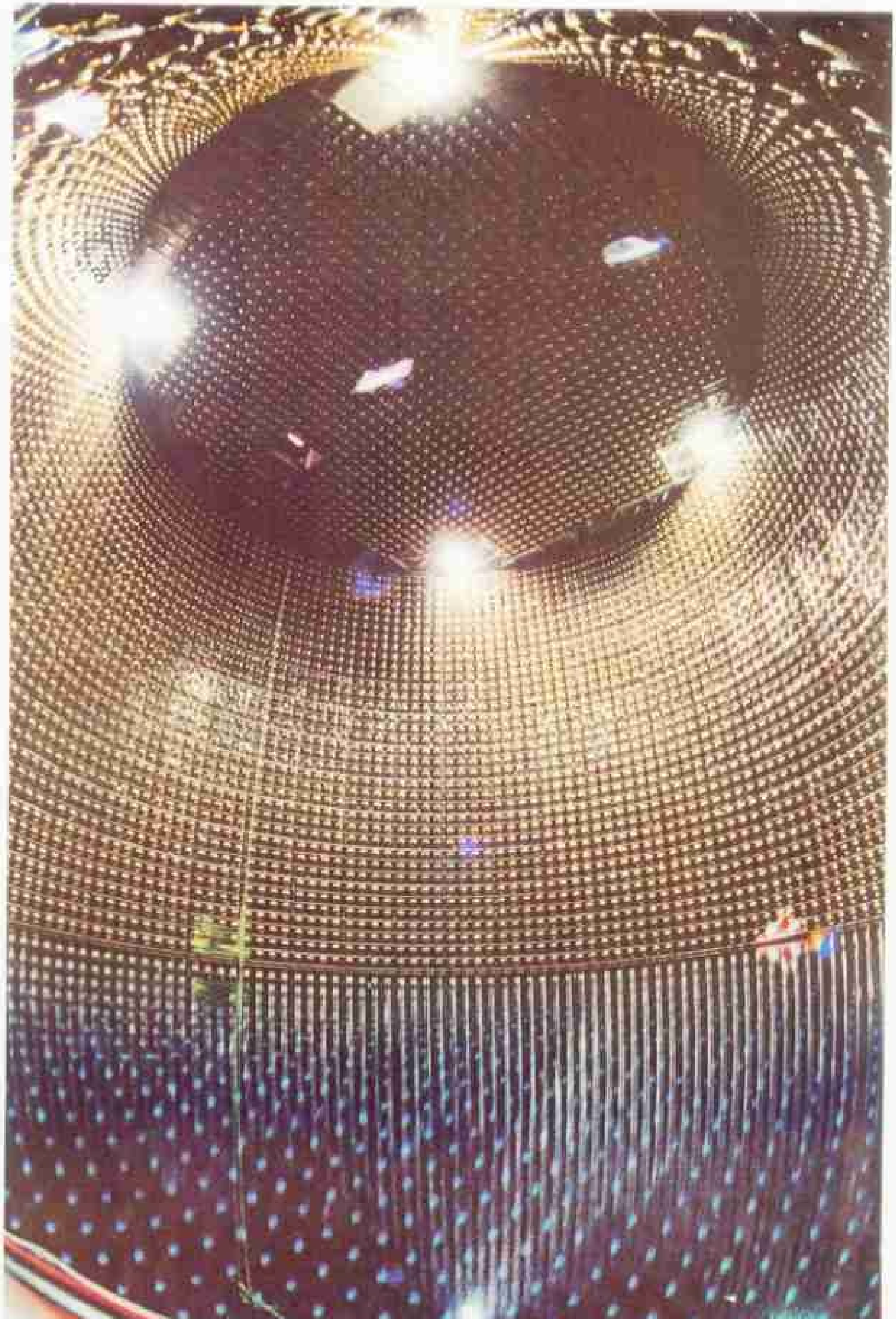
KAMIOKANDE

Allowed parameter regions of neutrino oscillations



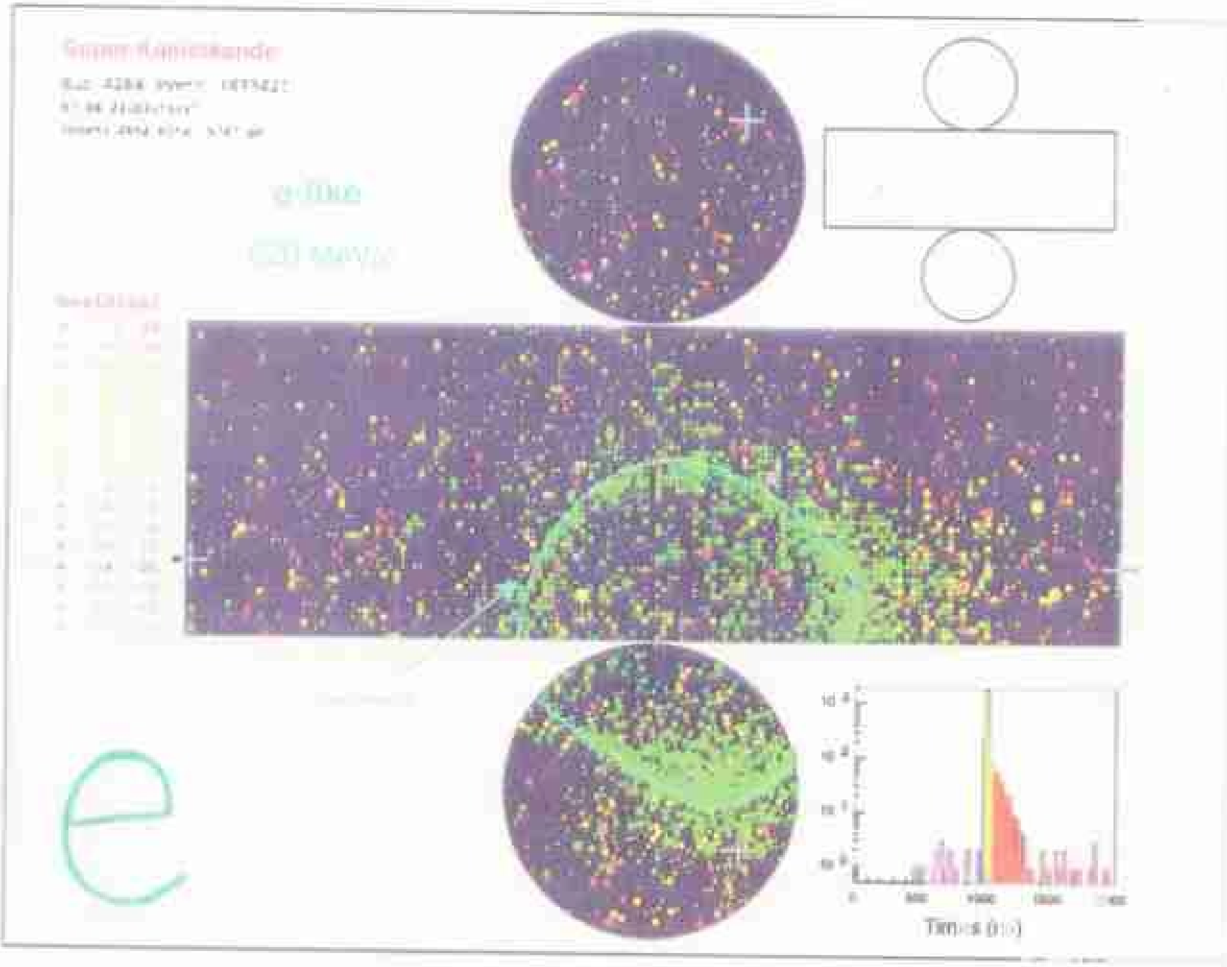
CHOOZ (excluded)

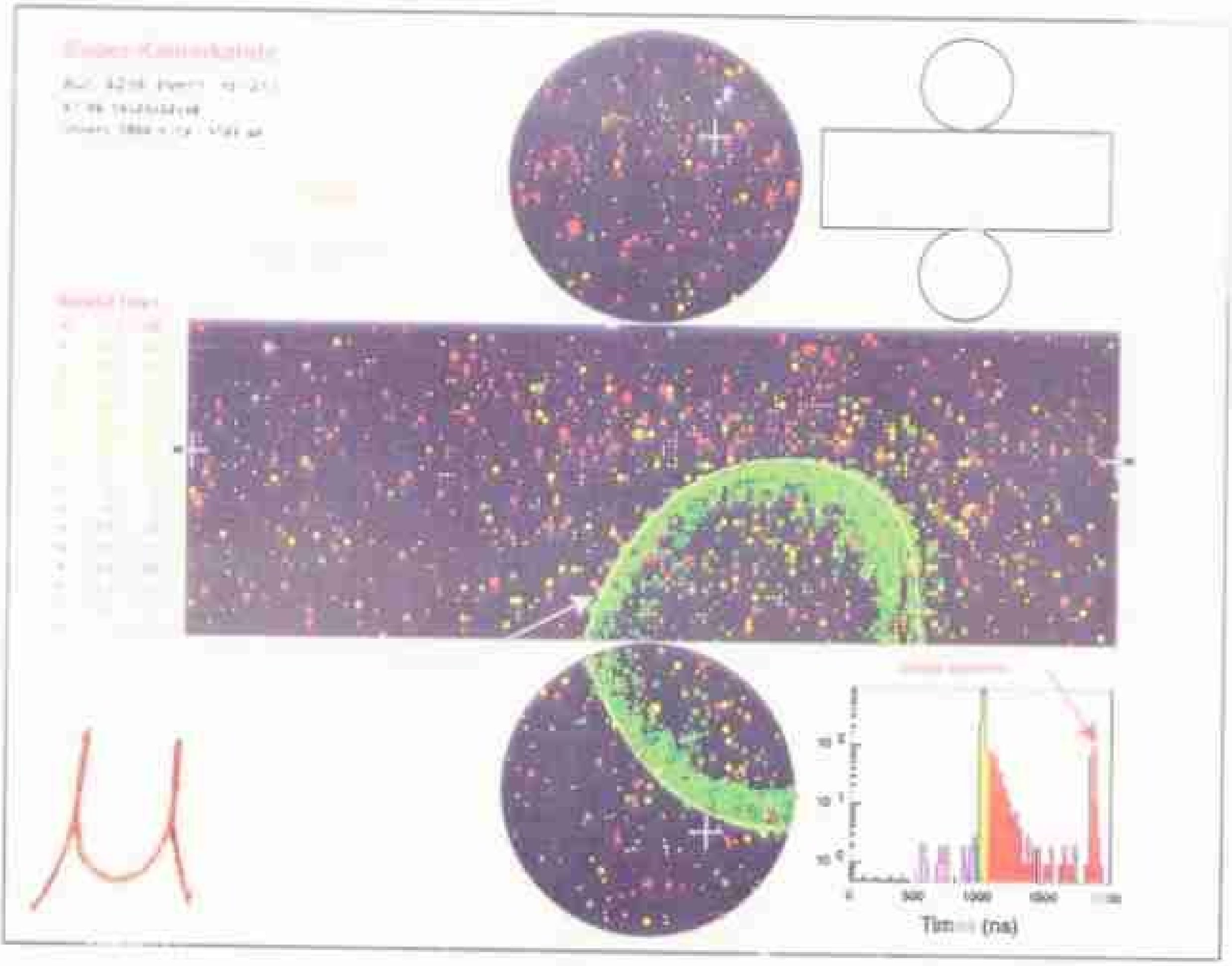
P.L.B 420 (98) 397



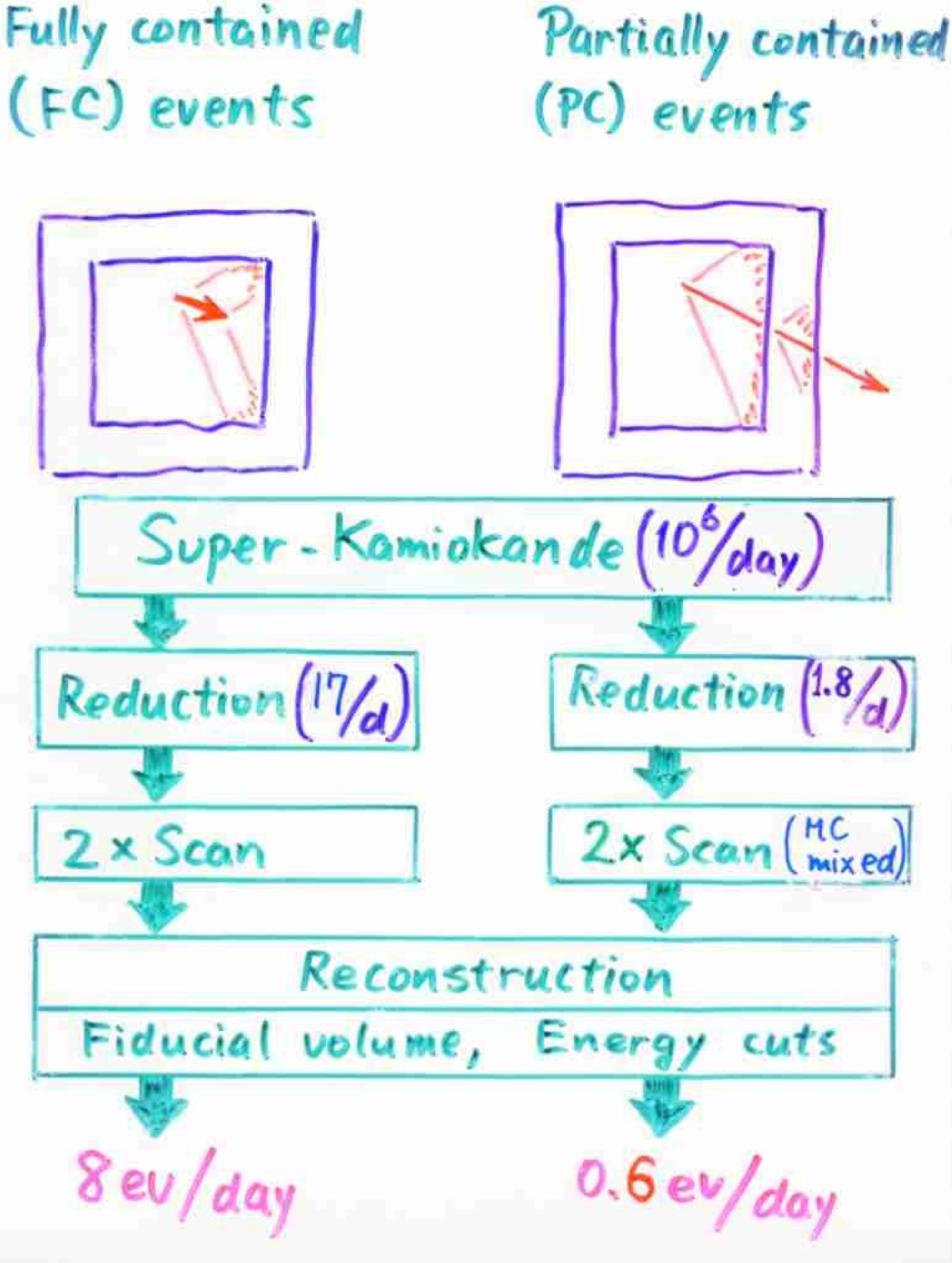
Filling water Jan. 1996

Data taking April 1996~


e


μ
Time (ns)

Data reduction



Super-Kamiokande

Sub-GeV

33.0 kt·yr (535 days)

$E_{vis} < 1.33$ GeV

$P_e > 100$ MeV/c

$P_\mu > 200$ MeV/c

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

MC: ~25% uncertainty in the absolute rate.

$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.63 \pm^{0.026}_{0.025} \pm 0.05$$

(stat; syst. + MC stat)

Kam.

$$= 0.60 ^{+0.06}_{-0.05} \pm 0.054$$

Super-Kamiokande

Multi-GeV

- Fully contained ($E_{vis} > 1.33$ 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

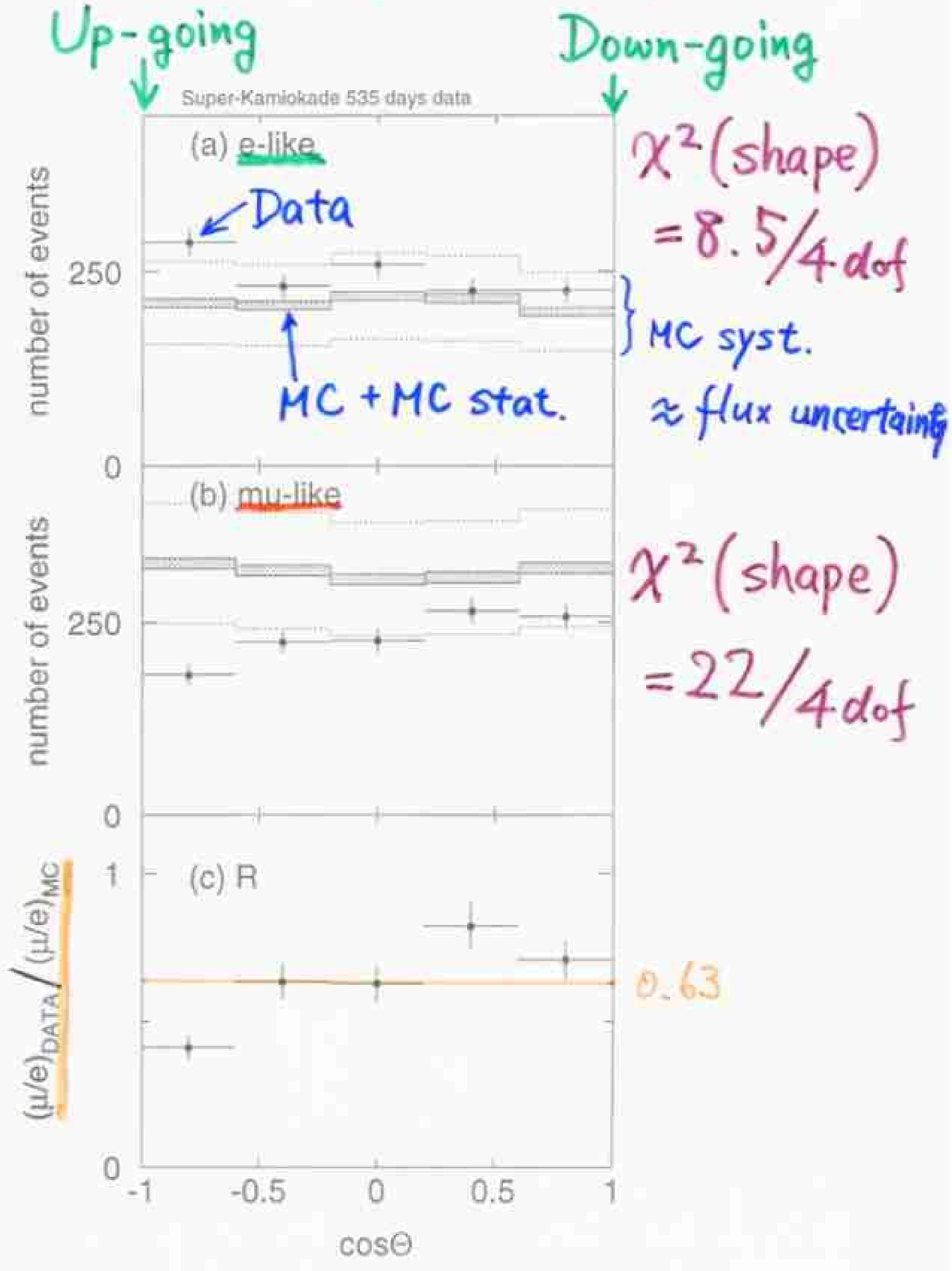
※ CC $\overset{(-)}{\nu}_\mu$ / all p.c. = 0.98

$$\frac{(\mu/e)_D}{(\mu/e)_{MC}} = 0.65 \pm \underset{\text{stat}}{0.05} \pm \underset{\text{syst + MC stat}}{0.08}$$

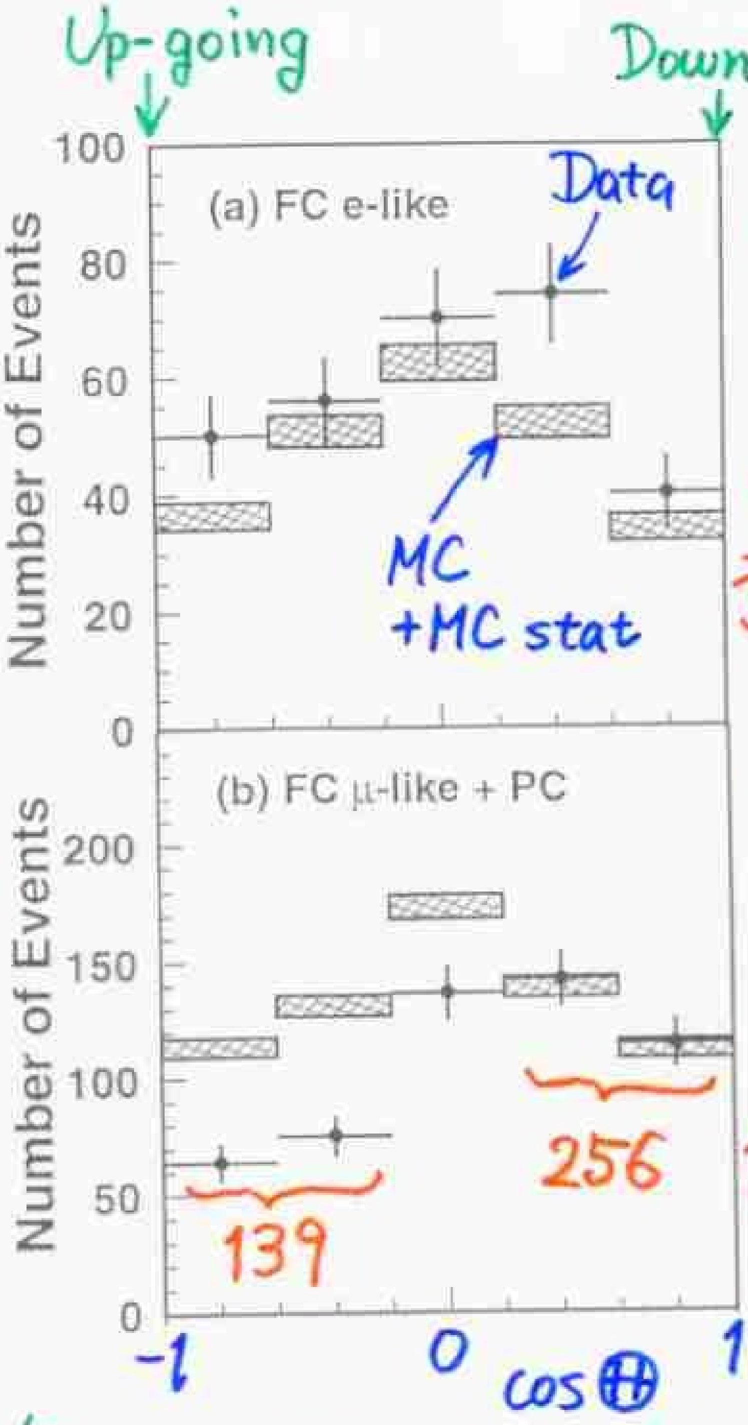
Kam.

$$= 0.57 \,^{+0.08}_{-0.07} \pm 0.07$$

Zenith angle dependence (Sub-GeV)



Zenith angle dependence
(Multi-GeV)



e: χ^2(shape) $= 2.8/4$ dof

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

μ: χ^2(shape) $= 30/4$ dof

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

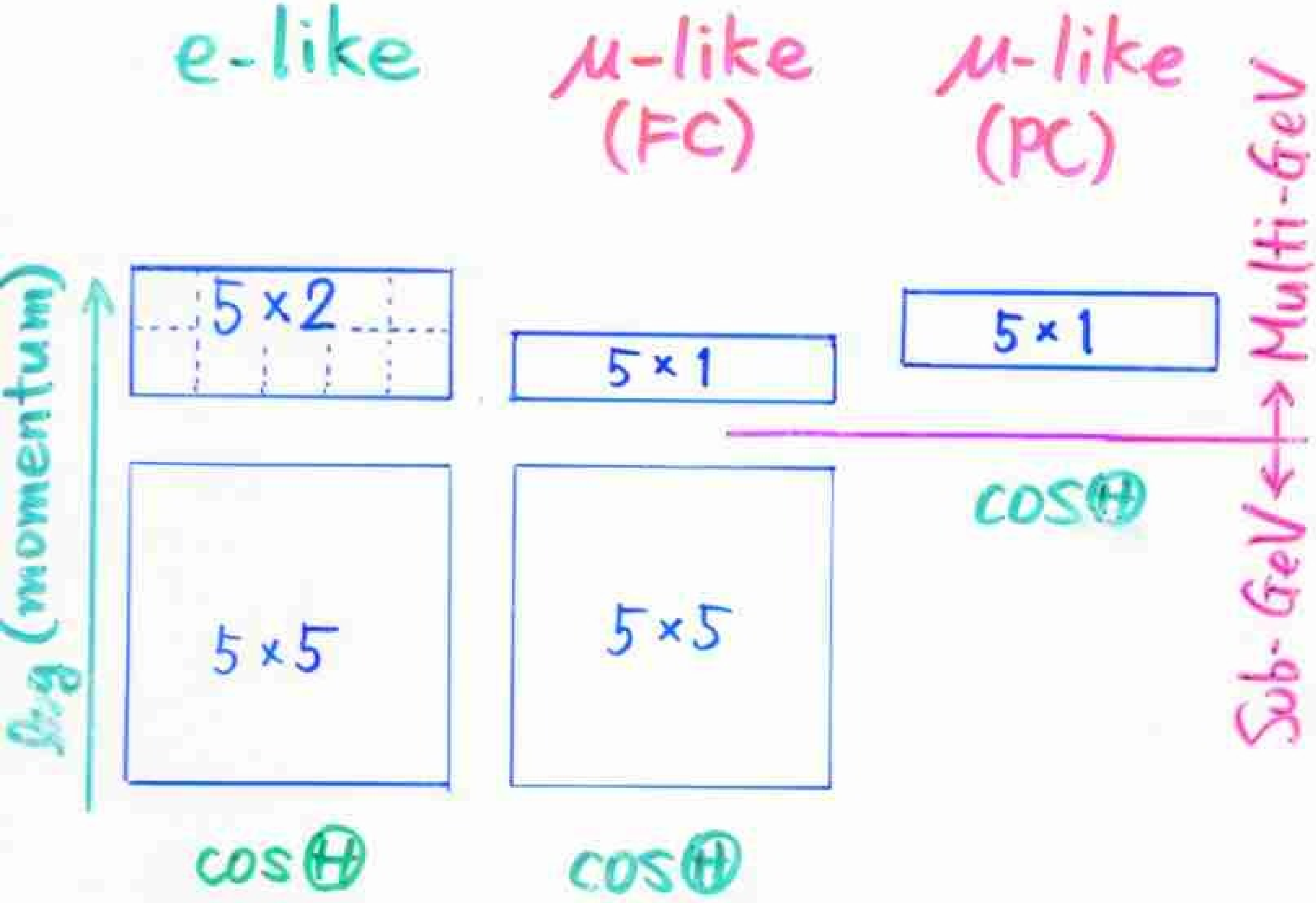
(6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background ….. < 2%) 2.1%

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



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

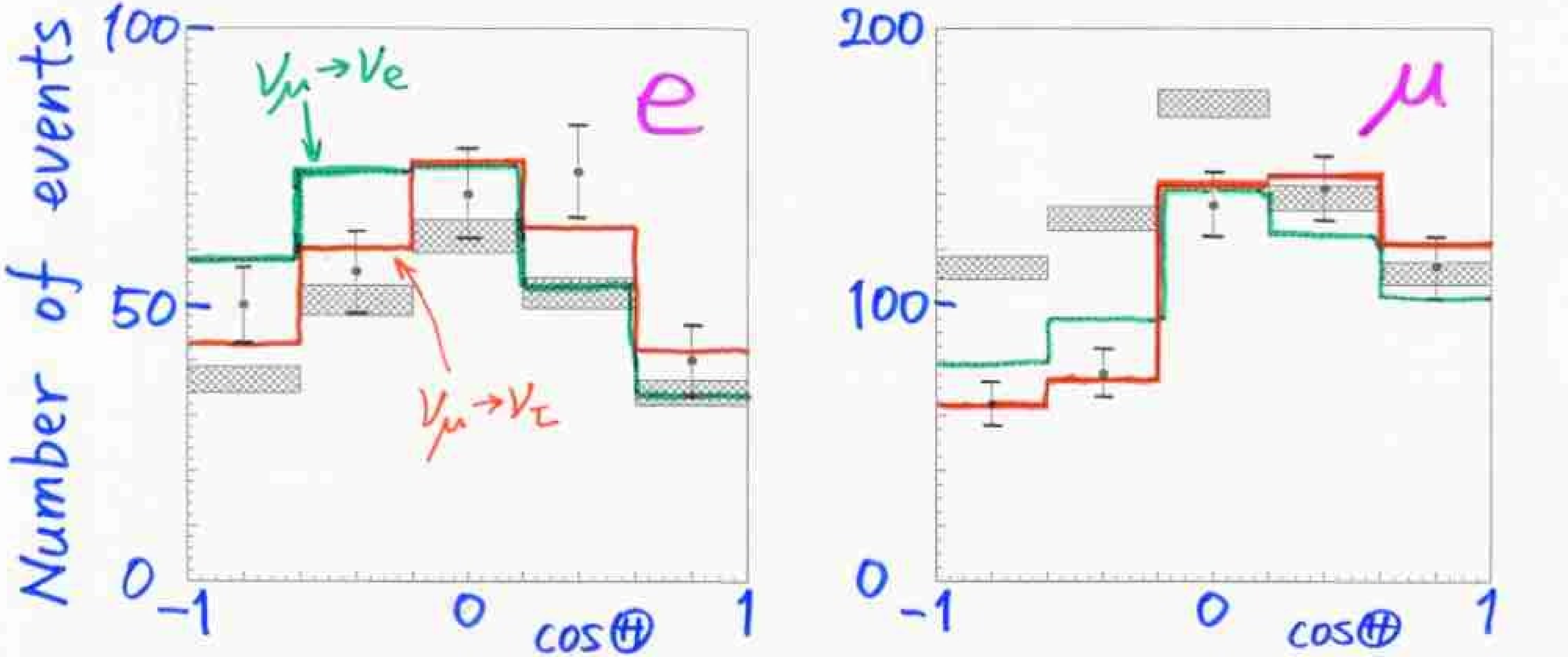
$$+ \sum_i \left(\frac{\alpha_i}{\sigma_i}\right)^2 \leftarrow \text{syst. error}$$

↓

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

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

Multi-GeV



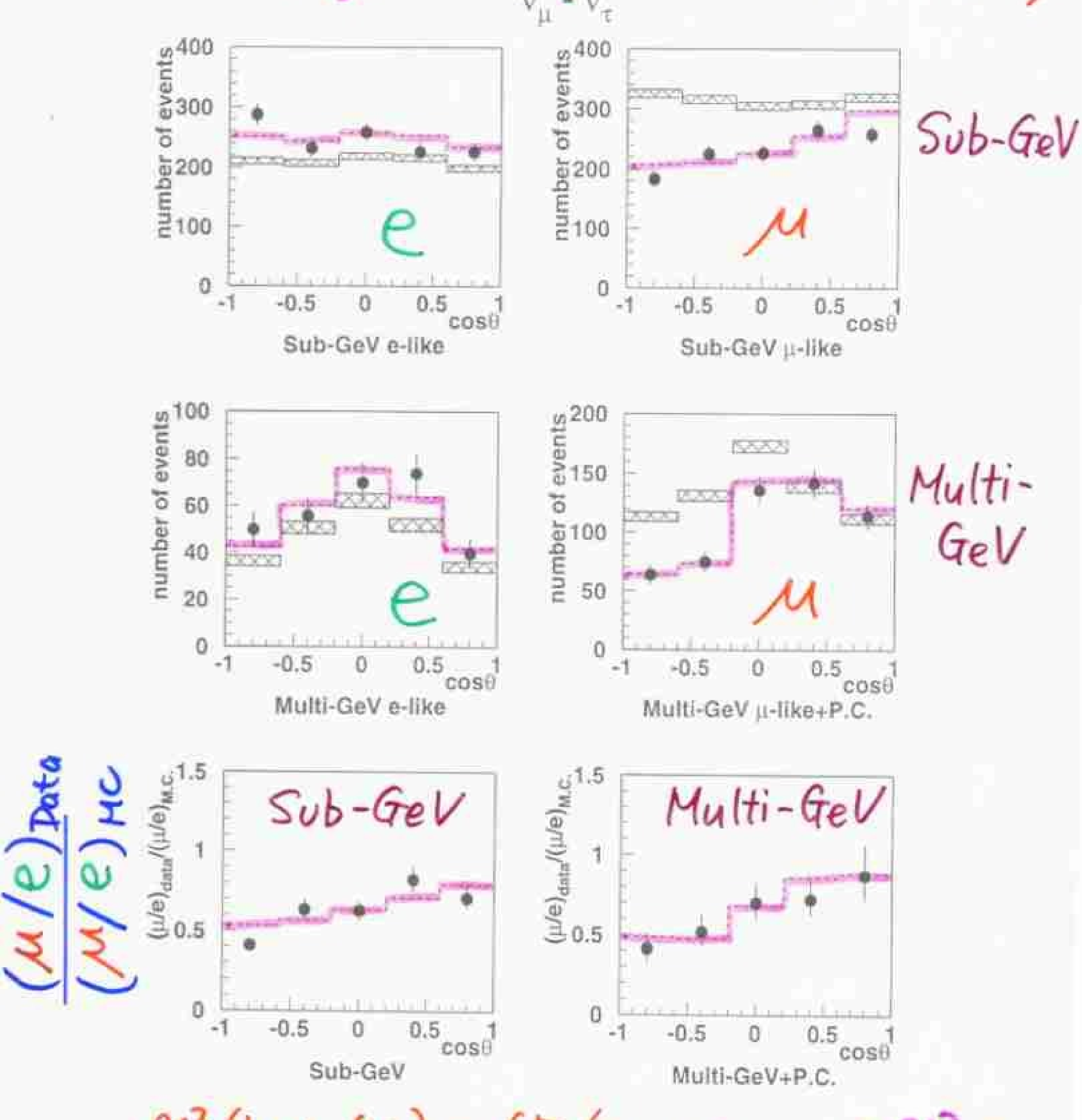
$\chi^2(\nu_\mu \to \nu_\tau \text{ best fit}) = 65/67\,\text{dof}$

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

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

Data vs. Oscillations

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

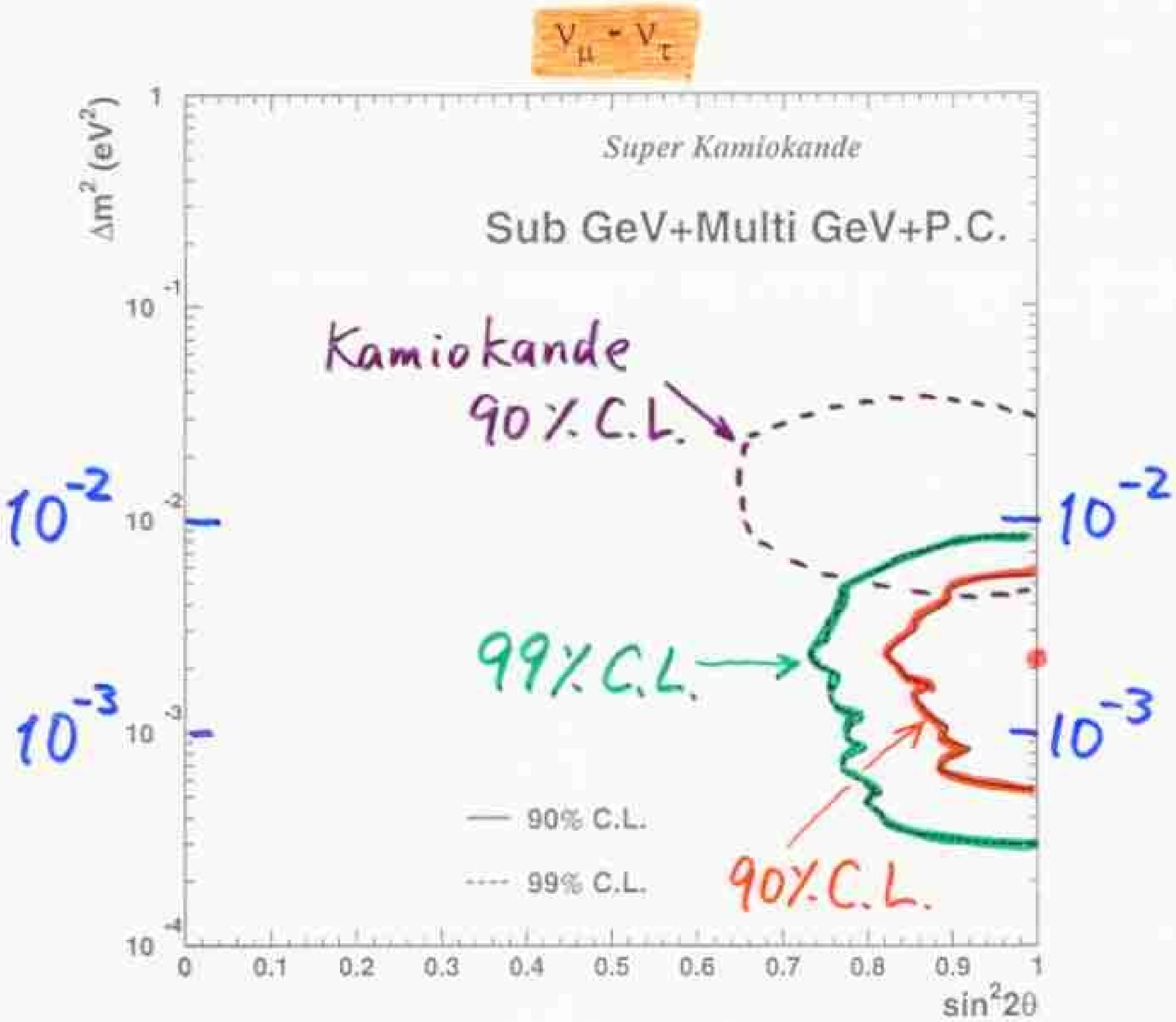


χ^2(best fit) = 65/67 d.o.f.

χ^2(No oscillation) = 135/67 d.o.f

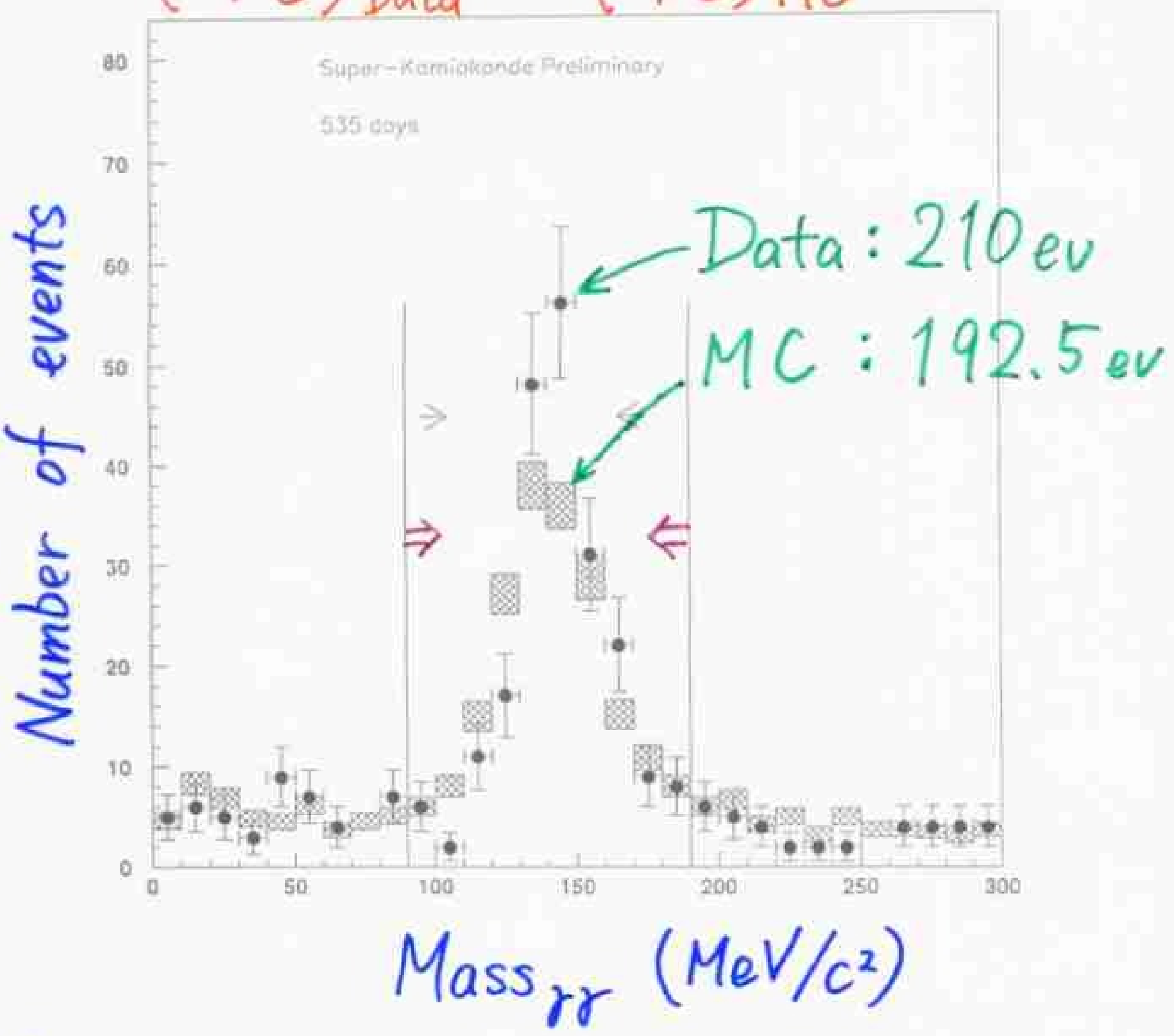
$\Delta\chi^2 = 70!$

Allowed region based on contained events



- If $\nu_\mu \to \nu_\tau$ oscillations, **Check**
  - NC (π^0-events) ---- no oscillation
  - ν_e (e-like events) --- no oscillation

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

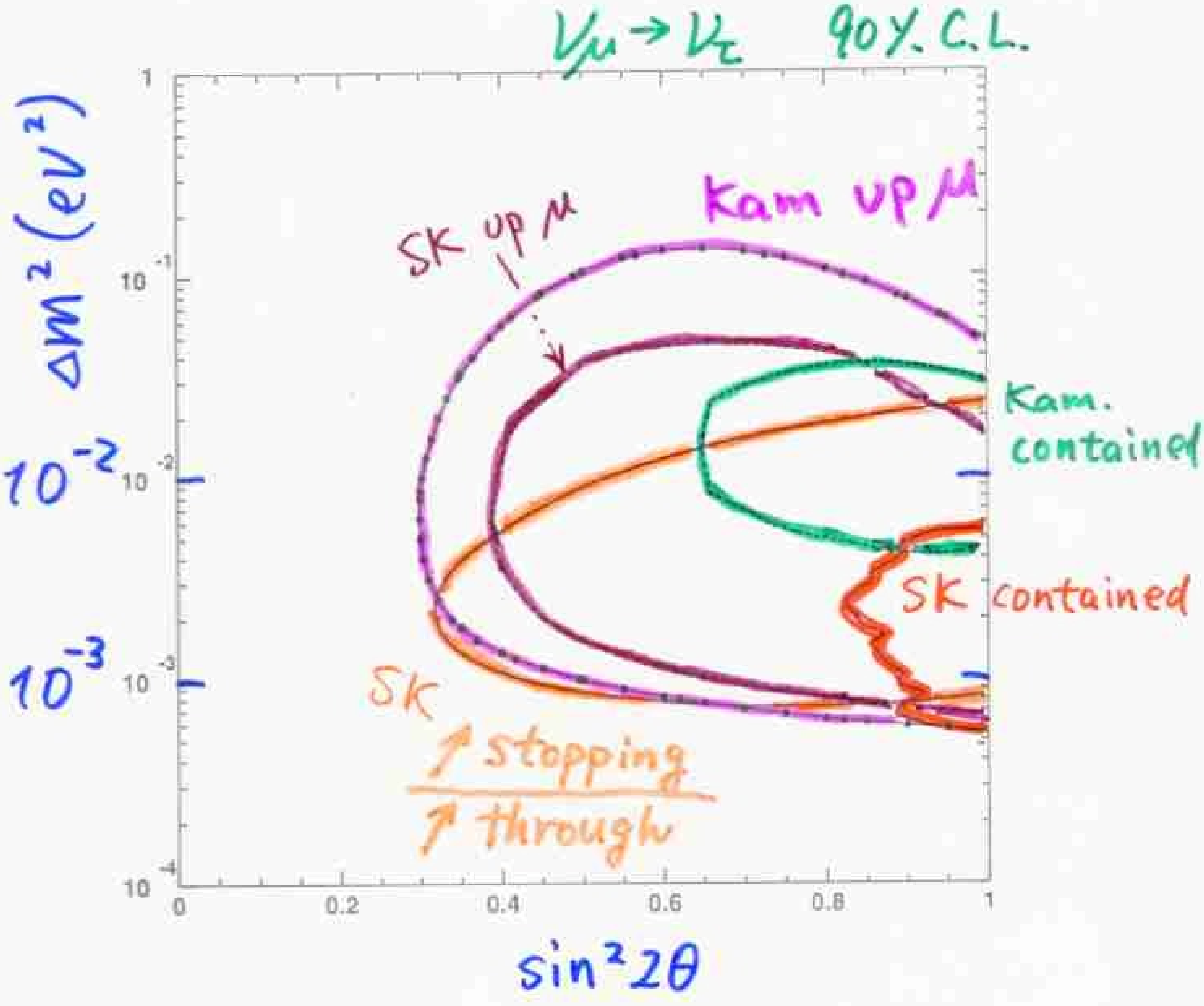


$$\frac{\left(\pi^0/e\right)_{Data}}{\left(\pi^0/e\right)_{MC}} = \frac{210/1231}{192.5/1049.1} = 0.93 \pm 0.07\,(stat) \pm 0.19\,(syst)$$

Consistent with $\nu_\mu \to \nu_\tau$

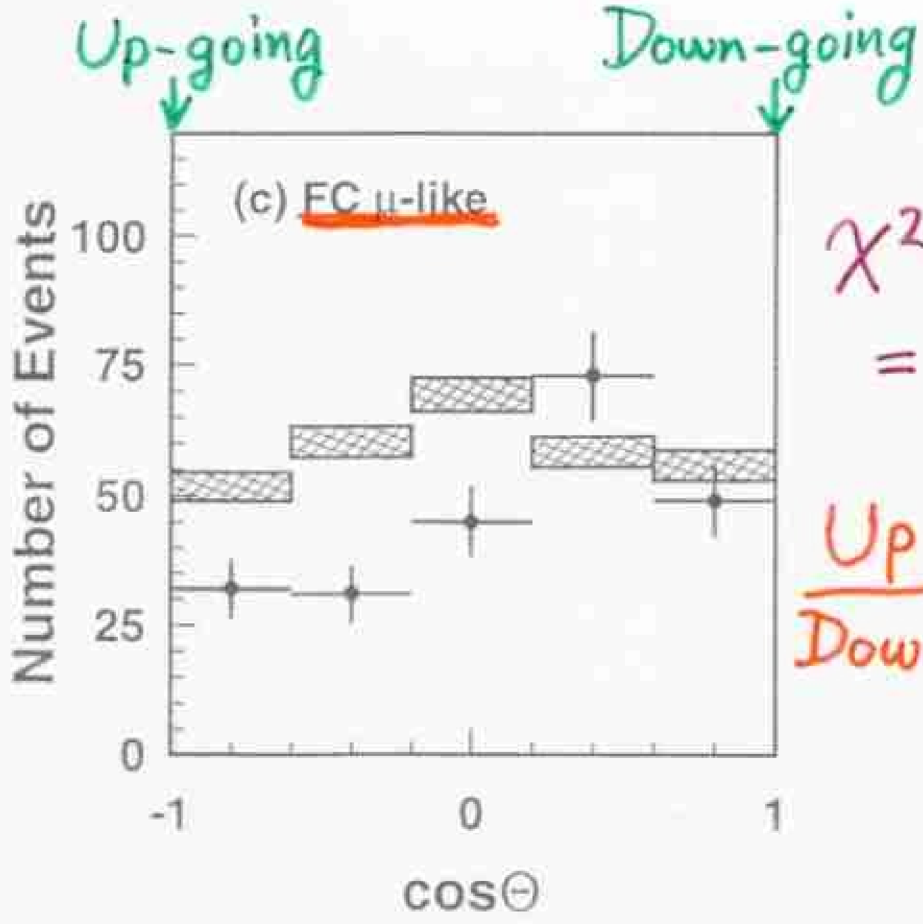
Summary

Evidence for ν_μ oscillations



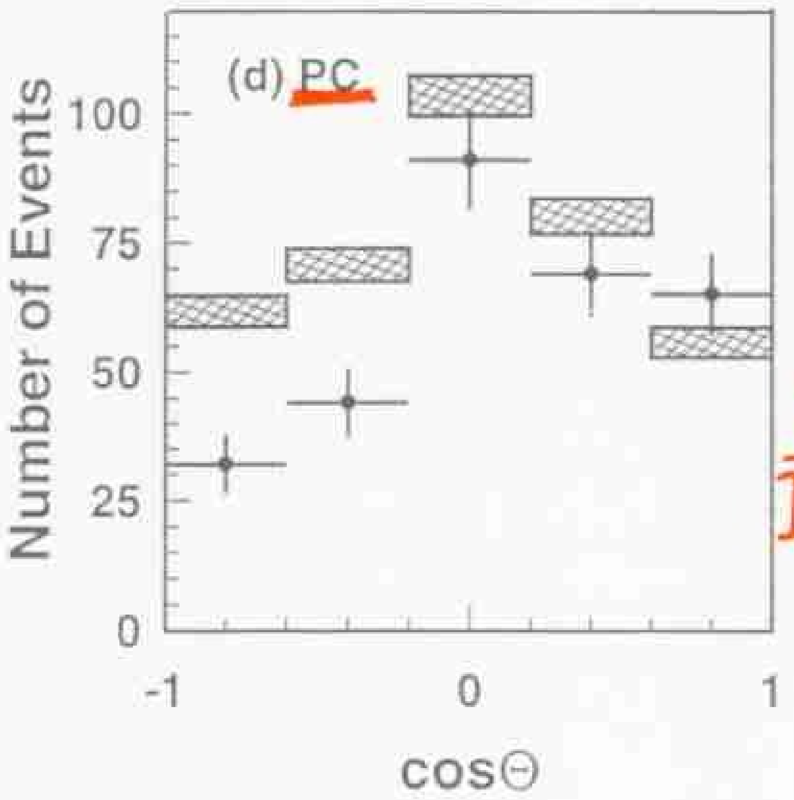
- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)



χ^2 (shape) $= 19/4$ d.o.f.

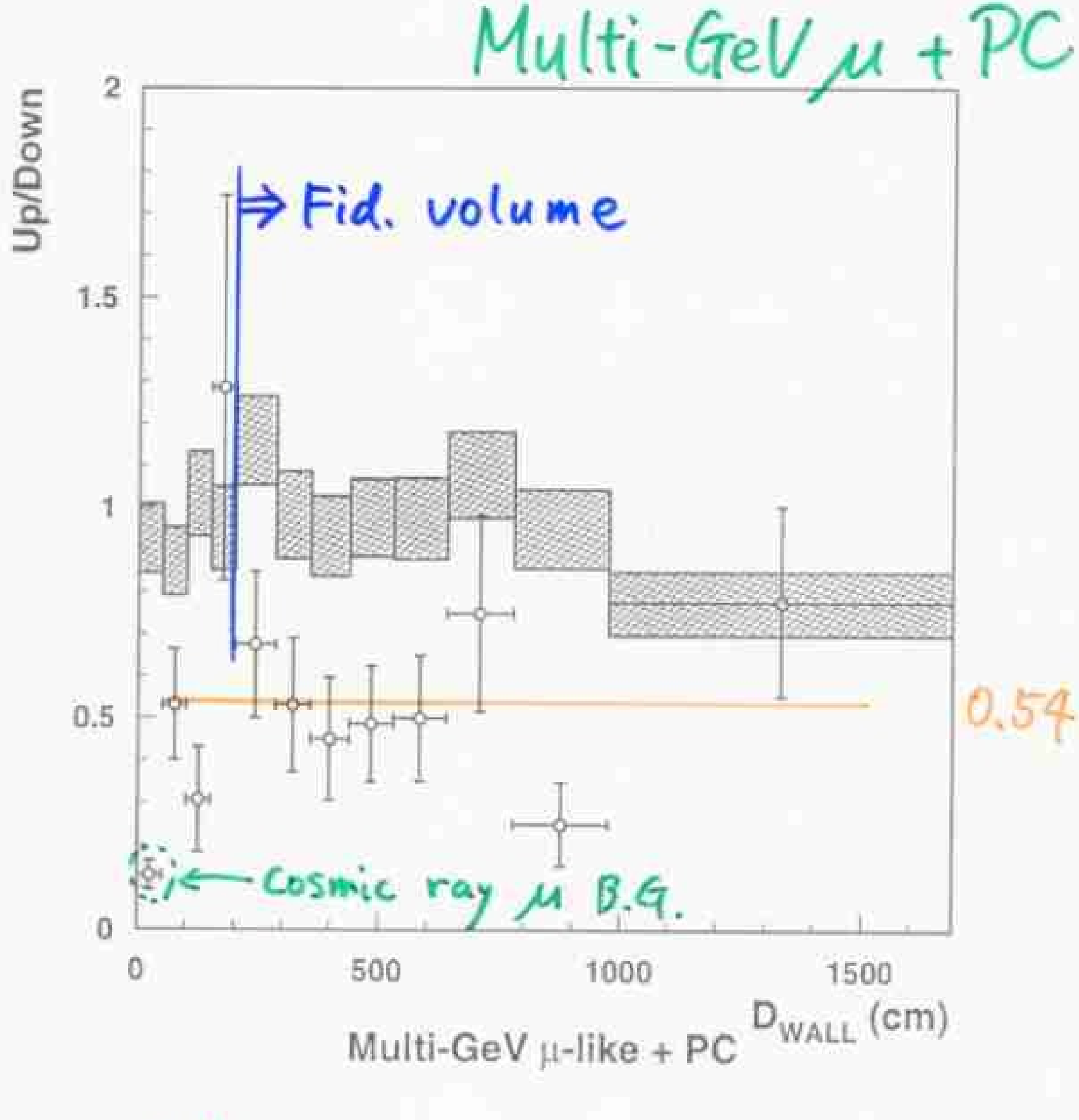
$\frac{\text{Up}}{\text{Down}} = 0.52^{+0.09}_{-0.07}$



χ^2 (shape) $= 18/4$ d.o.f.

$\frac{\text{Up}}{\text{Down}} = 0.57^{+0.09}_{-0.08}$

$\frac{Up}{Down}$ vs. Distance from Wall



⇒ $\frac{Up}{Down}$ has no significant Dwall dependence

Systematic errors included in the oscillation fit

	σ	fit result
Abs. normalization	∞	16%
flux * $E_\nu^{-d\delta}$	5%	0.6%
$\left[\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}\right]_{Sub\text{-}GeV}$	8%	5%
$\left[\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}}\right]_{Multi\text{-}GeV}$	12%	12%
$\frac{PC}{FC_\mu}$	8%	2%
$\left[\frac{Up}{Down}\right]_{Sub\text{-}GeV}$	2.5%	2.4%
$\left[\frac{Up}{Down}\right]_{Multi\text{-}GeV}$	2.7%	0.1%
L/E	20%	3%