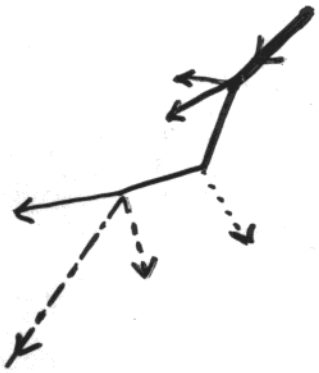
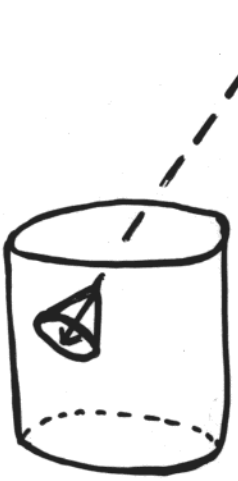


ATMOSPHERIC NEUTRINOS at SUPER-KAMIOKANDE

AN UPDATE



Kate Scholberg

Boston University

February 24, 1999

OUTLINE

ATMOSPHERIC ν's AT SUPER-K

- What's New

LATEST RESULTS

- Fully and Partially Contained
- Upward-going Muons

  + combined analysis

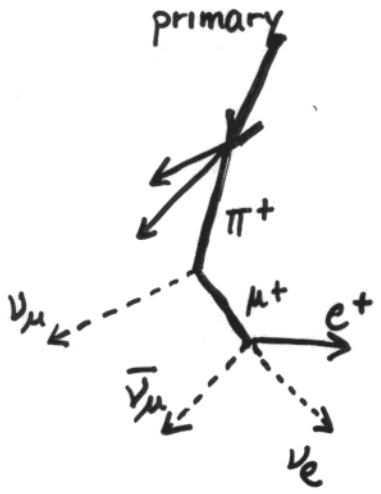
OSCILLATION HYPOTHESES

$$\nu_\mu \rightarrow \nu_{x \; ?}$$

- FC/PC angular distributions
- single π's

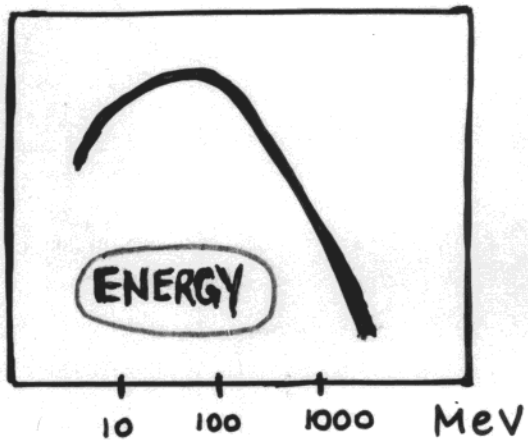
ATMOSPHERIC NEUTRINOS

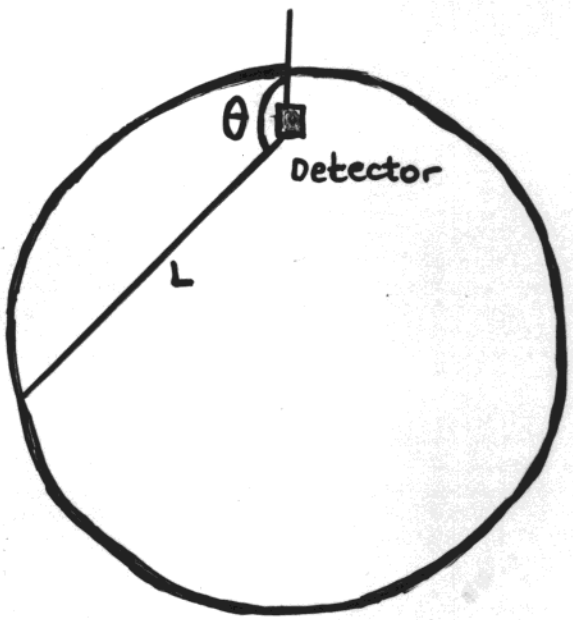
produced by cosmic ray showers

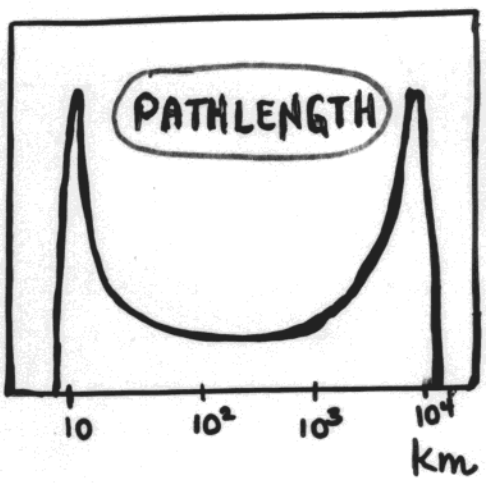


$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$$

$$\mathcal{R} \equiv \frac{\left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{DATA}}{\left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{MC}}$$







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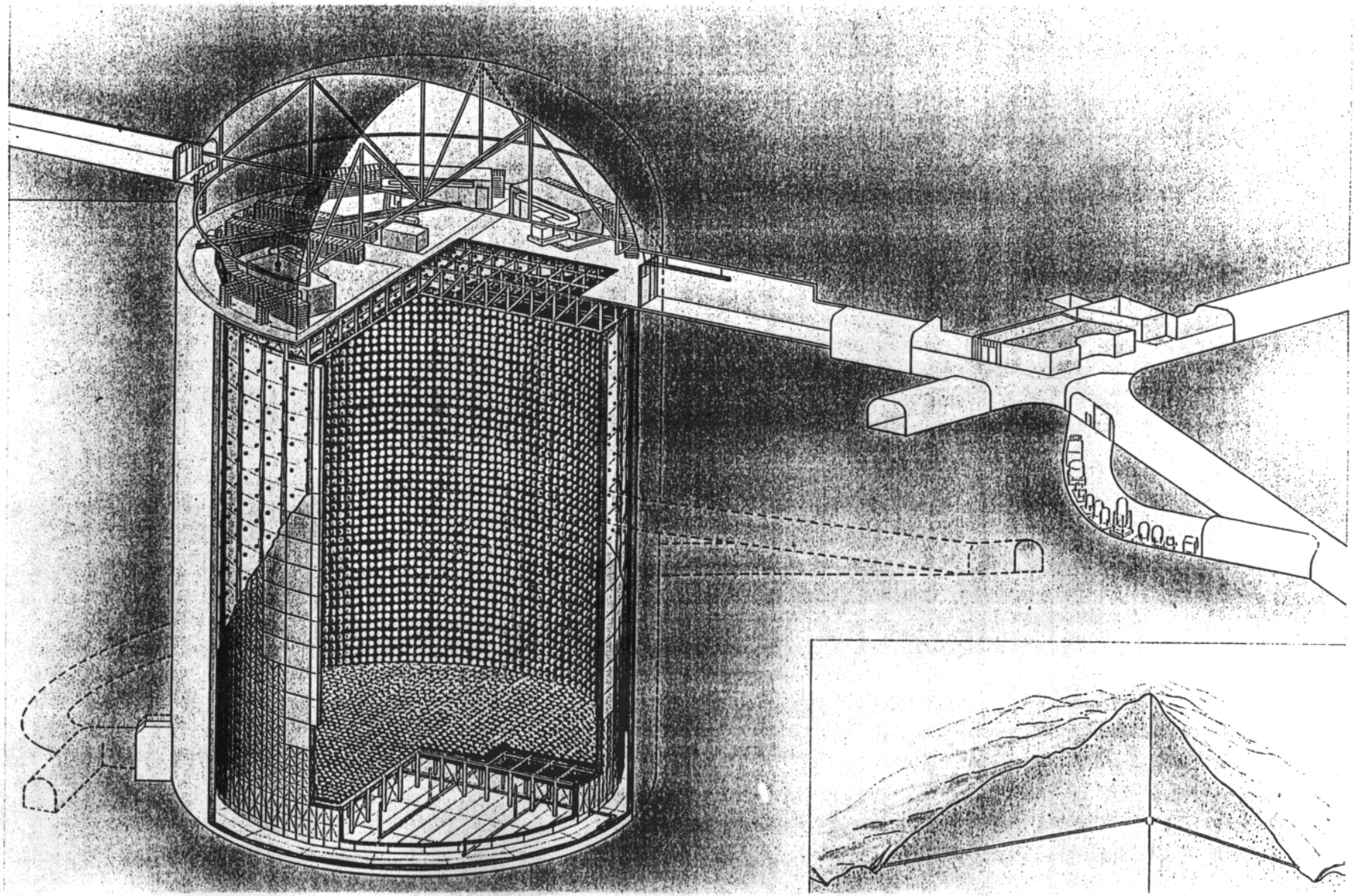
J.S. George, A.L. Stachyra, L.L. Wai, R.J. Wilkes, K.K. Young

Department of Physics, Seoul National University
S.B. Kim

2 concentric cylindrical detectors, optically separated

INNER (ID):
- 32 kton
- 32 m x 16.9 m radius
- 11146 20" PMTs

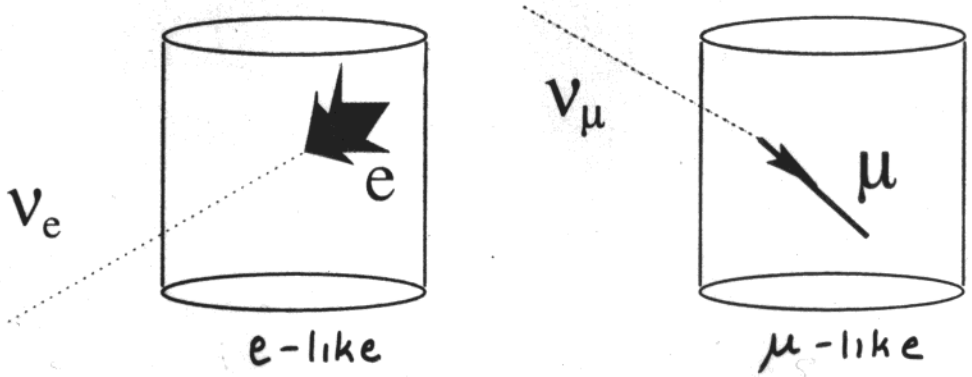
OUTER: (OD)
- 2.75 m thick
- 1885 8" PMTs
- radioactivity shield & incoming particle veto



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

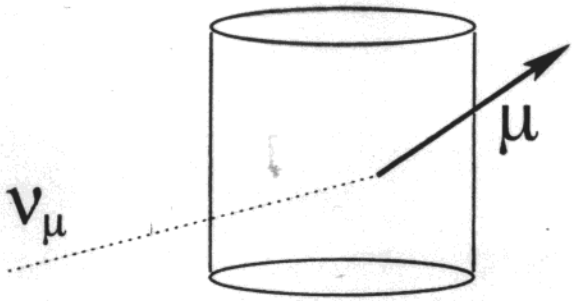
NIKKEN SEKKEI

9



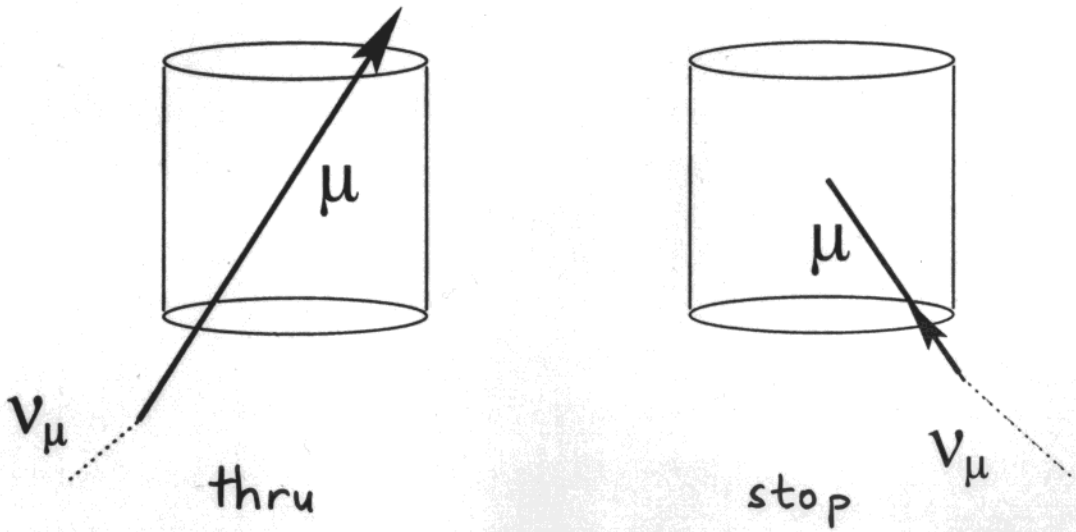
FULLY CONTAINED

{ sub-GeV $E < 1.33$ GeV
{ multi-GeV $E > 1.33$ GeV



PARTIALLY CONTAINED

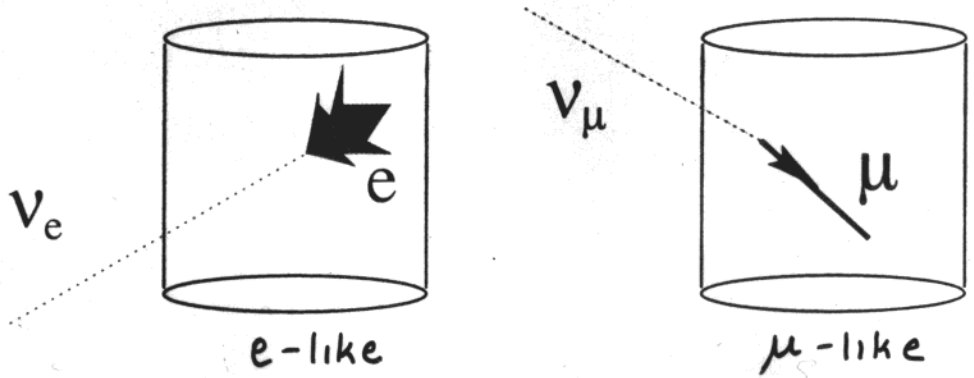
$\langle E \rangle \sim 15$ GeV



UPWARD GOING MUONS

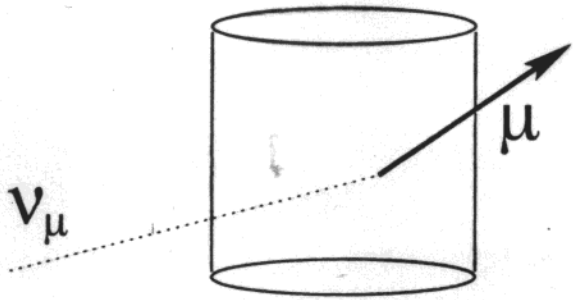
$\langle E \rangle \sim 100$ GeV

$\langle E \rangle \sim 10$ GeV



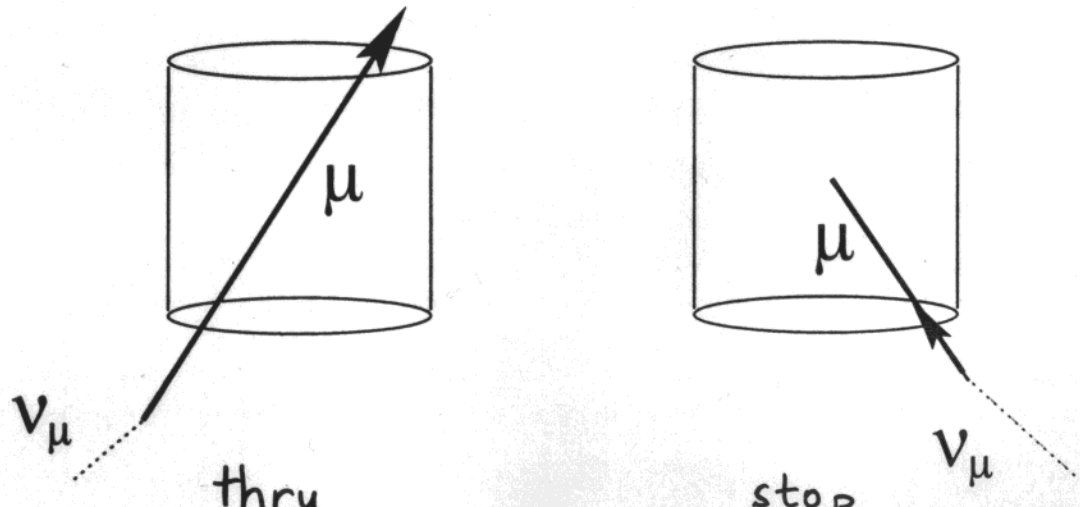
FULLY CONTAINED

{ sub-GeV $E < 1.33$ GeV
{ multi-GeV $E > 1.33$ GeV



PARTIALLY CONTAINED

$\langle E \rangle \sim 15$ GeV



UPWARD GOING MUONS

UPDATE - WHAT'S NEW SINCE JUNE '98

DATA

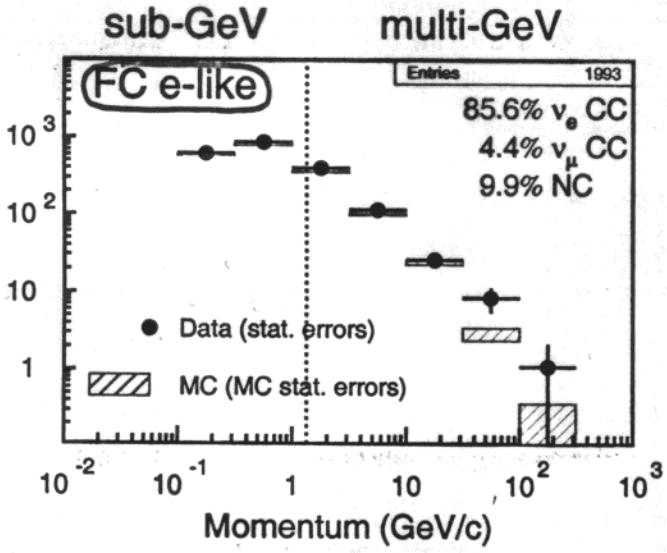
	OLD	NEW
LIVETIME		
FC	535 days	736 days
PC	535 days	685 days
upmu	516 days	516 days
RECONSTRUCTION (fitting, ring counting)		minor improvements

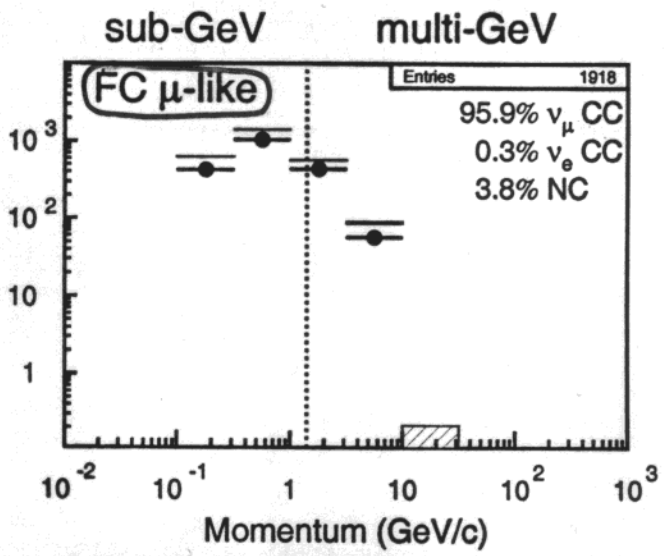
MONTE CARLO

LIVETIME	10 yr	20 yr
X-scns	CCFR structure functions	for DIS use GRV 1994 PDF
solar wind	solar cycle average	solar cycle min

Now have <u>combined</u> FC/PC/upmu analysis

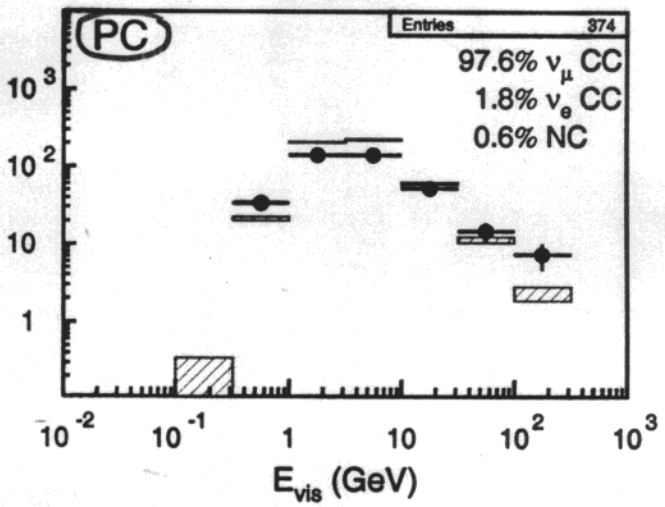
FULLY AND PARTIALLY CONTAINED





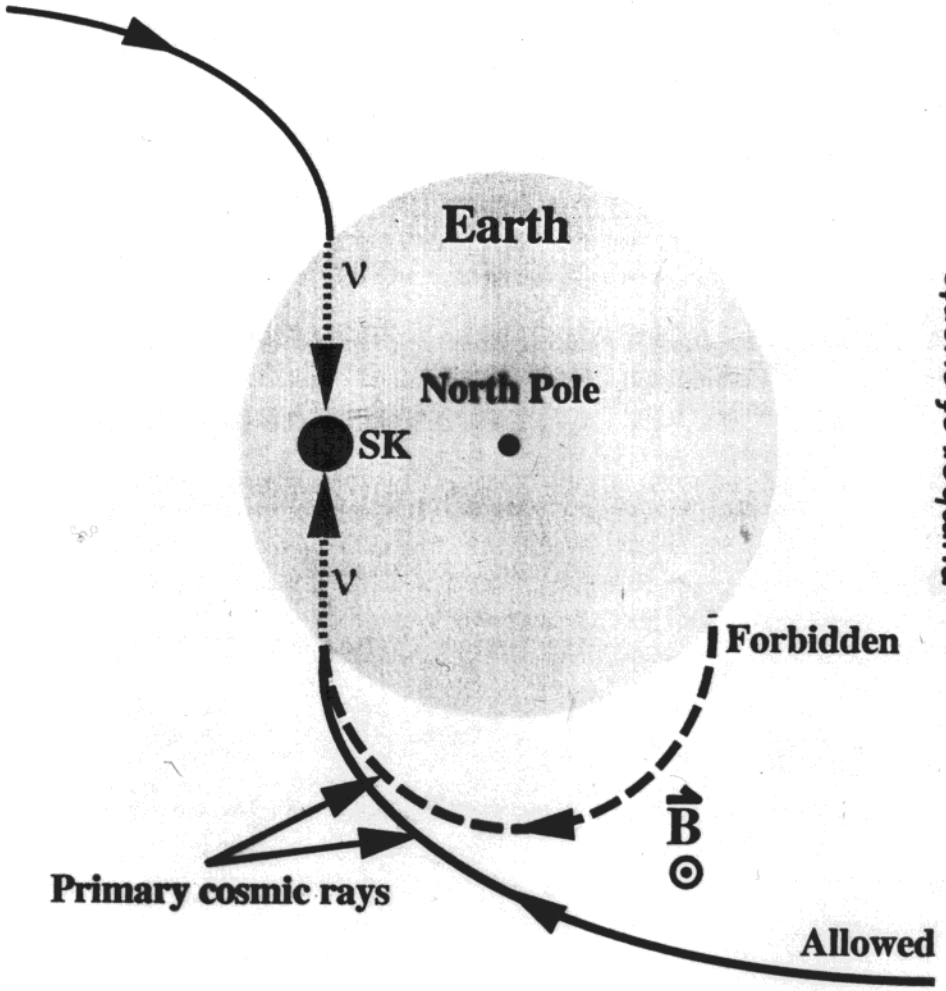
Fully Contained (FC) Sample
- select single ring events to enhance CC-qe fraction
- divide sample into sub-GeV and multi-GeV (E_{vis}>1.33 GeV)

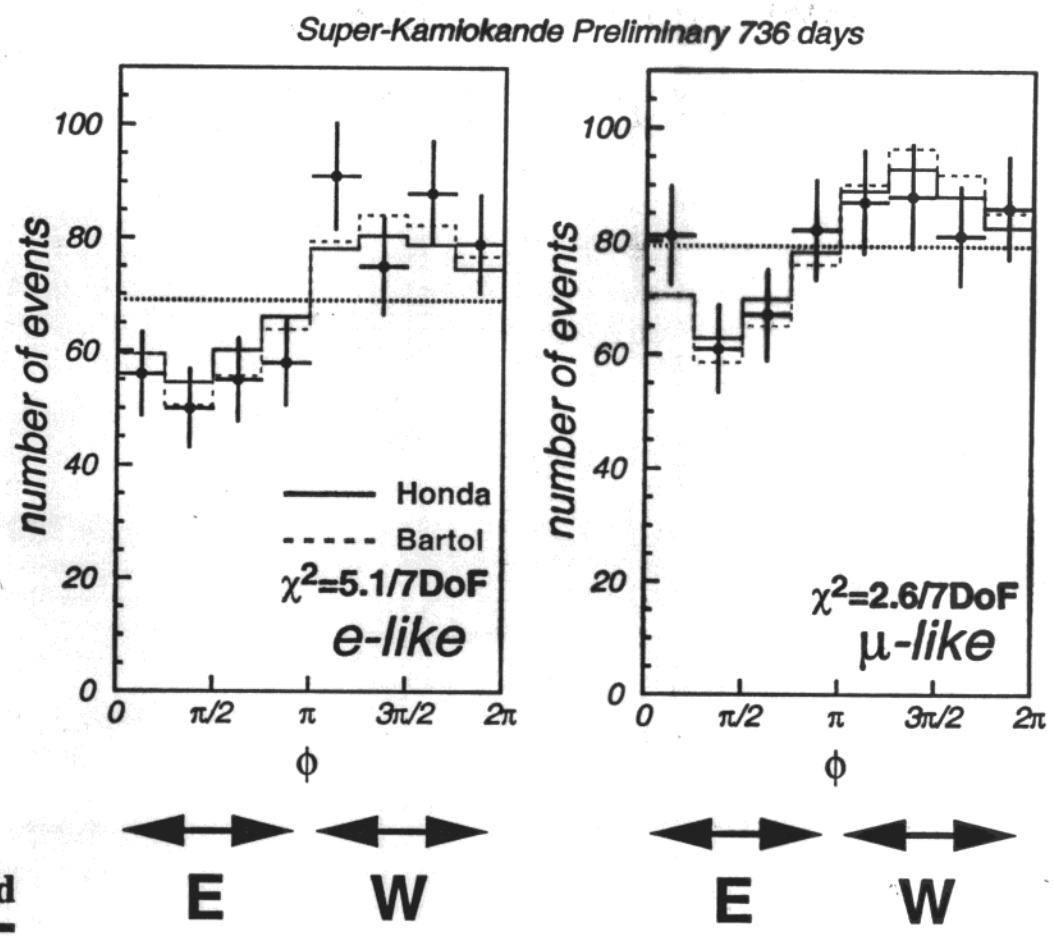
Partially Contained (PC) Sample
- no single ring requirement



East–West Effect

of geomagnetic field on primaries





Require:

Fiducial Volume

$|\cos\theta|<0.5$

400 MeV/c < P < 3000 MeV/c ← select low energy

NEW RESULTS

{ 736 days FC + 685 PC preliminary
  New 20 yr MC

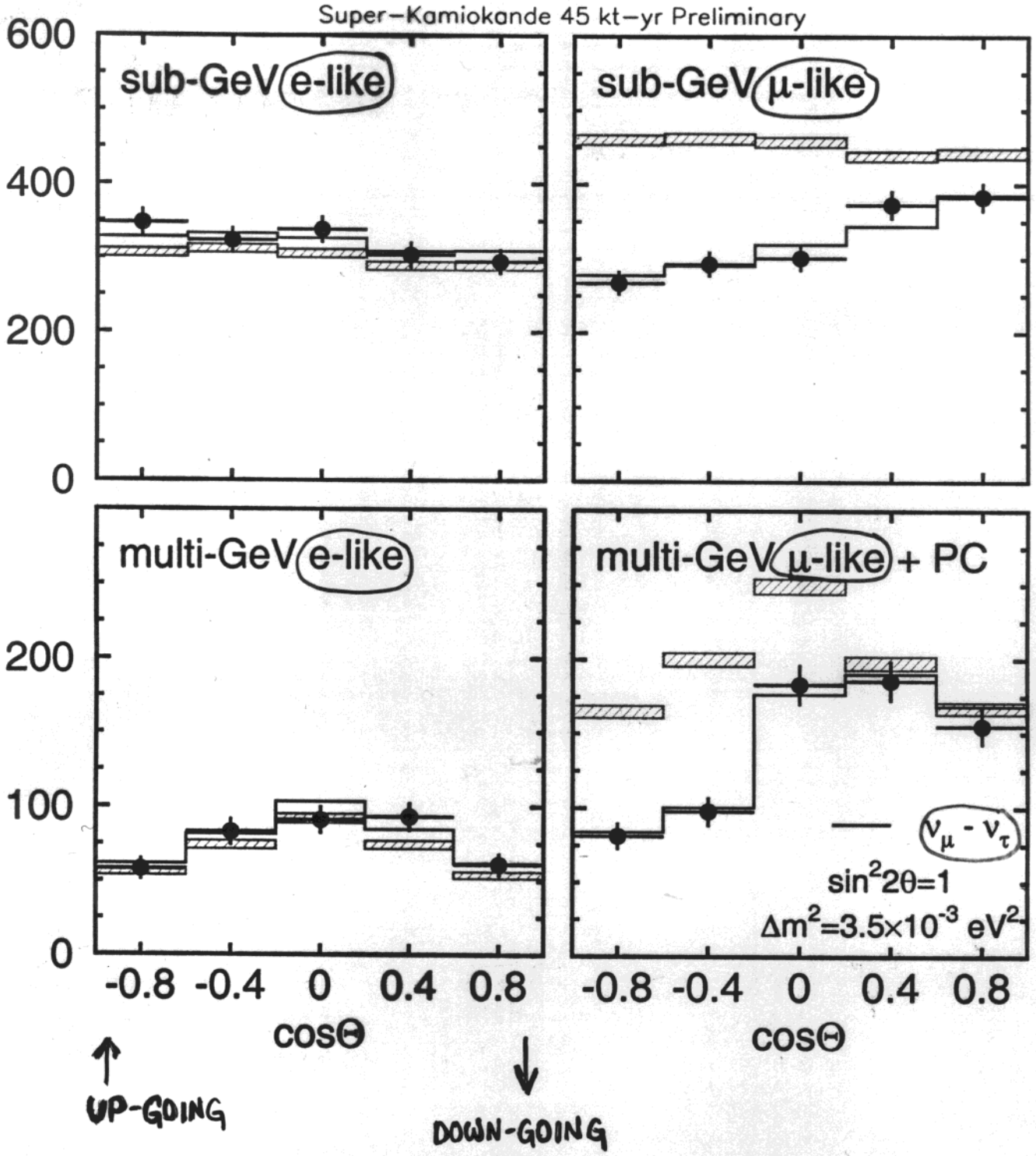
		DATA	MC	
single ring	e-like	1607	1502.7	SUB GeV
	μ-like	1617	2262.6	
multi-ring		1271	1631.0	
Total		4495	5396.3	

$$\mathcal{R} = 0.67 \pm 0.02 \pm 0.05$$

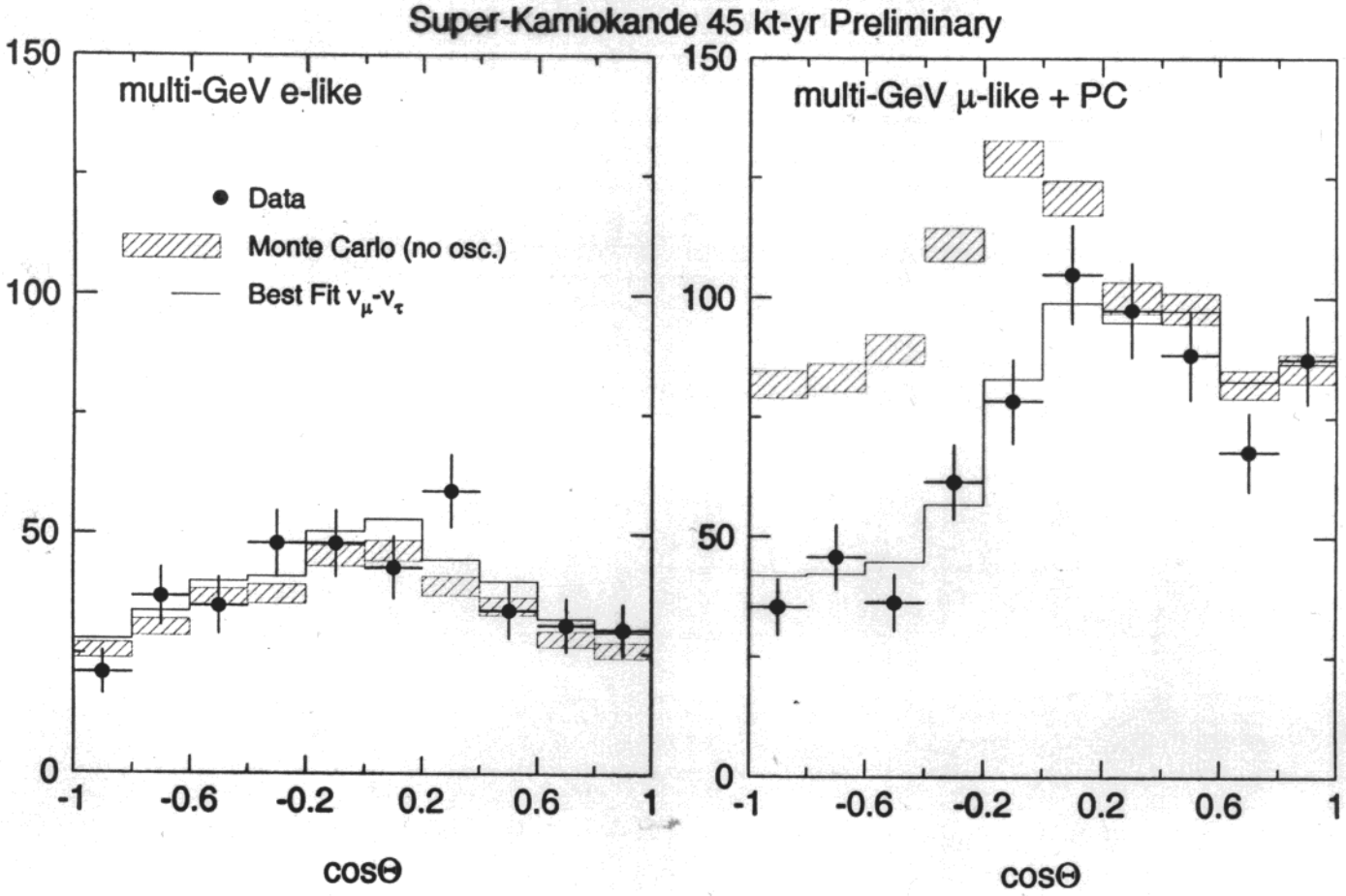
single ring	e-like	386	351.9	MULTI GEV
	μ-like	301	419.1	
multi-ring		737	935.4	
Total		1424	1706.4	
PC (μ-like)		374	508.9	

$$\mathcal{R}_{FC+PC} = 0.66 \pm 0.04 \pm 0.08$$

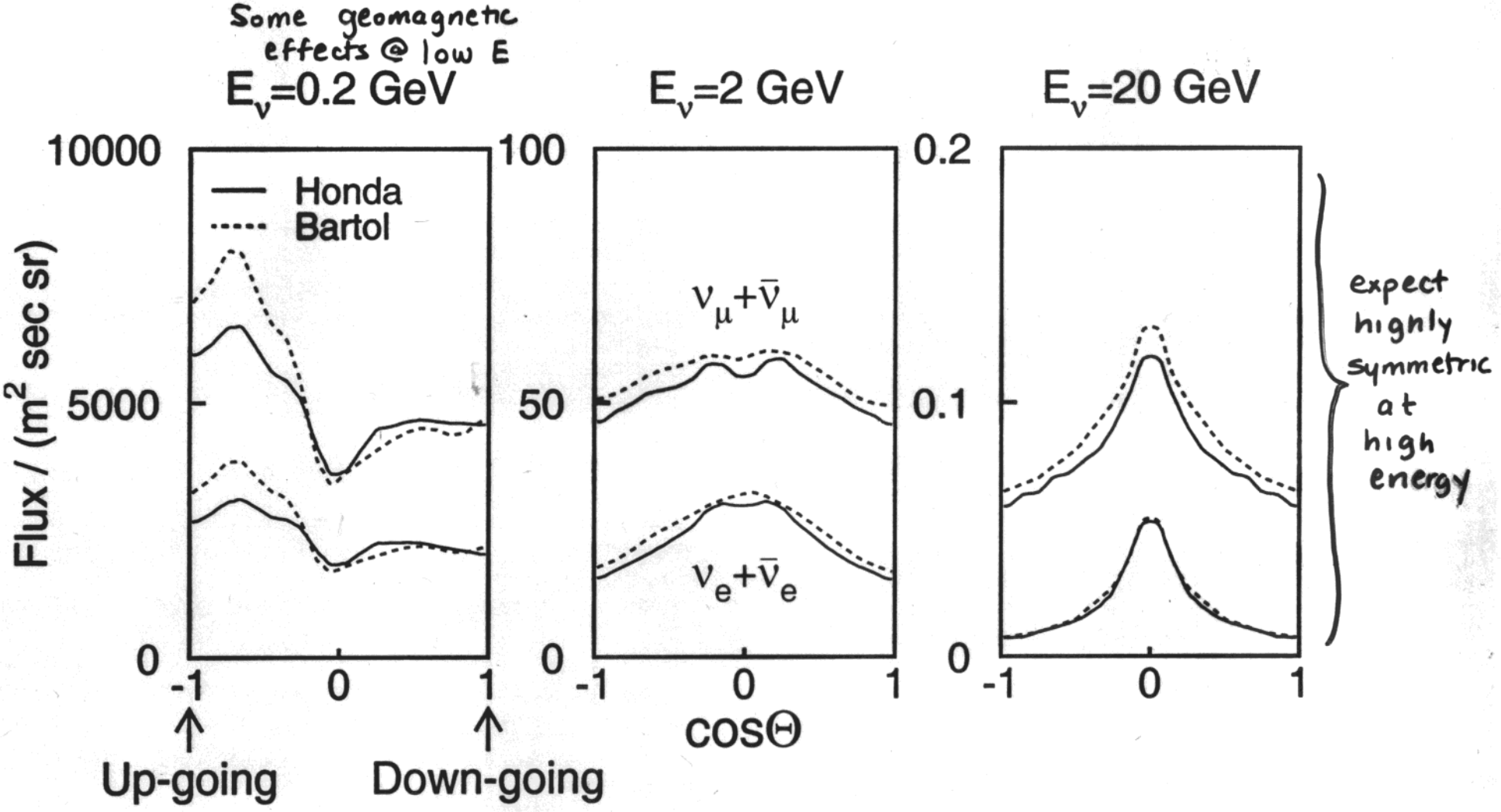
ANGULAR DISTRIBUTIONS



10 ANGULAR BINS



Neutrino Flux vs. Zenith Angle

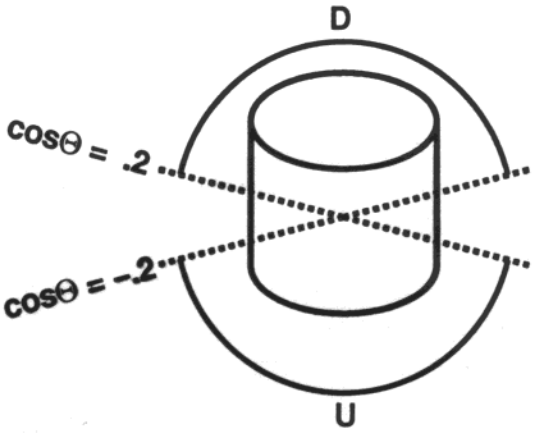


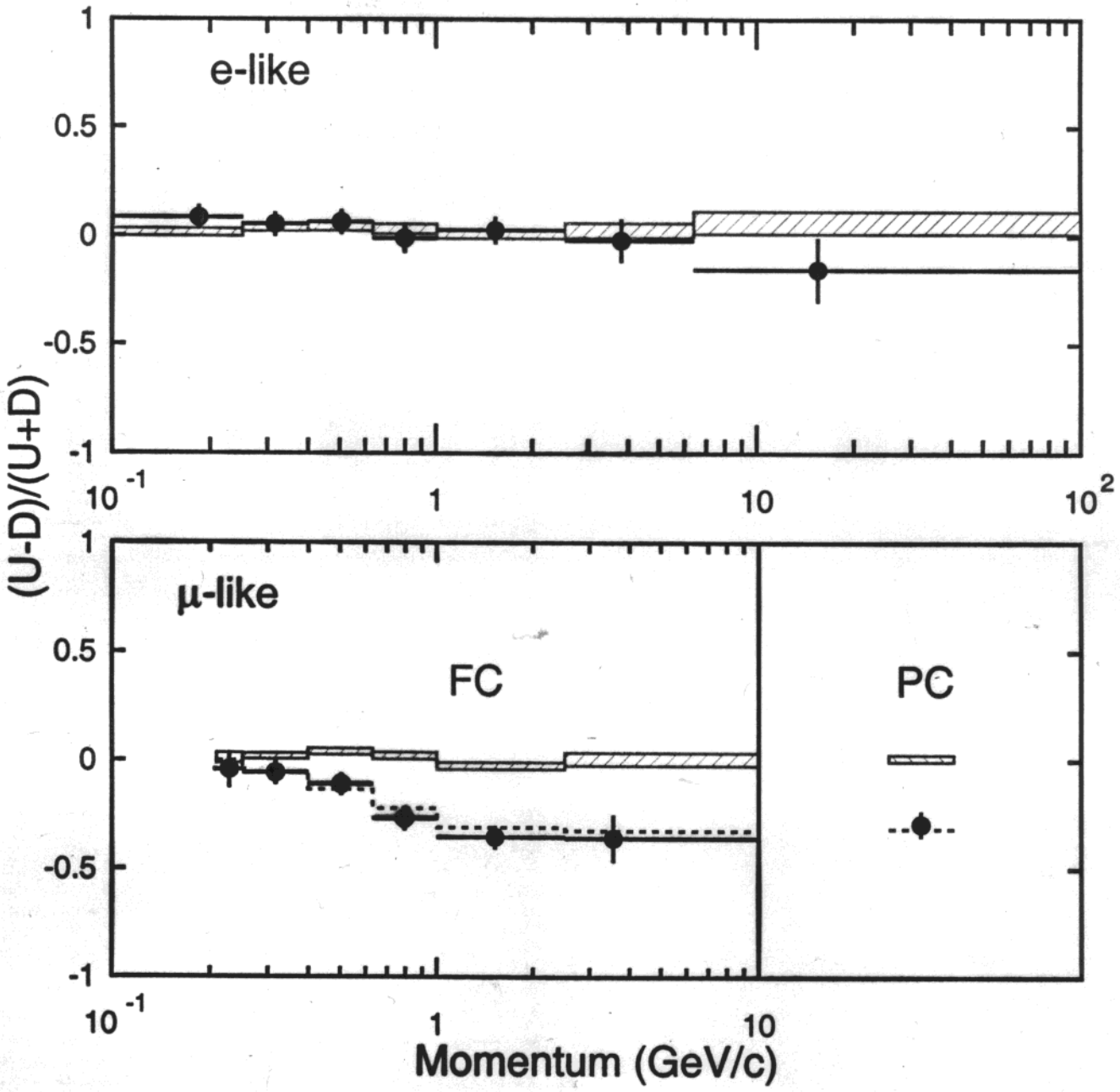
Asymmetry A = (U-D)/(U+D)

$U=N_{events}$ cosΘ<-0.2
$D=N_{events}$ cosΘ> 0.2

Zenith Angle Asymmetry

$$A = (U-D)/(U+D)$$





$$A_{\text{multi-GeV }\mu} = -0.311 \pm 0.043 \pm 0.01$$ (>7σ from 0)

FIT TO OSCILLATION HYPOTHESIS

$$\chi^2 = \sum_{e,\mu,\cos\theta_i,\, p_i} (N_{DATA} - N_{osc})^2/\sigma^2 + \sum_j \varepsilon_j^2/\sigma_j^2$$

70 bins: (e,μ) × 5 $\cos\theta$ × 7 $\log P$

estimated systematics

WEIGHTED MC

$$N_{osc} = \frac{\mathcal{L}_{data}}{\mathcal{L}_{MC}} \sum_{\text{events}} w(\sin^2 2\theta, \Delta m^2, \alpha, \varepsilon_j)$$

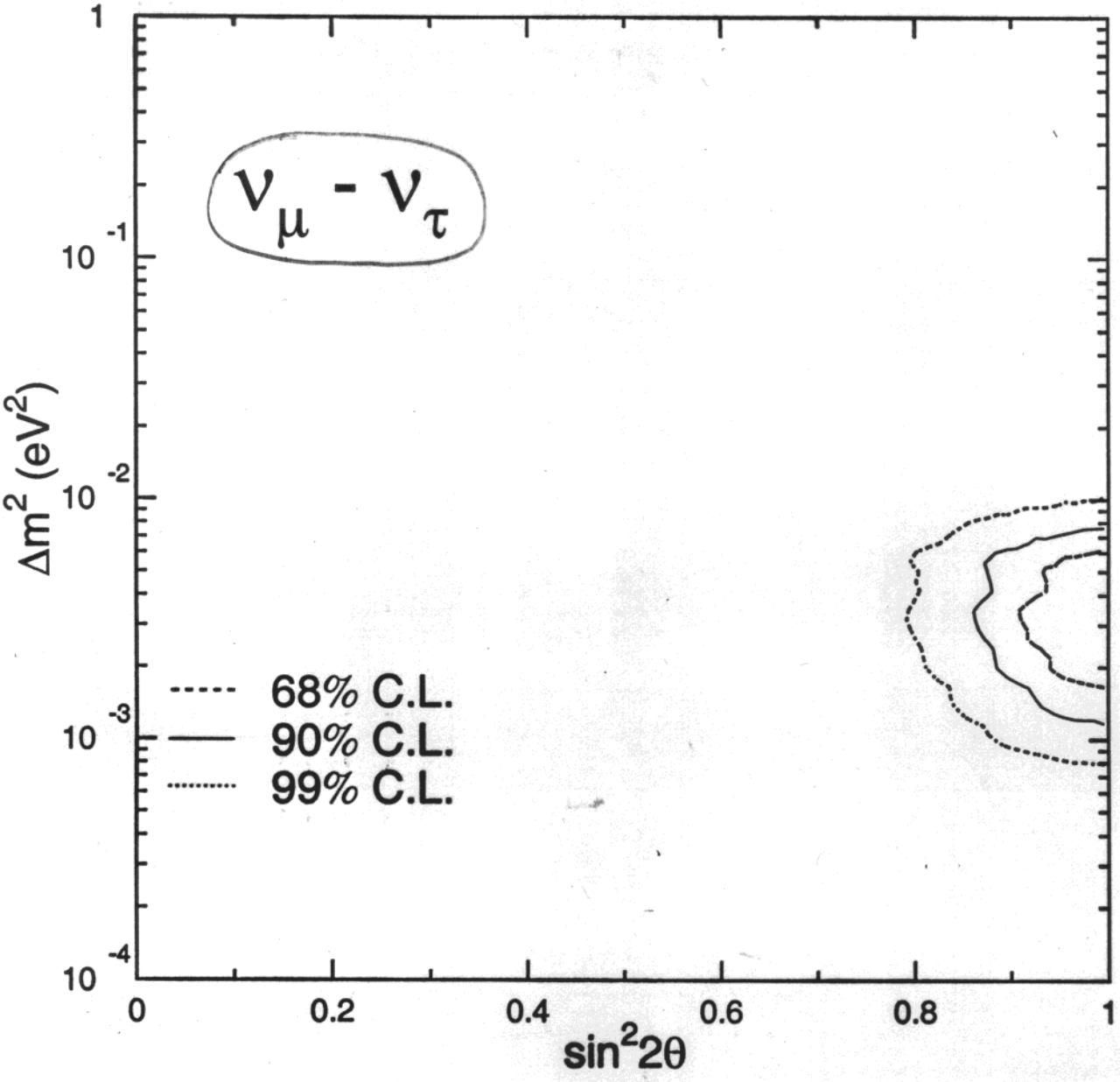
Systematic parameters

$$\varepsilon_j = (\delta, \beta_s, \beta_m, \rho, \eta_s, \eta_m, \lambda)$$

	PARAM	Assumed σ
ν flux $= (1 \pm \alpha) E^{-2.7 \pm \delta}$	α	25%
	δ	0.05
μ-like/e-like ratio	β_s	8%
	β_m	12%
FC/PC ratio	ρ	8%
Zenith angle asymmetry	η_s	2.4%
	η_m	2.7%
$\langle L/E_\nu \rangle$	λ	15%

- Minimize χ^2 at each $\sin^2 2\theta, \Delta m^2$ wrt ε_j's
- Find χ^2_{min}
- Build conf. level map as fcn of $\chi^2 - \chi^2_{min}$

ALLOWED REGION



90% CL = $\chi^2_{min} + 5.3$

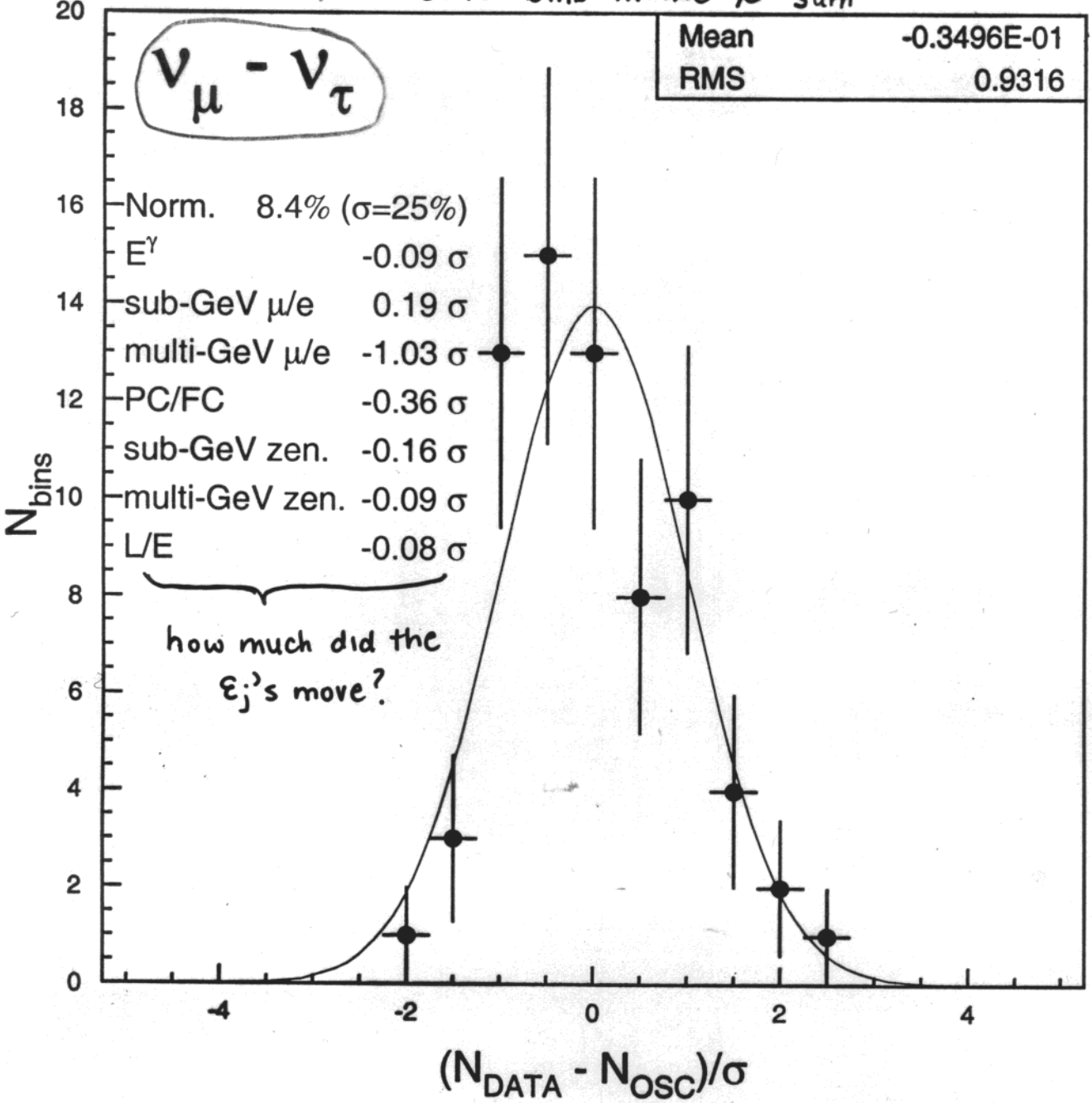
Best fit : $\chi^2 = 62.1/67$ d.o.f. , P = 65%.

$\sin^2 2\theta = 1.0$, $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2

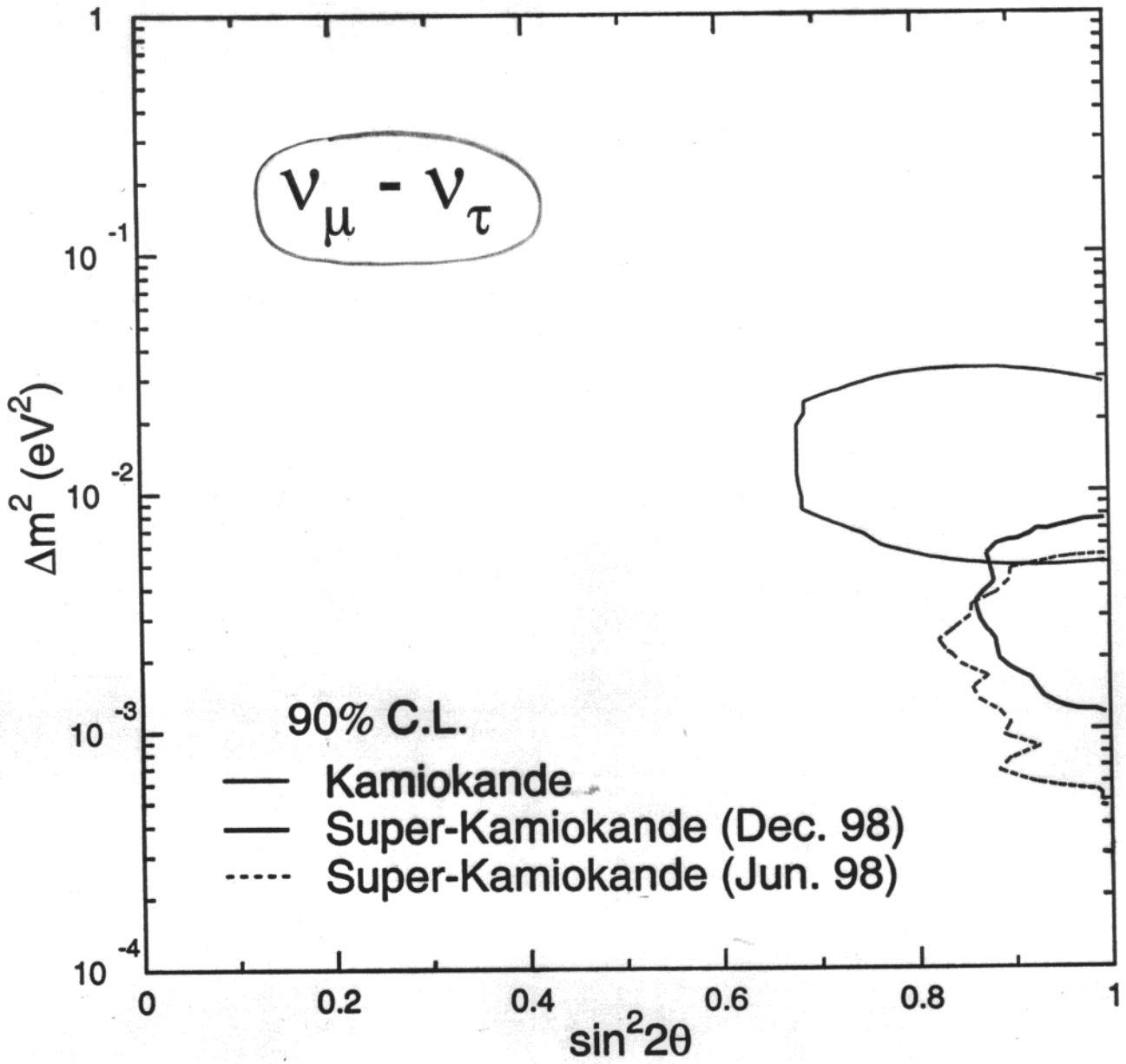
NO OSCILLATIONS : $\chi^2 = 175/69$ dof , P $\lesssim$ 0.0001%

Best-Fit Residuals

for the 70 bins in the χ^2 sum



Super-Kamiokande Preliminary: 736 days FC + 685 days PC

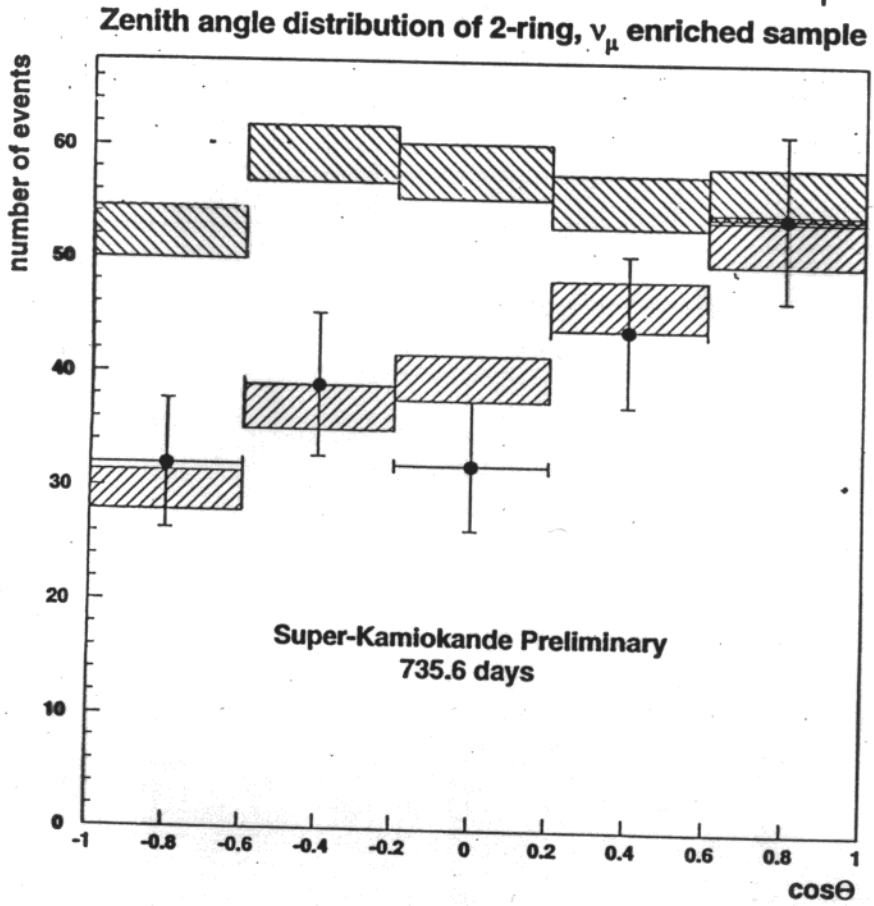


MULTIPLE RINGS

Angular distributions of selected samples to enrich ν_e, ν_μ

2 μ-like rings
OR
1 μ-like + 1 e-like
$P_\mu > P_e$
OR
≥ 1 $\mu \to e$ decays

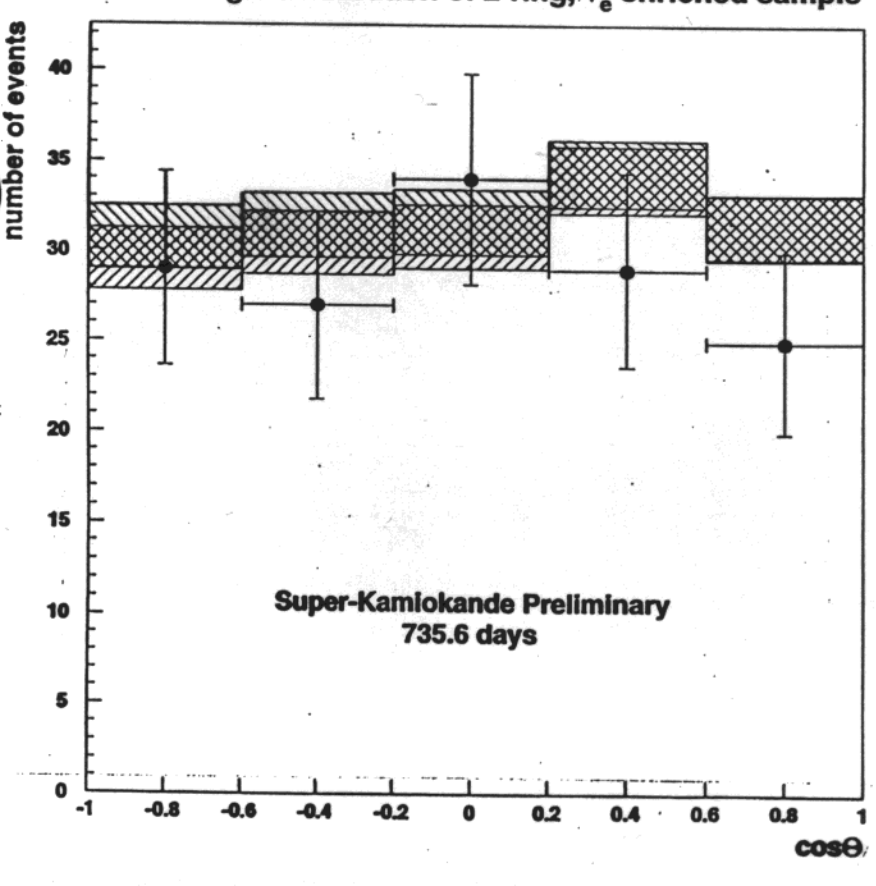
89% CC ν_μ
2% CC ν_e
8% NC



ENRICHED ν_μ

2 e-like rings
AND not π^0
($m_{inv} < 90, > 190$ MeV)
1 μ-like + 1 e-like,
$P_e > P_\mu$
no $\mu \to e$ decay

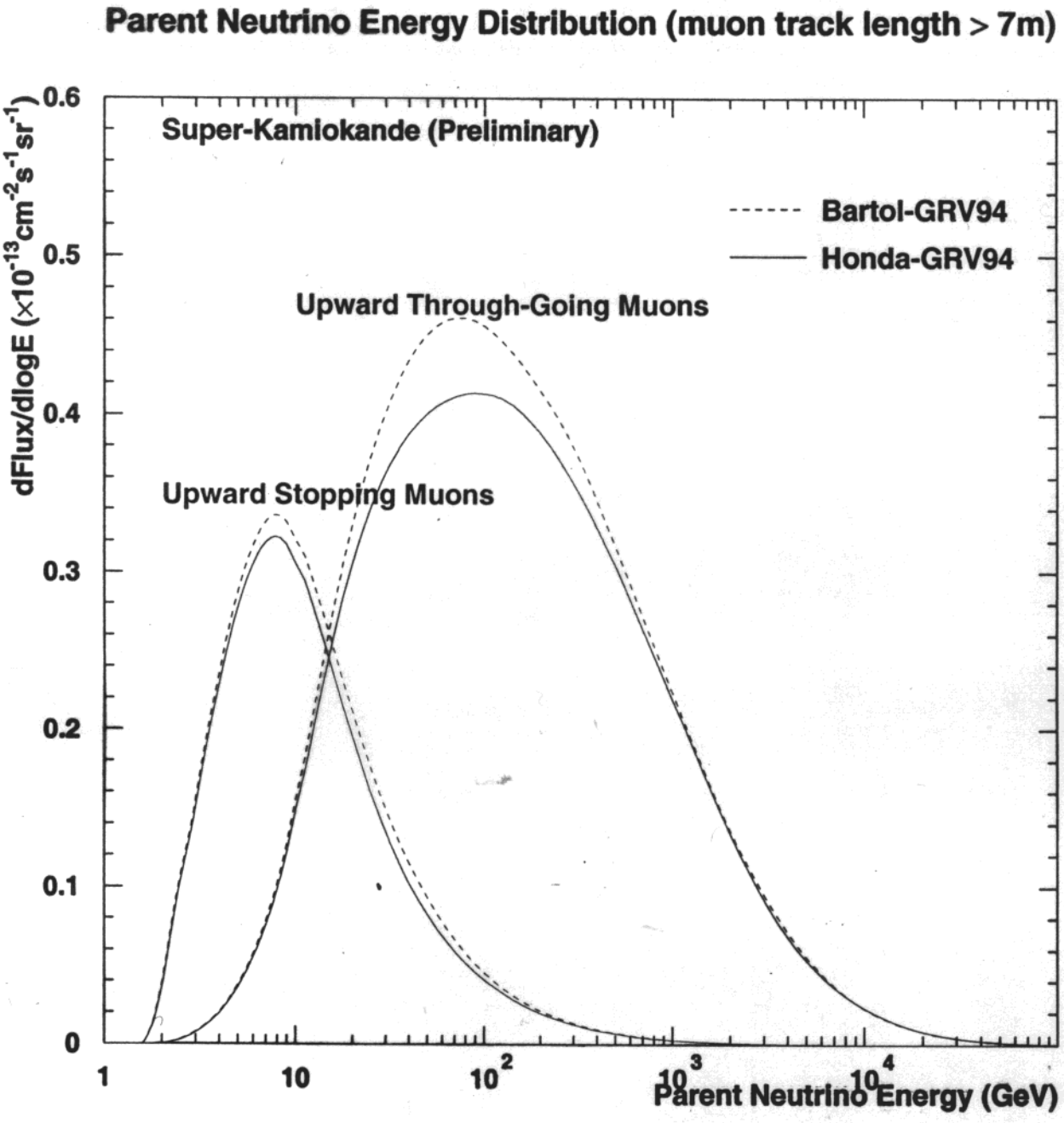
59% CC ν_e
7% CC ν_μ
34% NC



ENRICHED ν_e

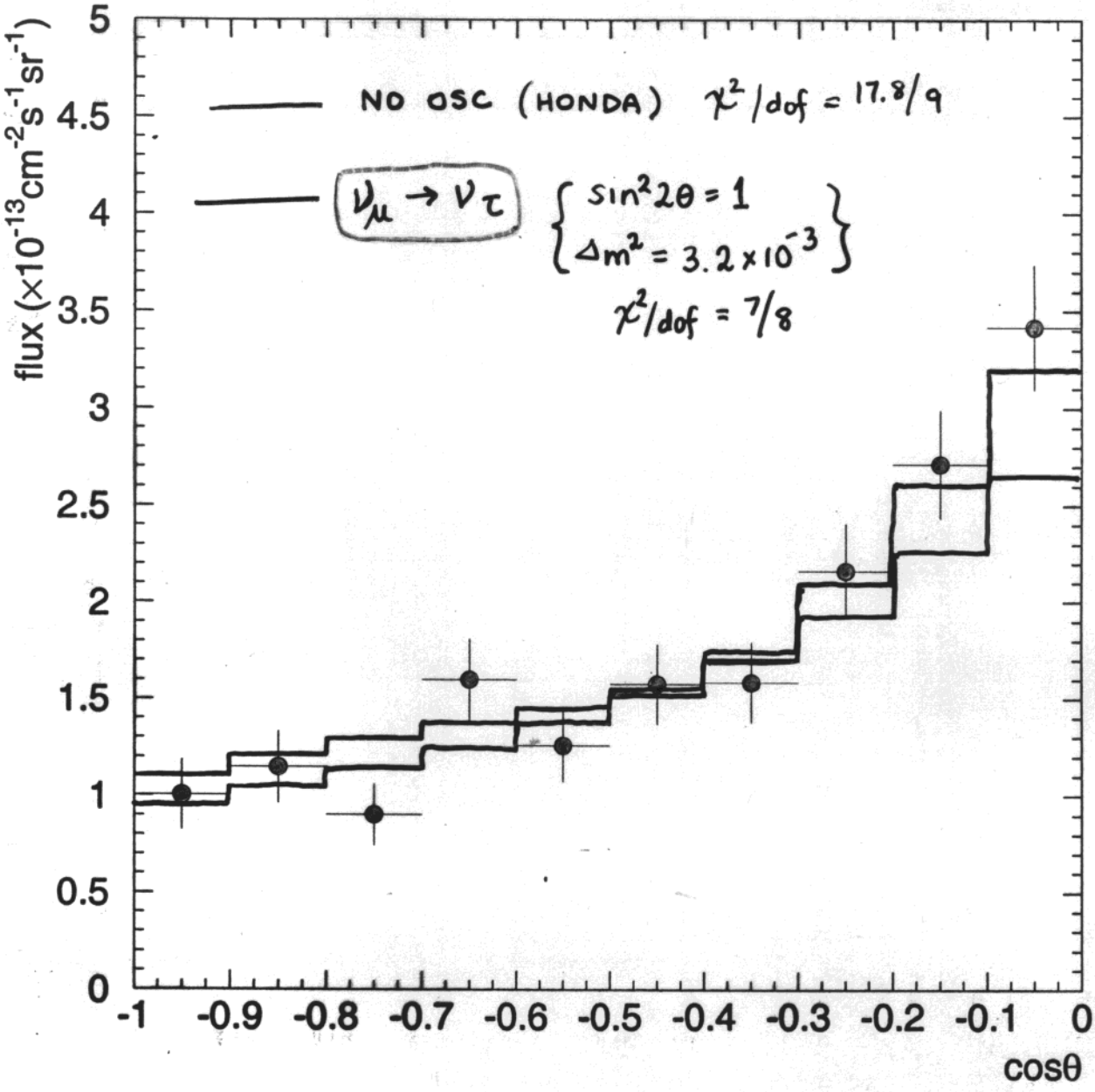
NEXT:

UPWARD-GOING MUONS

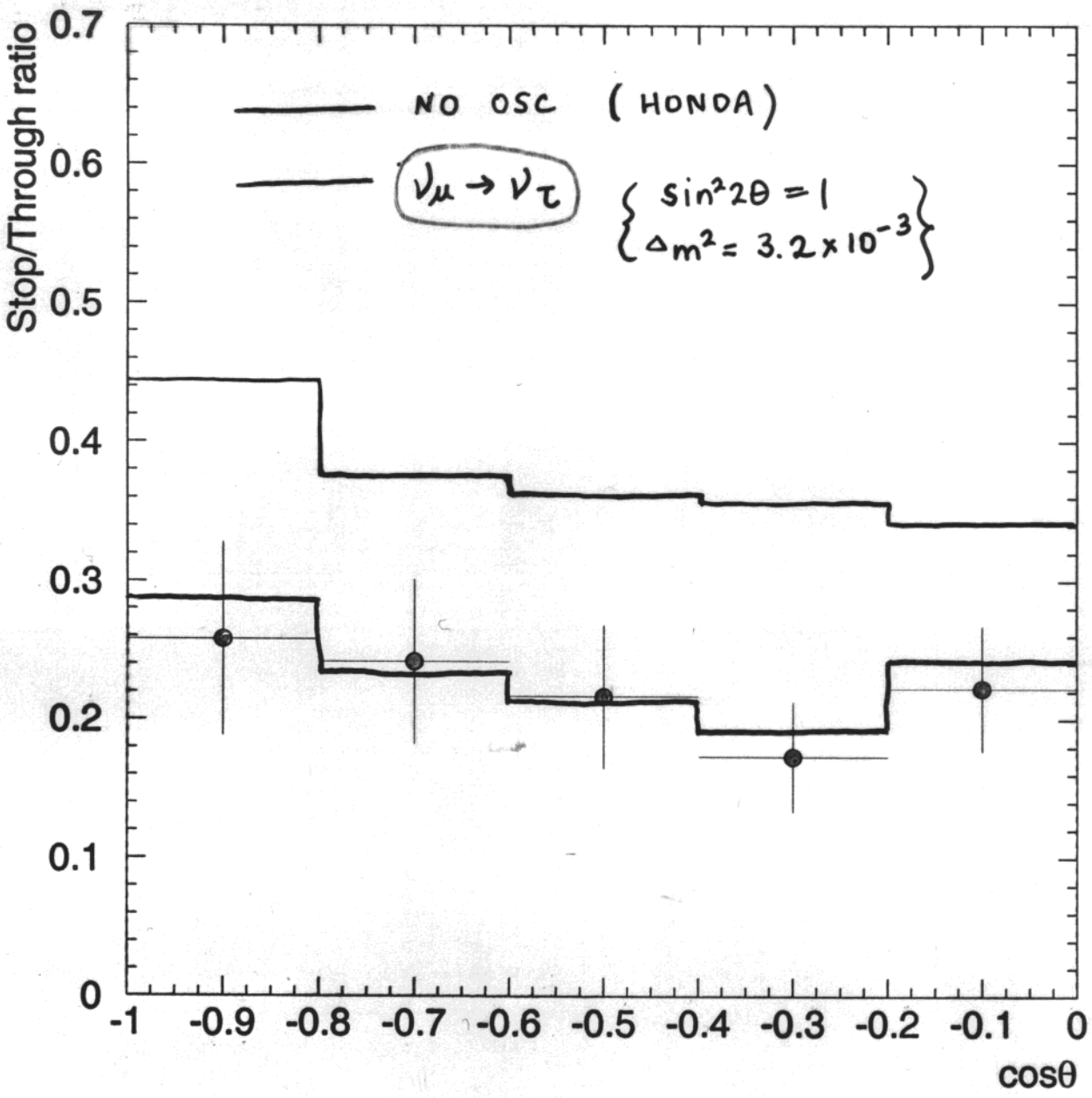


- angular dist
- stop / thru (different suppression for different E)

ZENITH ANGLE DISTRIBUTION OF UP-THRU



STOP/THRU RATIO VS. ANGLE

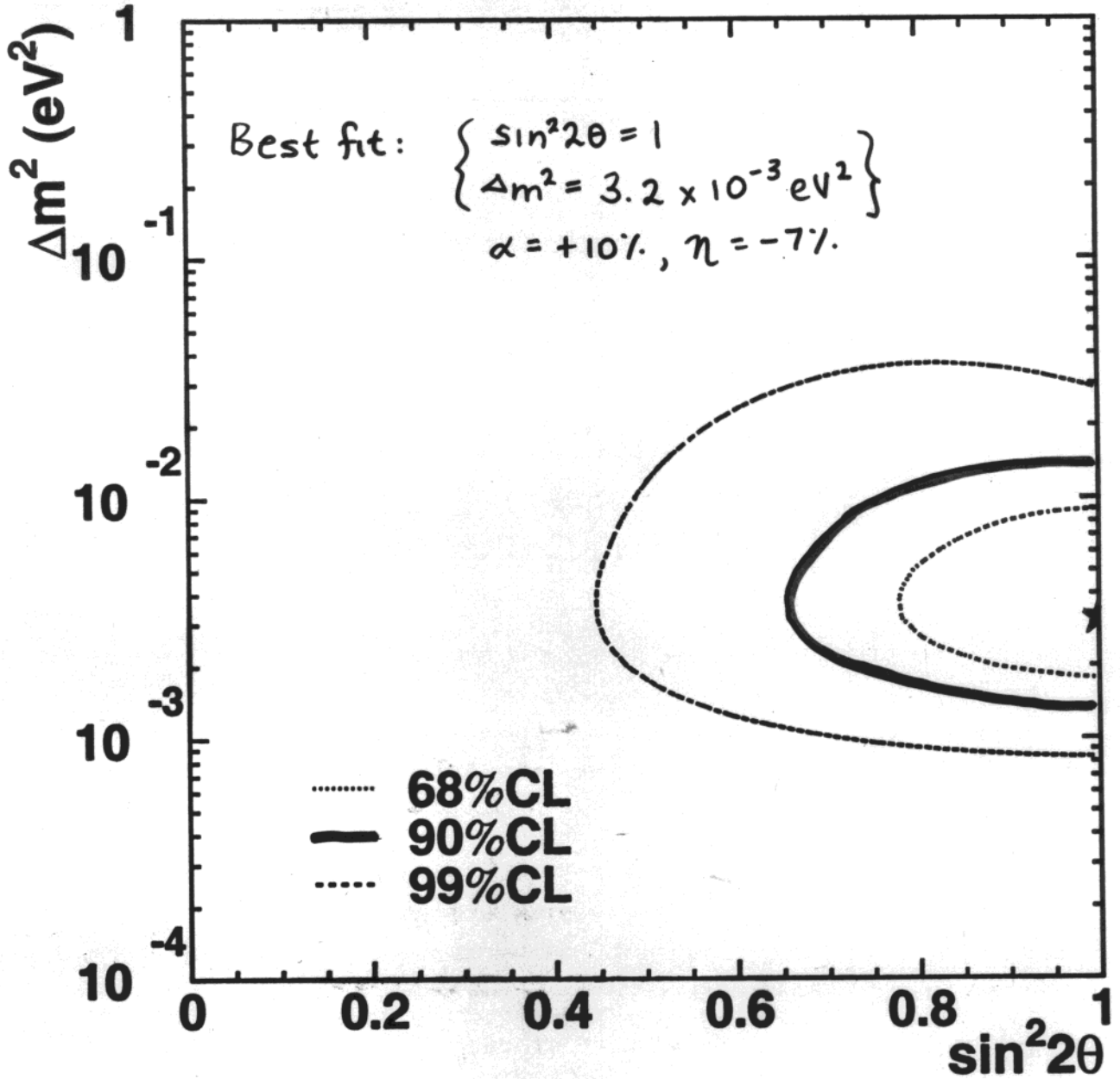


EXPECTED : (NO OSC) Stop/Thru = 0.37 ± 0.05

MEASURED : Stop/Thru = $\underline{0.22 \pm 0.03}$

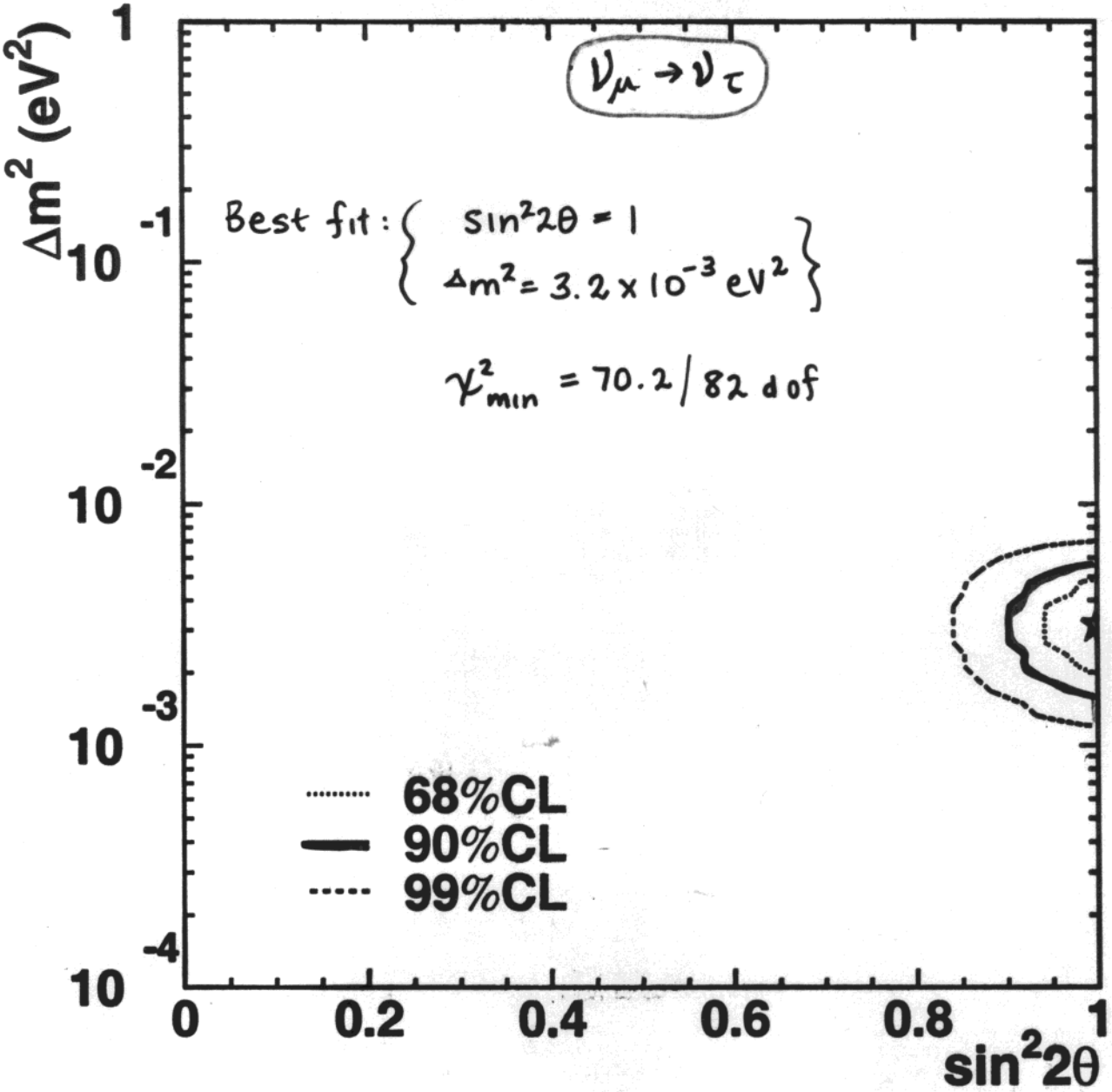
UPMU ALLOWED REGION (THRU & STOP)

$\nu_\mu \rightarrow \nu_\tau$



ALLOWED REGION, ALL SK DATA

FC + PC + upthru + upstop



WHAT FLAVORS ARE INVOLVED IN THIS $\nu_\mu \to \nu_x$ DISAPPEARANCE?

So far have assumed $\underline{\nu_\mu \to \nu_\tau}$

What about $\nu_\mu \to \nu_e$?

$\nu_\mu \to \nu_s$?

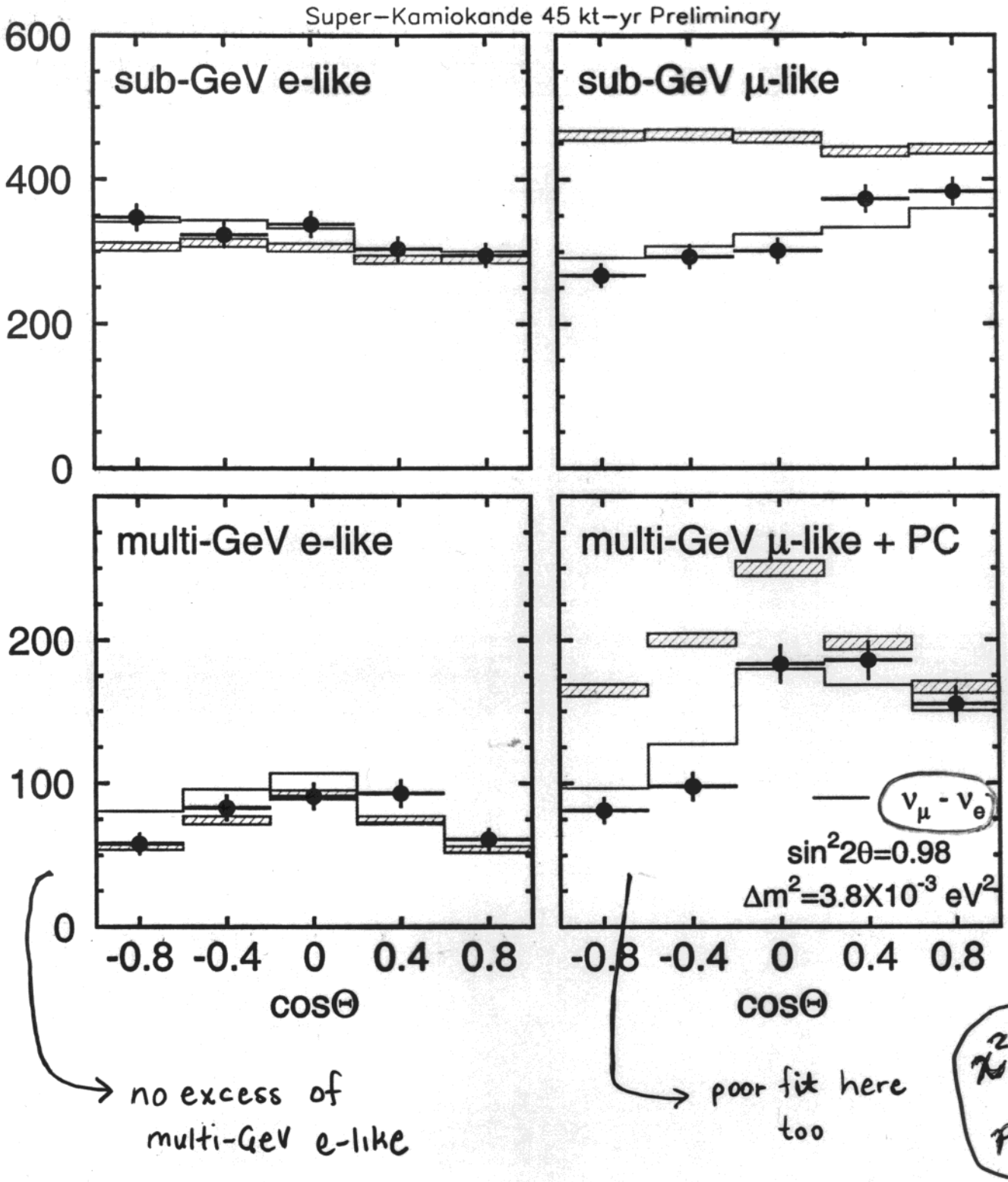
(or a combination)

WILL FOCUS ON:

(PRELIMINARY ANALYSES)

- why it's not (pure) $\nu_\mu \to \nu_e$
- $\nu_\mu \to \nu_s$ from FC/PC ang. dist
- $\nu_\mu \to \nu_s$ vs. $\nu_\mu \to \nu_\tau$ from single pions

$\nu_\mu \rightarrow \nu_e$



no excess of multi-GeV e-like

poor fit here too

$\chi^2 = \frac{110}{67}$ dof

$P < 0.1\%$

Also, excluded by Chooz!

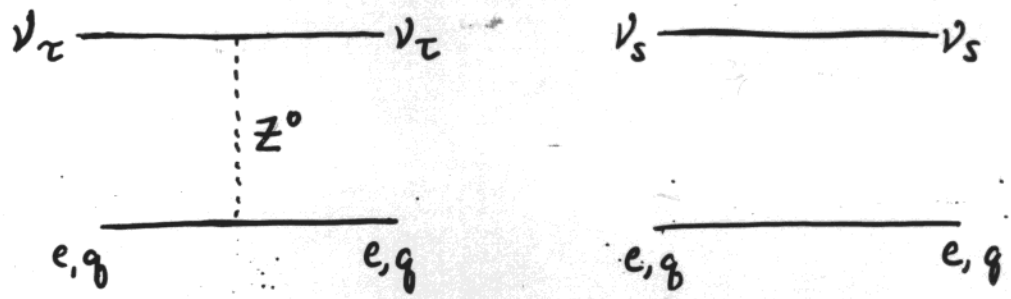
Could it be $\nu_\mu \to \nu_s$?

Hard to tell from $\nu_\mu \to \nu_\tau$...

expect only a few 10's of τ's in our data sample,
(look like ν_e's & ν_μ's anyway)

One approach: look carefully at angular distribution;

$\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$ give slightly different angular dist. due to matter effect



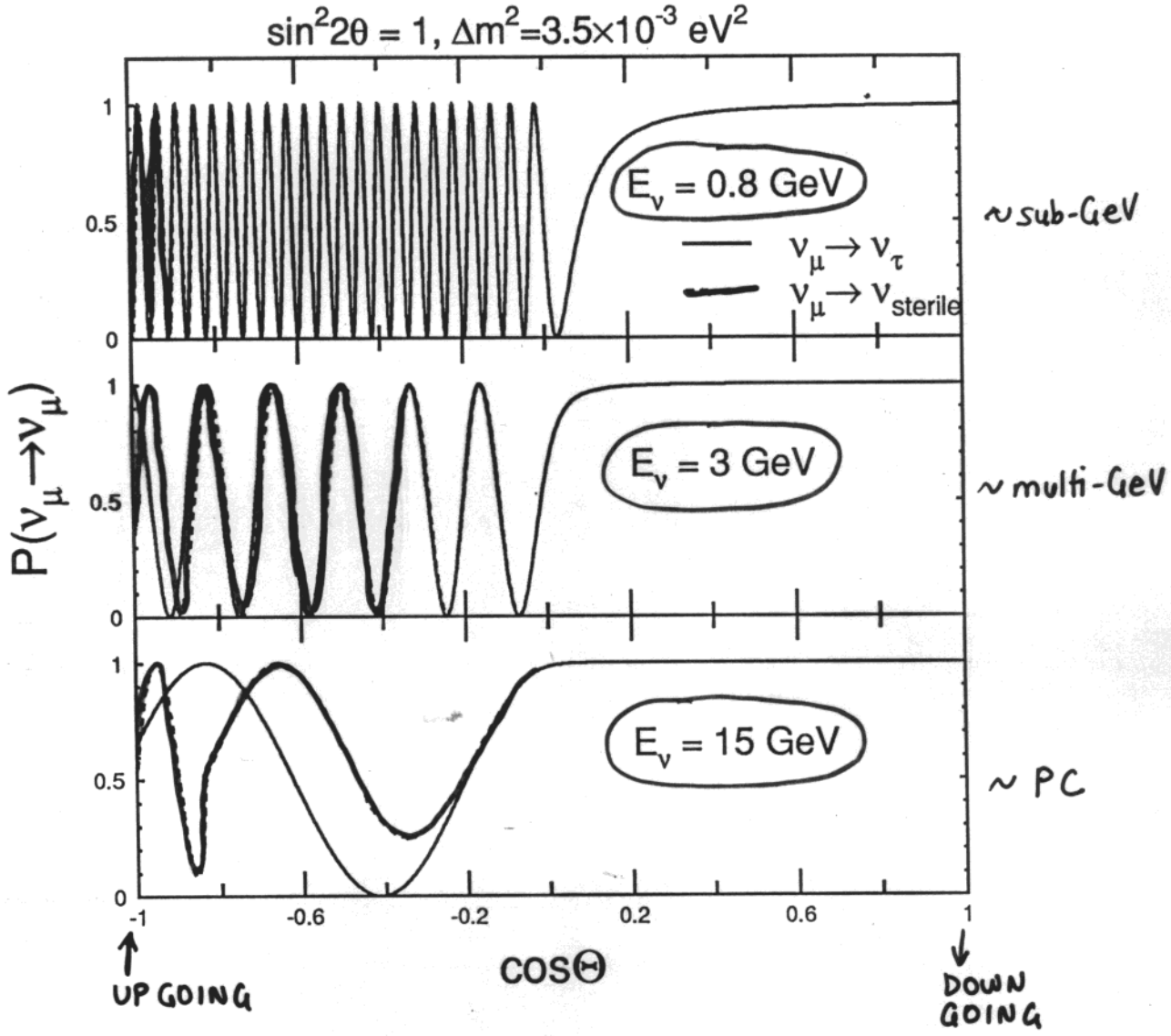
$\therefore V = \frac{G_F}{\sqrt{2}} N_n$, maximal mixing $\ell_m = \frac{2\pi}{V}[1+\xi^2]^{-1/2}$

$\sin^2 2\theta_m = \frac{\xi^2}{1+\xi^2}$

$\xi = \frac{\Delta m^2}{2EV}$

↳ effect large for high E or small Δm^2

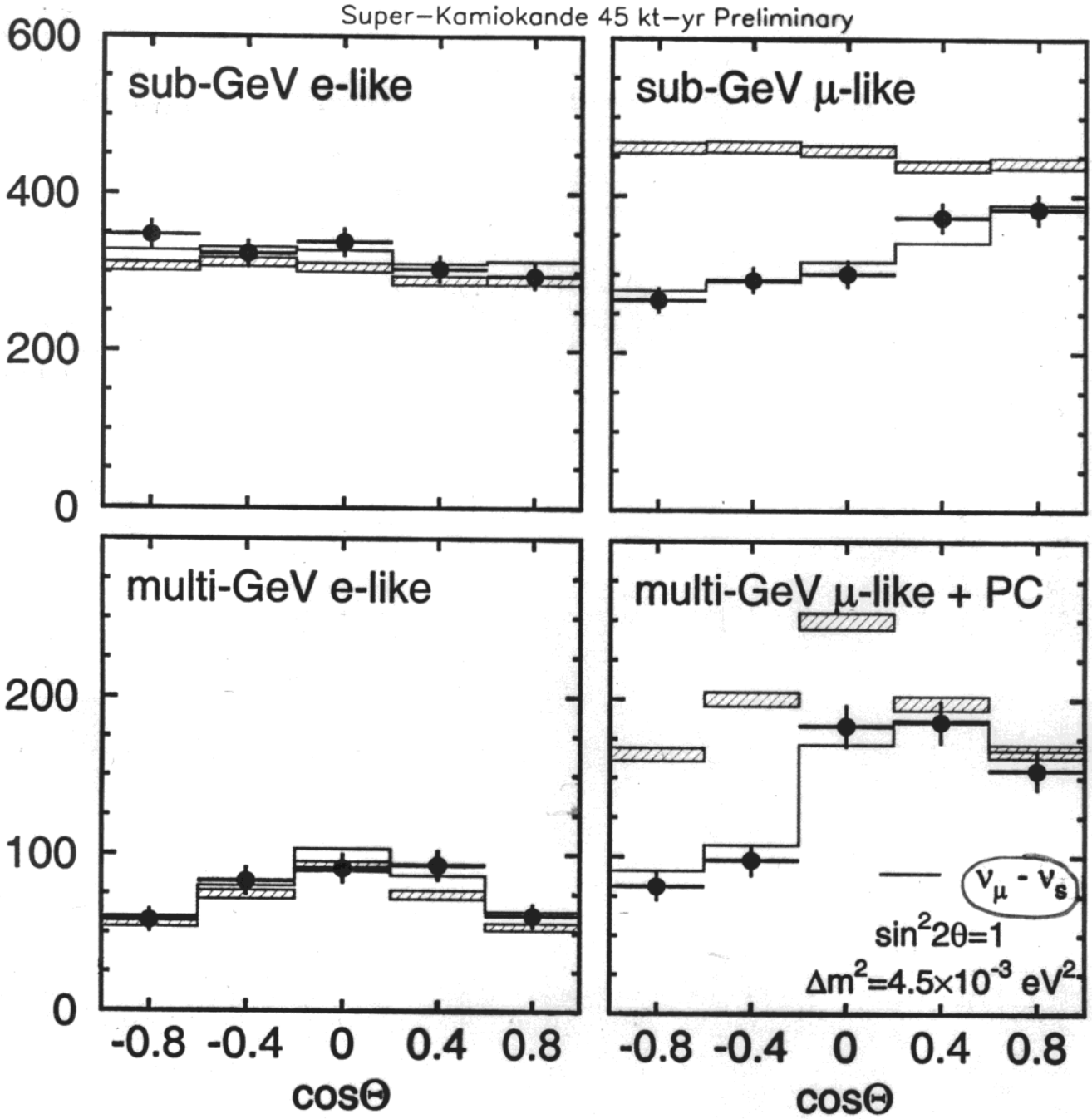
$\nu_\mu \to \nu_\tau$ vs $\nu_\mu \to \nu_s$



(Effect gets washed out over energies...)

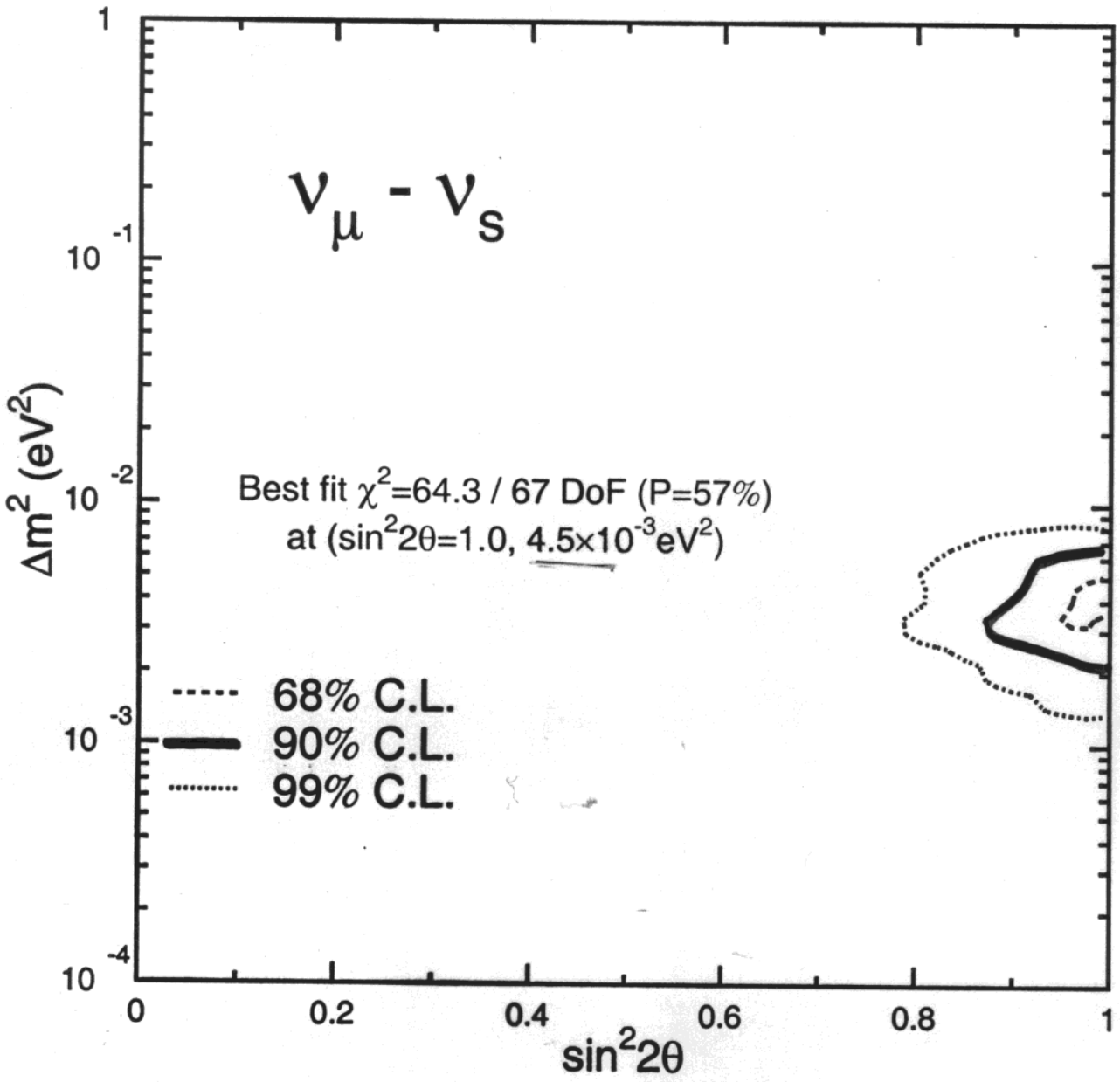
BUT: biggest effect for PC

$\nu_\mu \to \nu_s$



Can get good fit, $\chi^2 = 64.3/67$ d.o.f

$\nu_\mu \rightarrow \nu_s$ ALLOWED REGION



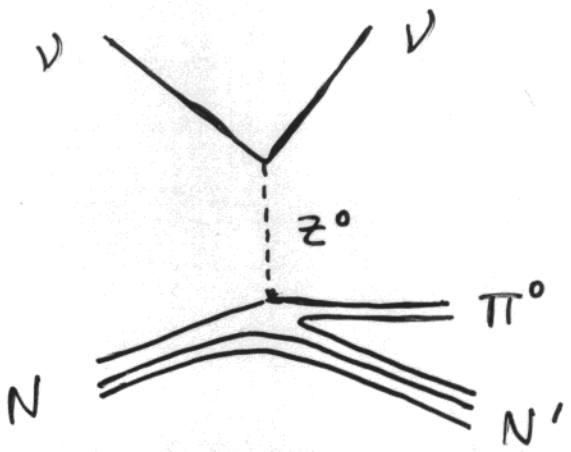
favors slightly higher Δm^2

(expect PC distortion @ small Δm^2)

ANOTHER WAY OF INVESTIGATING

$\nu_\mu \to \nu_\tau$ vs $\nu_\mu \to \nu_s$:

LOOK AT SINGLE PIONS



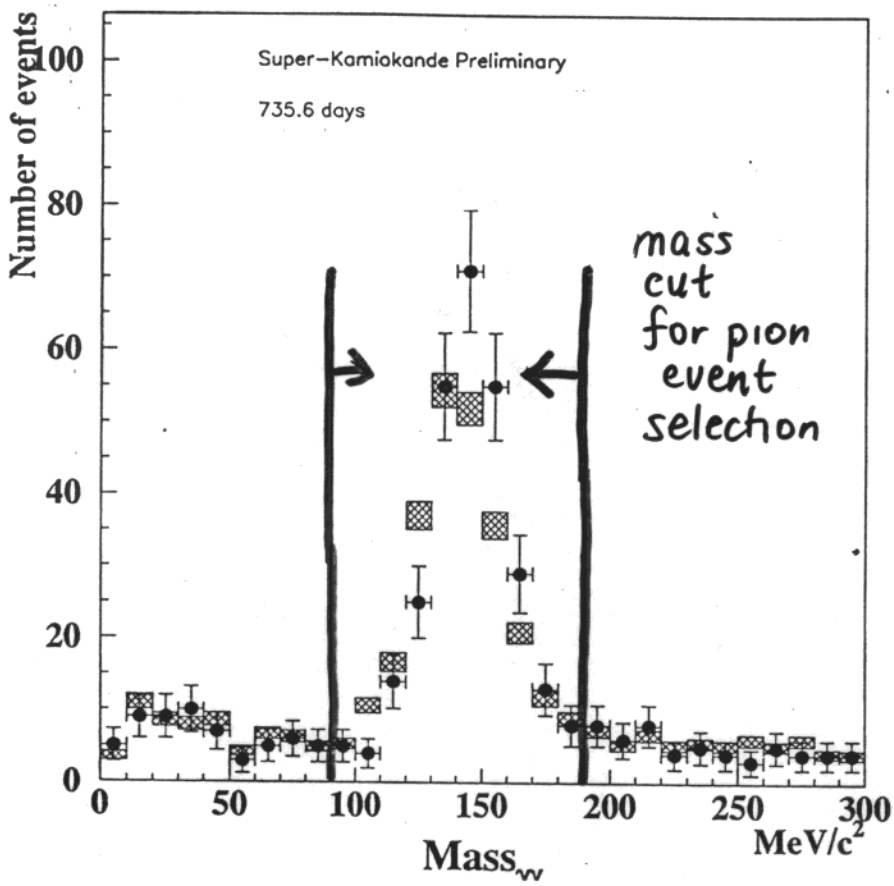
Single π^0 production tags NC,

can use for normalization $\begin{cases} \nu_\mu \to \nu_\tau : \text{NC} \\ \nu_\mu \to \nu_s : \text{no NC} \end{cases}$

$\Rightarrow$ look for 2 γ's : 2 e-like rings

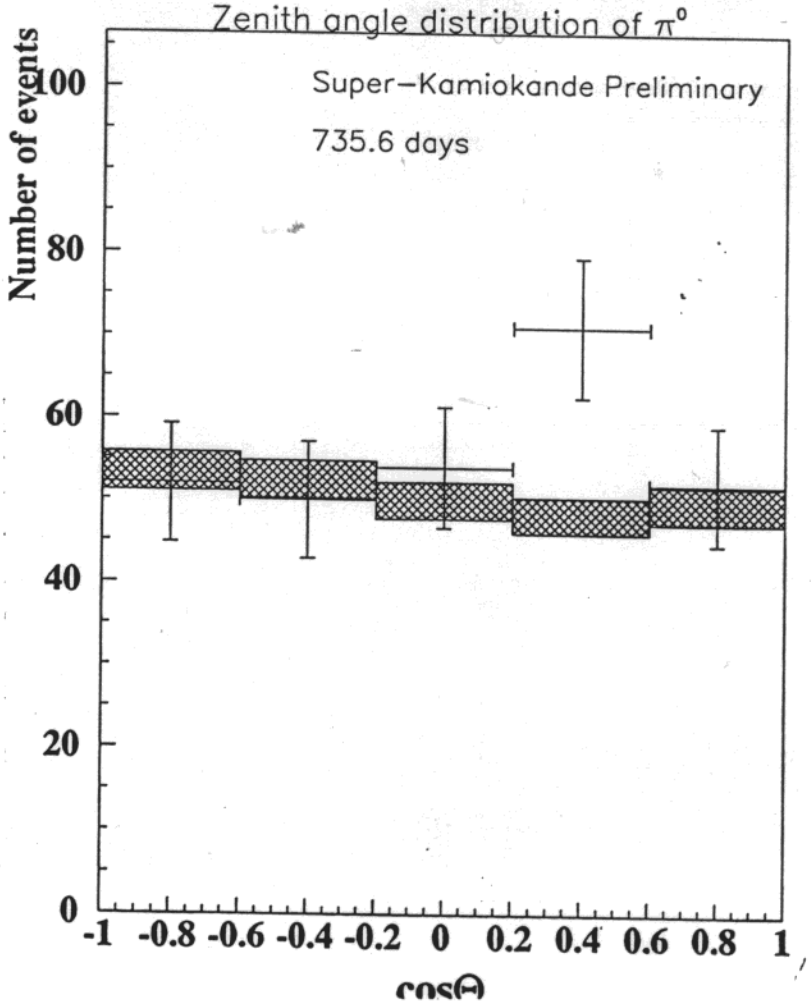
Selection :
- 2 rings
- both e-like
- no μ decay electron
- $90\ \text{MeV}/c^2 < M_{\gamma\gamma} < 190\ \text{MeV}/c^2$

INVARIANT MASS



86% NC

ANGULAR DISTRIBUTION



π^0/e-like RATIO

~ NC/CC , expect ~ 1 for $\nu_\mu \to \nu_\tau$ (ν_τ's make NC)

~0.75 for $\nu_\mu \to \nu_s$ (ν's really disappearing)

Background subtracted: 231.8 DATA

195.9 MC

$$\frac{(\pi^0/e)_{DATA}}{(\pi^0/e)_{MC}} = 1.11 \pm 0.06 \pm 0.02 \pm 0.26$$

DATA STAT · MC STAT · SYS

NOTE BIG ERROR BAR

dominated by x-scn uncertainty

⇓

K2K near detector will help

'Hint' of $\nu_\mu \to \nu_\tau$ preference...

Can play other games with π^0's & other multi-rings

SUMMARY

NEW RESULTS

- NEW DATA SAMPLE : 736 days FC + 685 days PC
- NEW 20 yr MC SAMPLE

$$\mathcal{R}_{sub} = 0.67 \pm 0.02 \pm 0.05$$

$$\mathcal{R}_{multi} = 0.66 \pm 0.04 \pm 0.08$$

$$A_{multi\mu} = -0.311 \pm 0.043 \pm 0.01$$

☺ $\nu_\mu \rightarrow \nu_\tau$: FITS VERY WELL

	Δm^2 eV^2	$\sin^2 2\theta$	χ^2/dof
FC/PC	3.5×10^{-3}	1.0	62.1/67
upmu	3.2×10^{-3}	1.0	8/13
all	3.2×10^{-3}	1.0	70.2/82

☺ $\nu_\mu \rightarrow \nu_s$ also fits well to FC/PC data

$\sin^2 2\theta = 1$, $\Delta m^2 = 4.5 \times 10^{-3}$ eV^2, $\chi^2 = 64.3/67$ dof

☹ $\nu_\mu \rightarrow \nu_e$ poor fit (also ruled out by Chooz)

MORE WORK IN PROGRESS: π^0's, multi-ring, 3-flavor, ...