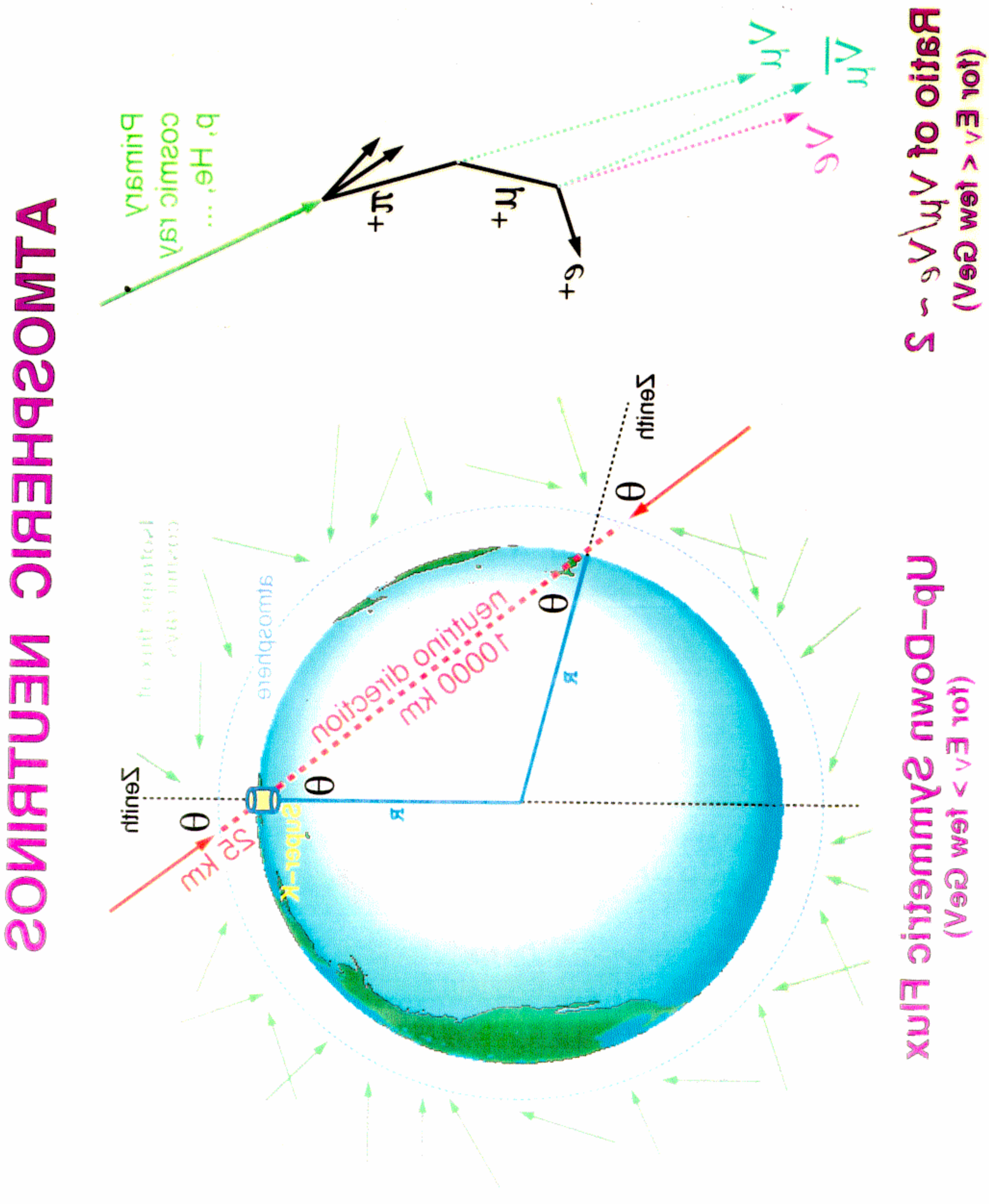
Ed Kearns
Boston U.
SSI 2000

Atmospheric Neutrinos

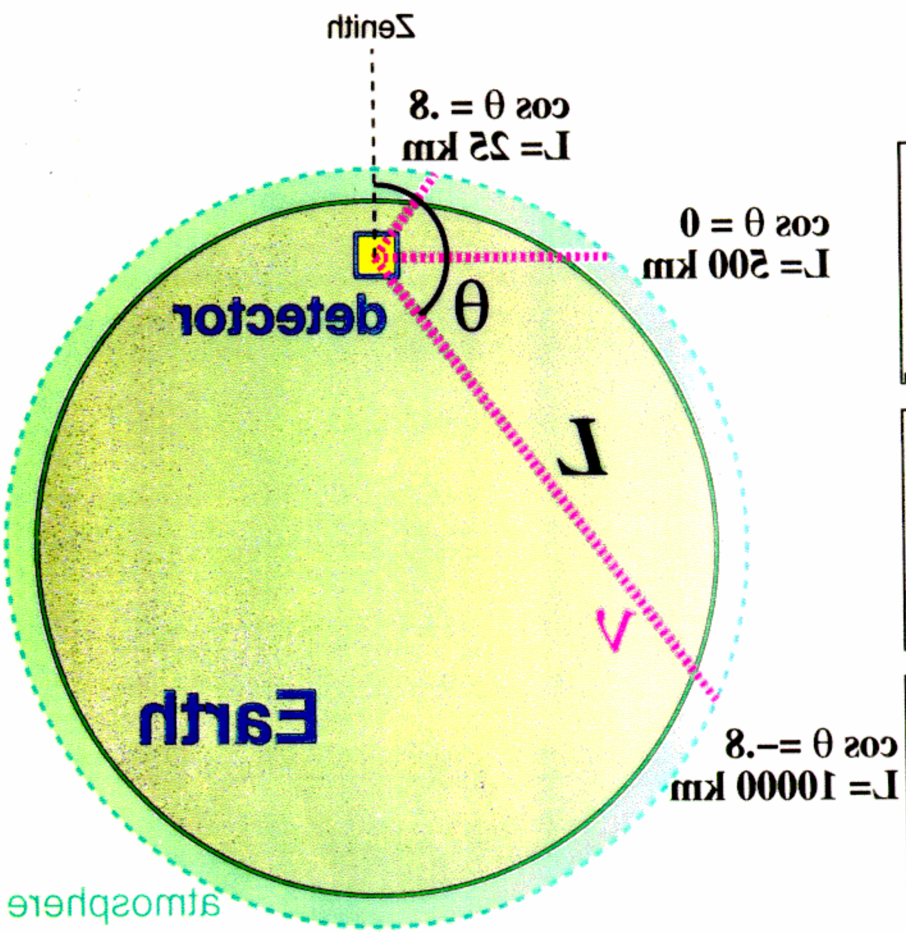
Lecture I) WITHOUT ν-OSC.
- FLUX CALCULATION
- ν CROSS SECTIONS
- EXPERIMENTAL METHODS

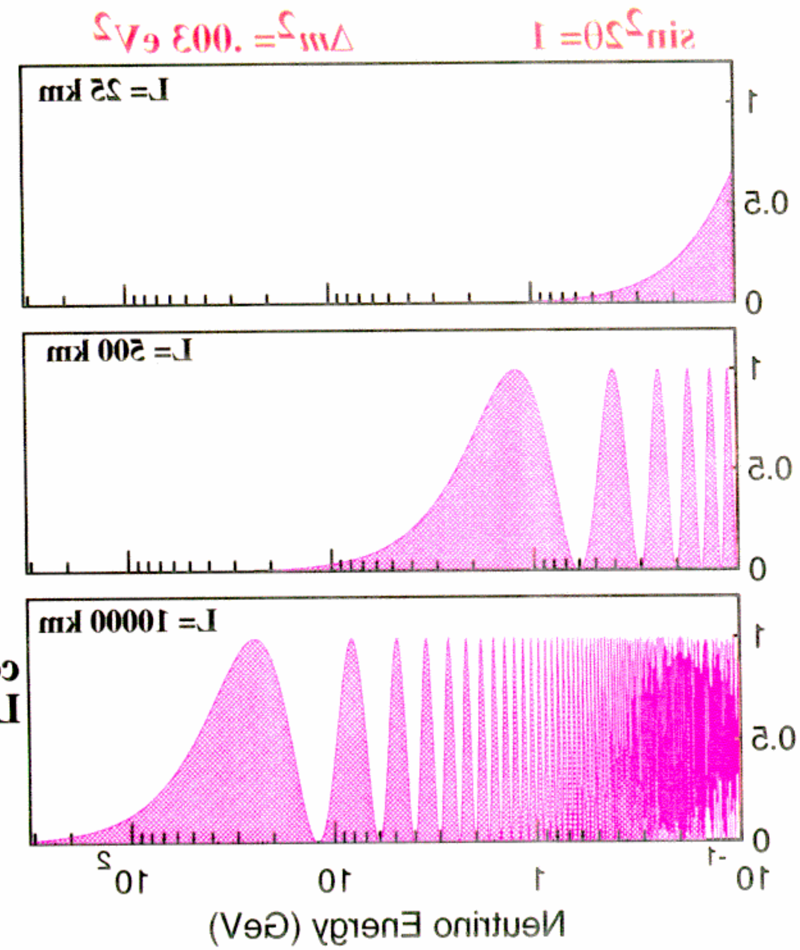
Lecture II) WITH ν-OSC.
- BRIEF HISTORY
- REVIEW EVIDENCE
- RECENT STUDIES


ATMOSPHERIC NEUTRINOS
Up-Down Symmetric Flux
(for E_ν > few GeV)
Ratio of ν_μ / ν_e ~ 2
(for E_ν < few GeV)
Primary
cosmic ray
p, He, ...
π^+
μ^+
e^+
ν_μ
$\bar{\nu}_\mu$
ν_e
Zenith
θ
neutrino direction
10000 km
25 km
atmosphere
Super-K
R

Atmospheric Neutrino Oscillation

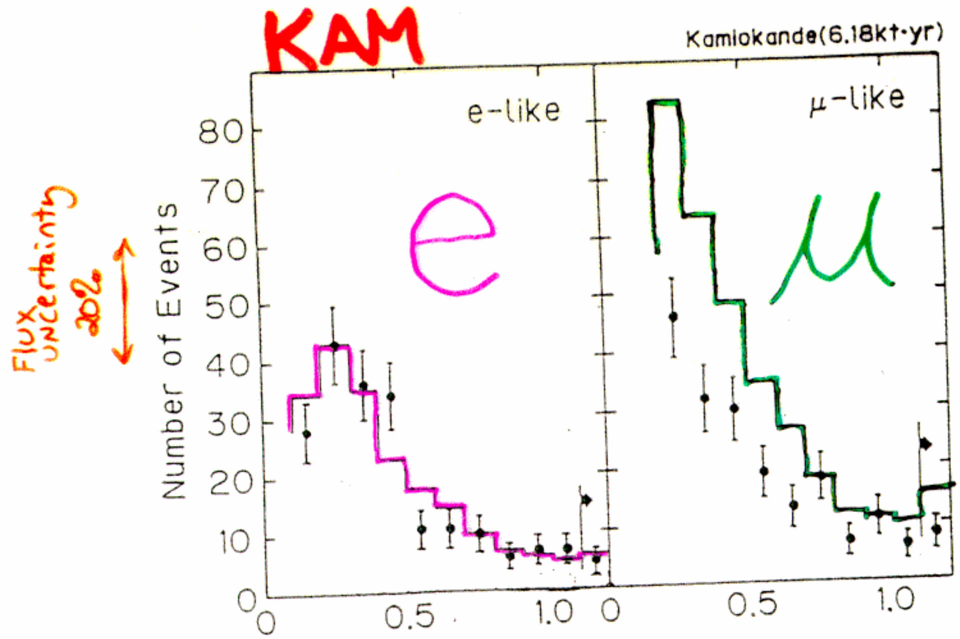
$$P_{\nu\nu'} = \sin^2 2\theta \, \sin^2 \frac{1.27 \, \Delta m^2 L}{E}$$



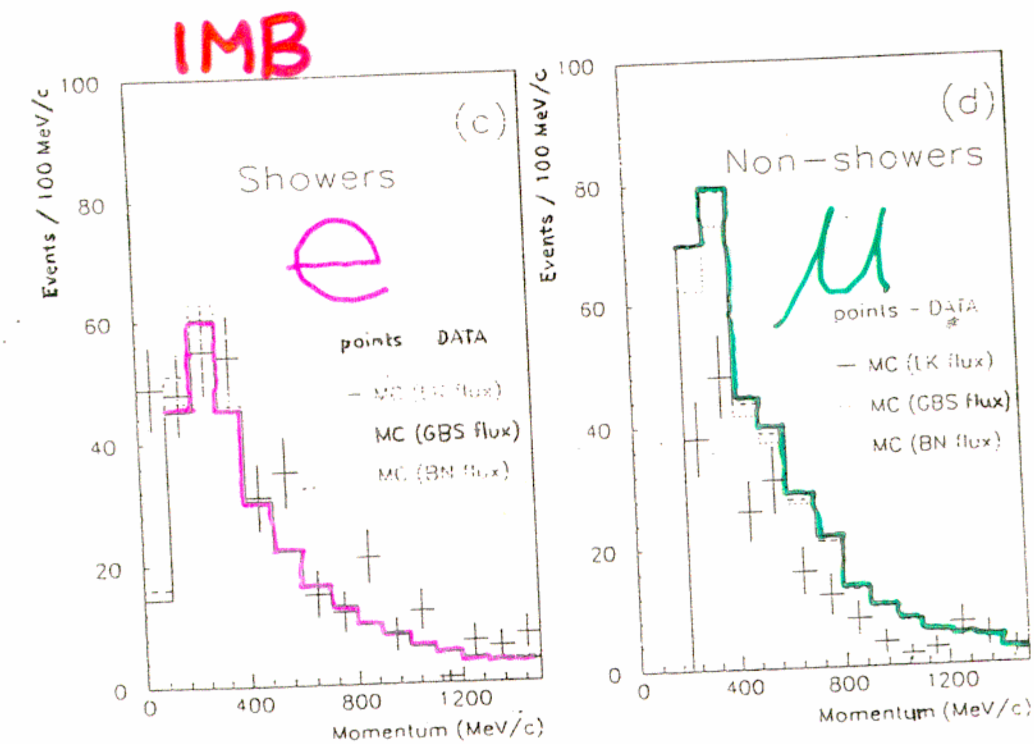


KAMIOKANDE & IMB

$$R \equiv \frac{(N_\mu / N_e)_{DATA}}{(N_\mu / N_e)_{M.C.}}$$



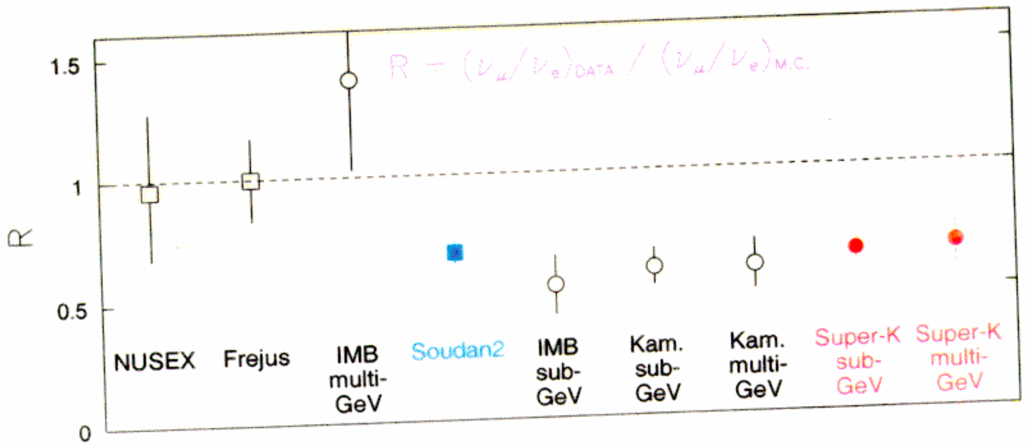
R=.60
±.08



R=.54
±.12

$STAT^2 + SYS^2$

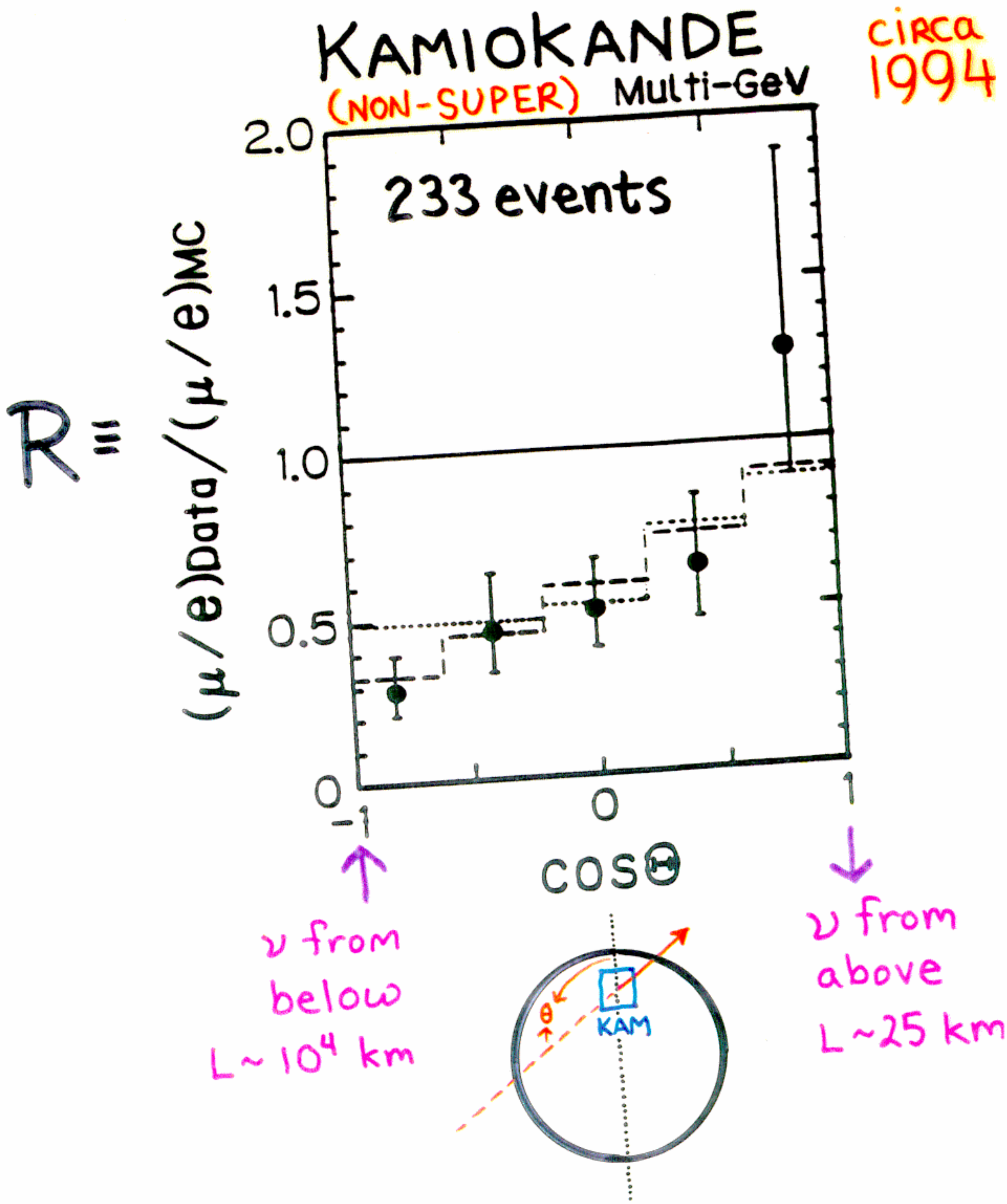
Summary of Double-Ratio Results



Experiment	kt-yr	events	R (data/MC)
Super-K sub-GeV[a]	70	5017	$0.65 \pm .02 \pm .05$
Super-K multi-GeV[a]	70	1743	$0.67 \pm .03 \pm .08$
IMB[b]	7.7	610	$0.54 \pm .05 \pm .11$
Kam.I/II/III sub-GeV[c]	7.7	482	$0.60^{+.06}_{-.05} \pm .05$
Kam.II/III multi-GeV[c]	6/8.2	233	$0.57^{+.08}_{-.07} \pm .07$
Soudan-II[d]	3.9	~240	$0.68 \pm .11 \pm .06$
IMB multi-GeV[e]	2.1	72	$1.4^{+0.45}_{-0.34} \pm .14$
Frejus[f]	2.0	200	$1.00 \pm .15 \pm .08$
NUSEX[g]	0.74	50	$0.96^{+.32}_{-.28}$

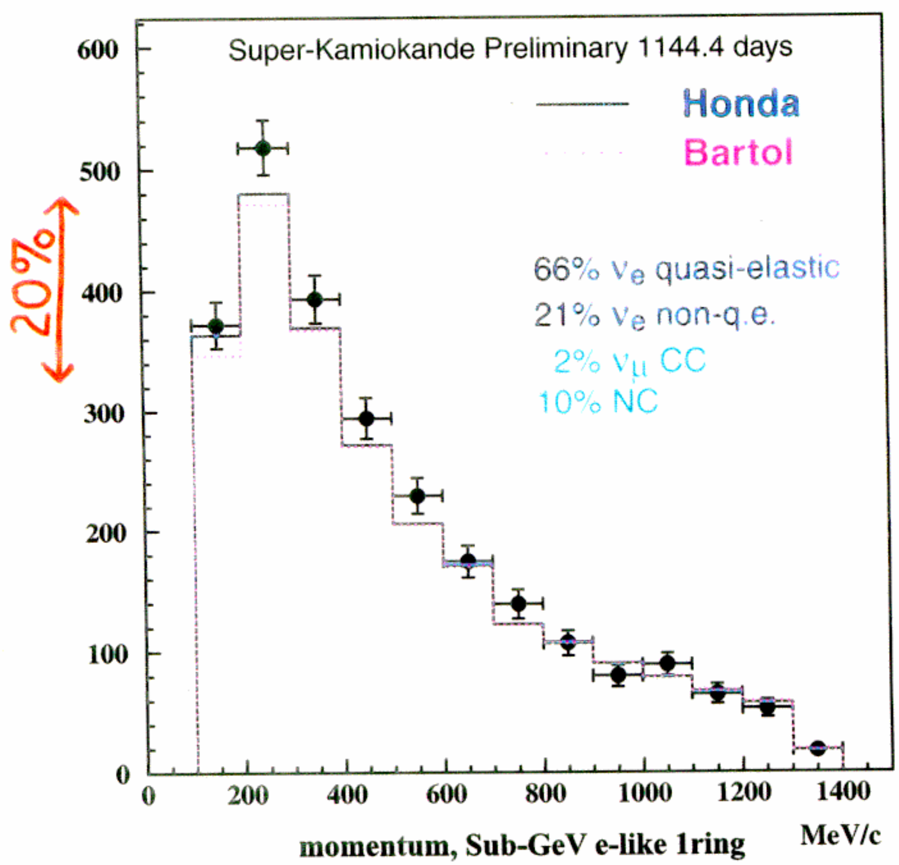
(a) Super-Kamiokande Collaboration, 2000 summer conferences.
(b) R.Becker-Szendy et al. Phys. Rev. D46 (1992) 3720
(c) Y.Fukuda et al. Physics Letters B335 (1994) 237
(d) Soudan II Collaboration, 2000 summer conferences.
(e) R.Clark et al. Phys.Lett.79(1997) 345
(f) K.Daum et al. Z.Phys. C66 (1995) 417
(g) M.Aglietta et al. Europhys.Lett. 8 (1989) 611

R + ZENITH ANGLE

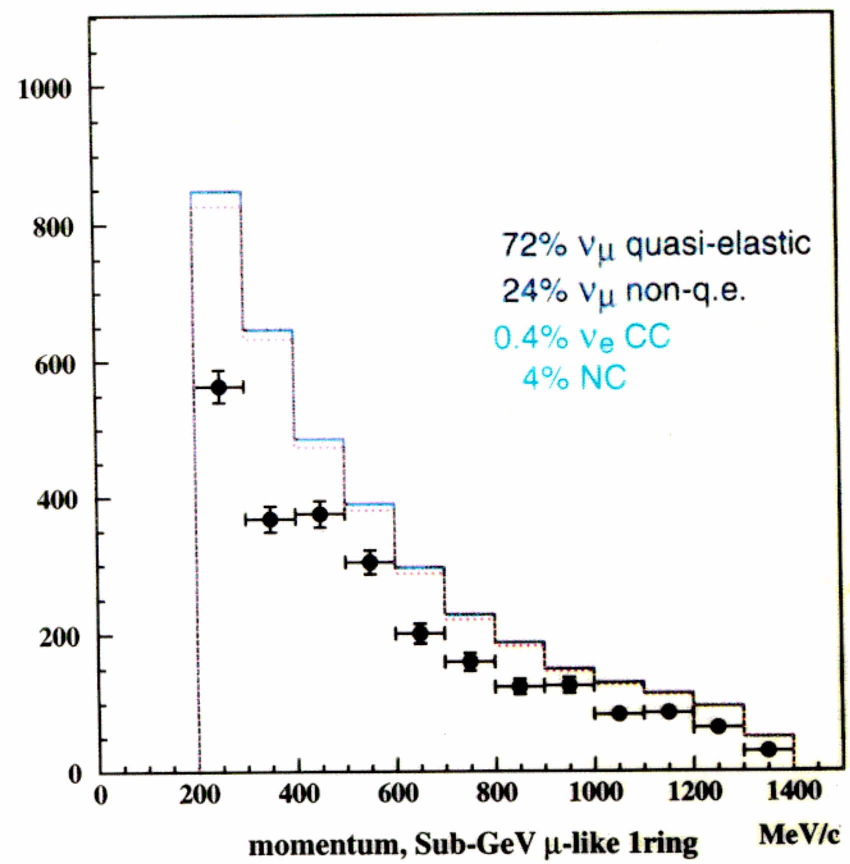


Super-K Sub-GeV Momentum Distributions

1-ring, Fiducial Volume
$p_e > 100$ MeV/c
$p_\mu > 200$ MeV/c
Evis < 1.33 GeV

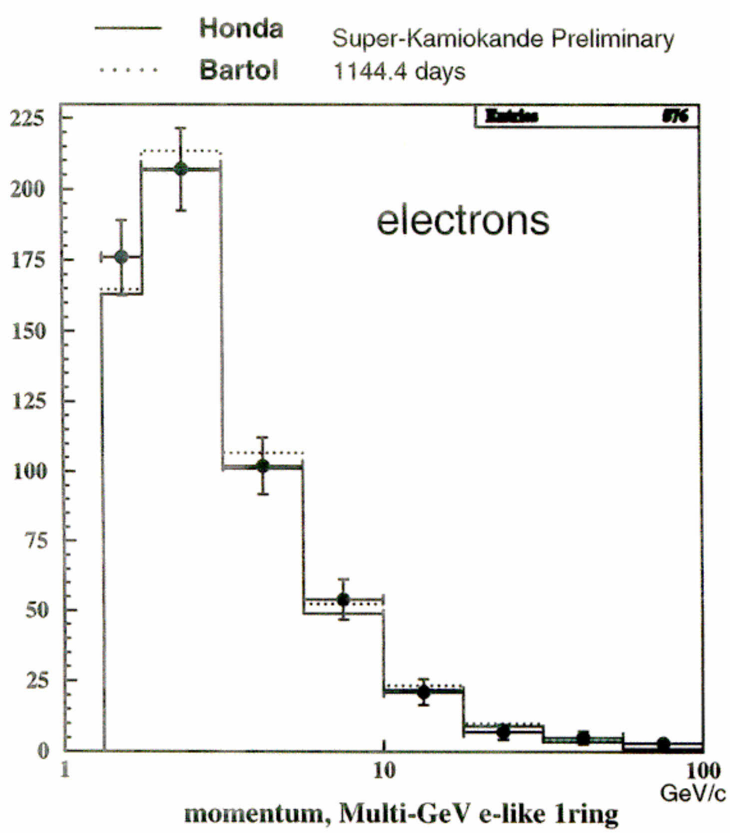


electrons

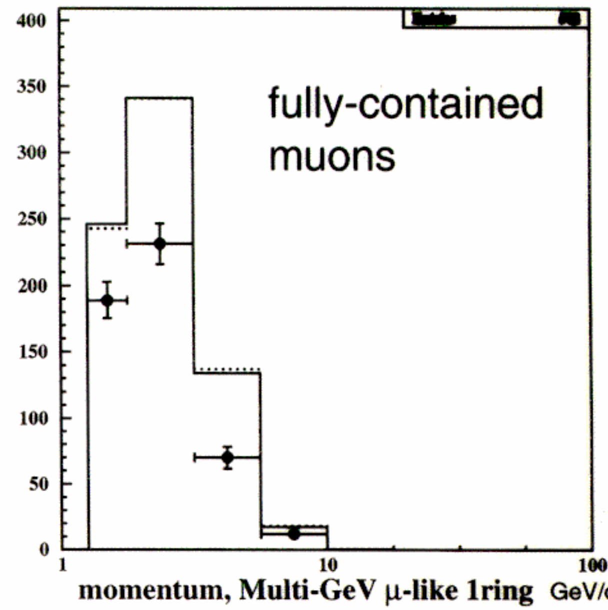


muons

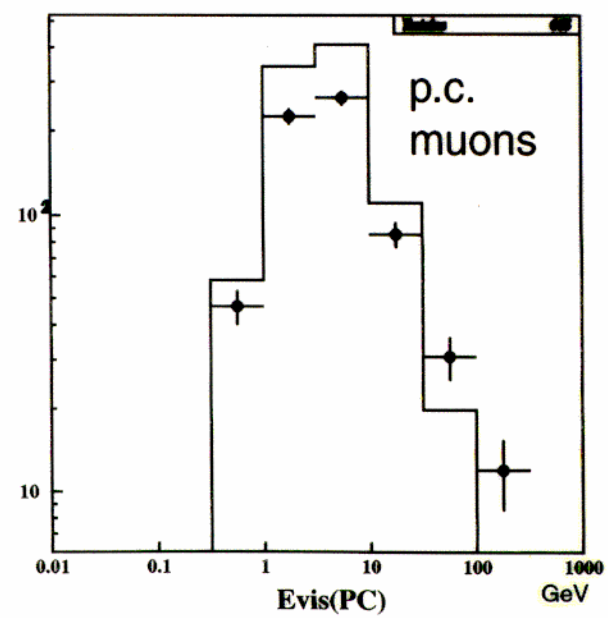
SK Multi-GeV + PC



34% ν_e quasi-elastic
49% ν_e non-q.e.
7% ν_μ CC
9% NC

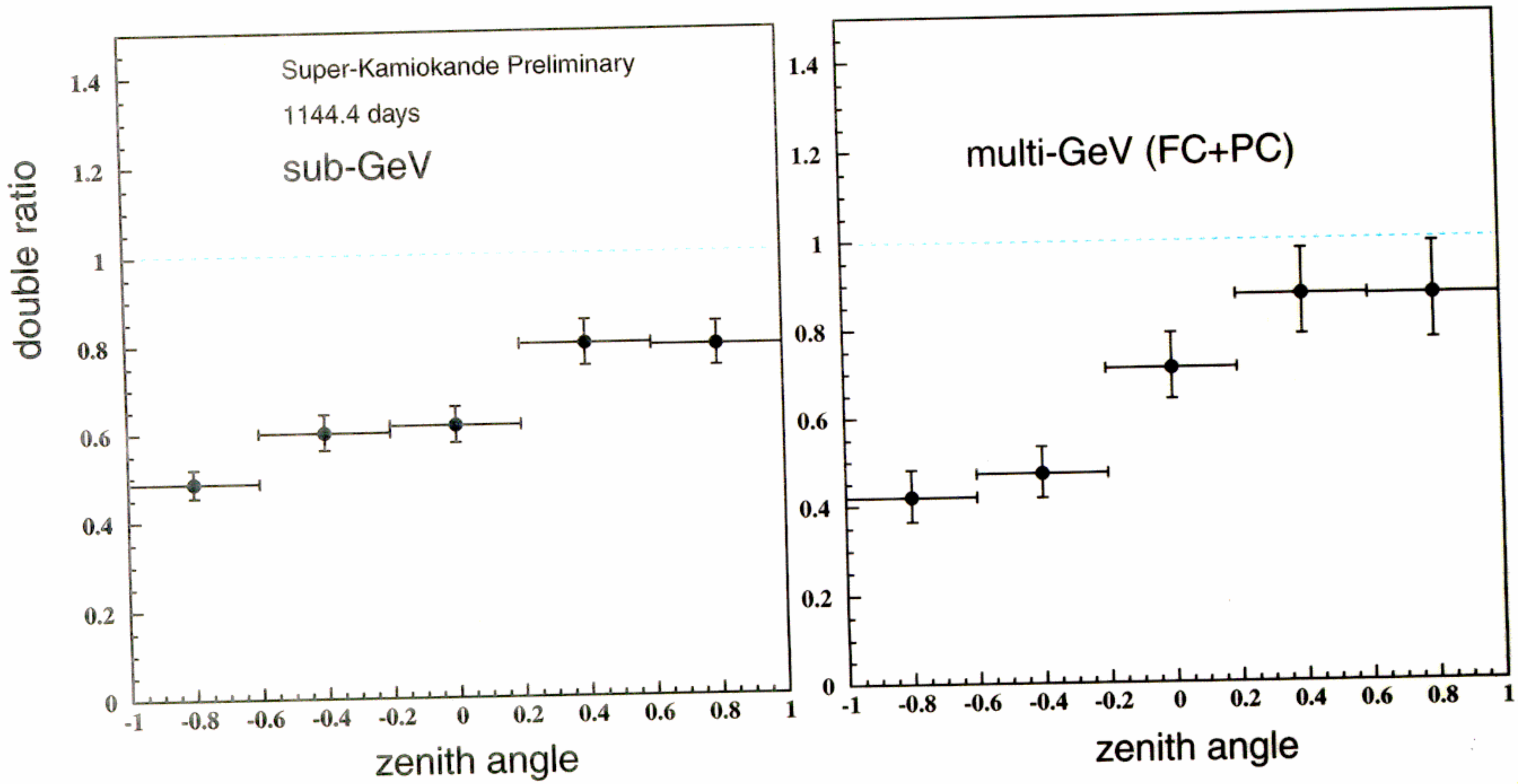


46% ν_μ quasi-elastic
54% ν_μ non-q.e.
0.2% ν_e CC
0.3% NC



17% ν_μ quasi-elastic
81% ν_μ non-q.e.
2% ν_e CC
1% NC

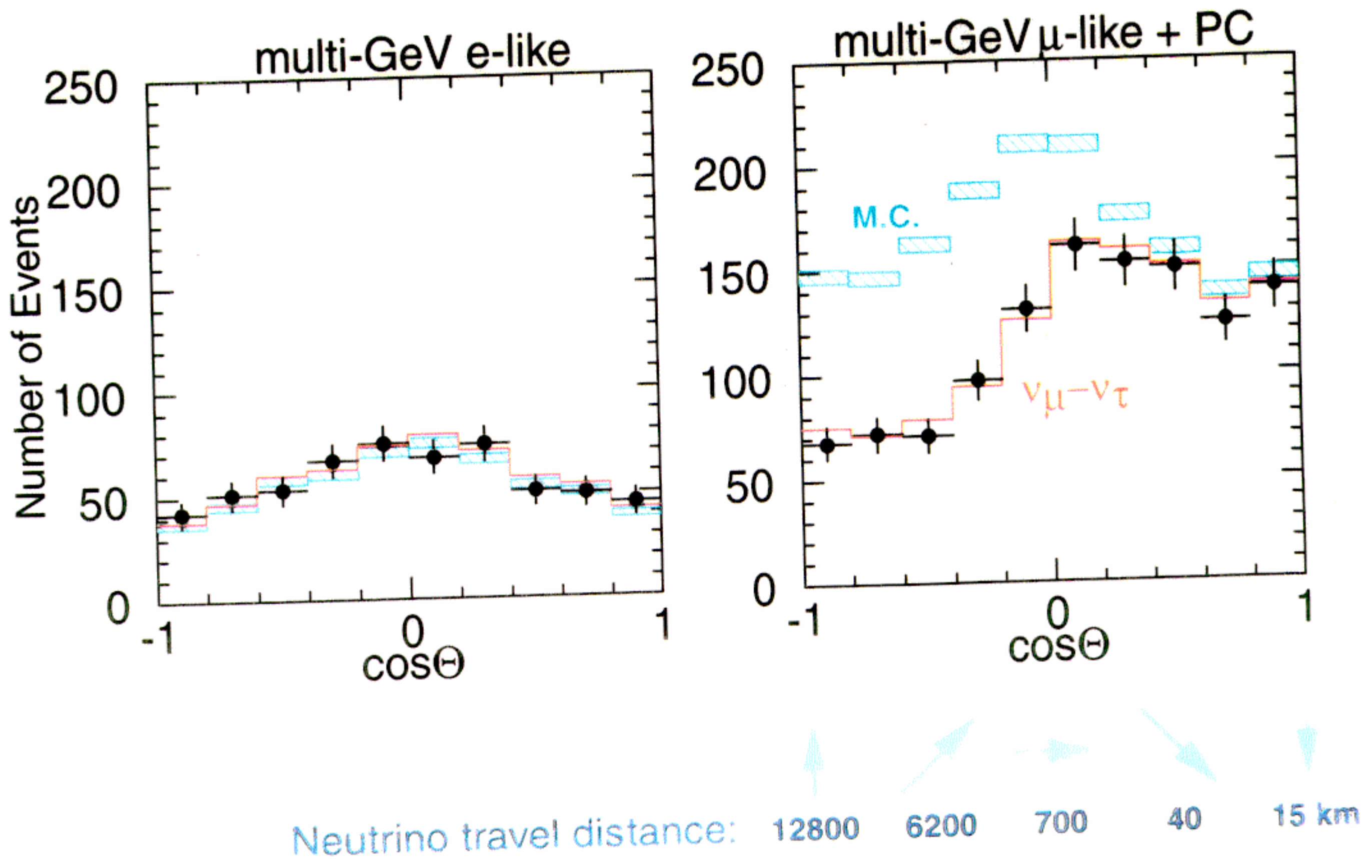
SK Ratio-of-Ratios: $\frac{(N_\mu/N_e)_{data}}{(N_\mu/N_e)_{m.c.}}$



R = 0.65 ±0.02 ±0.05

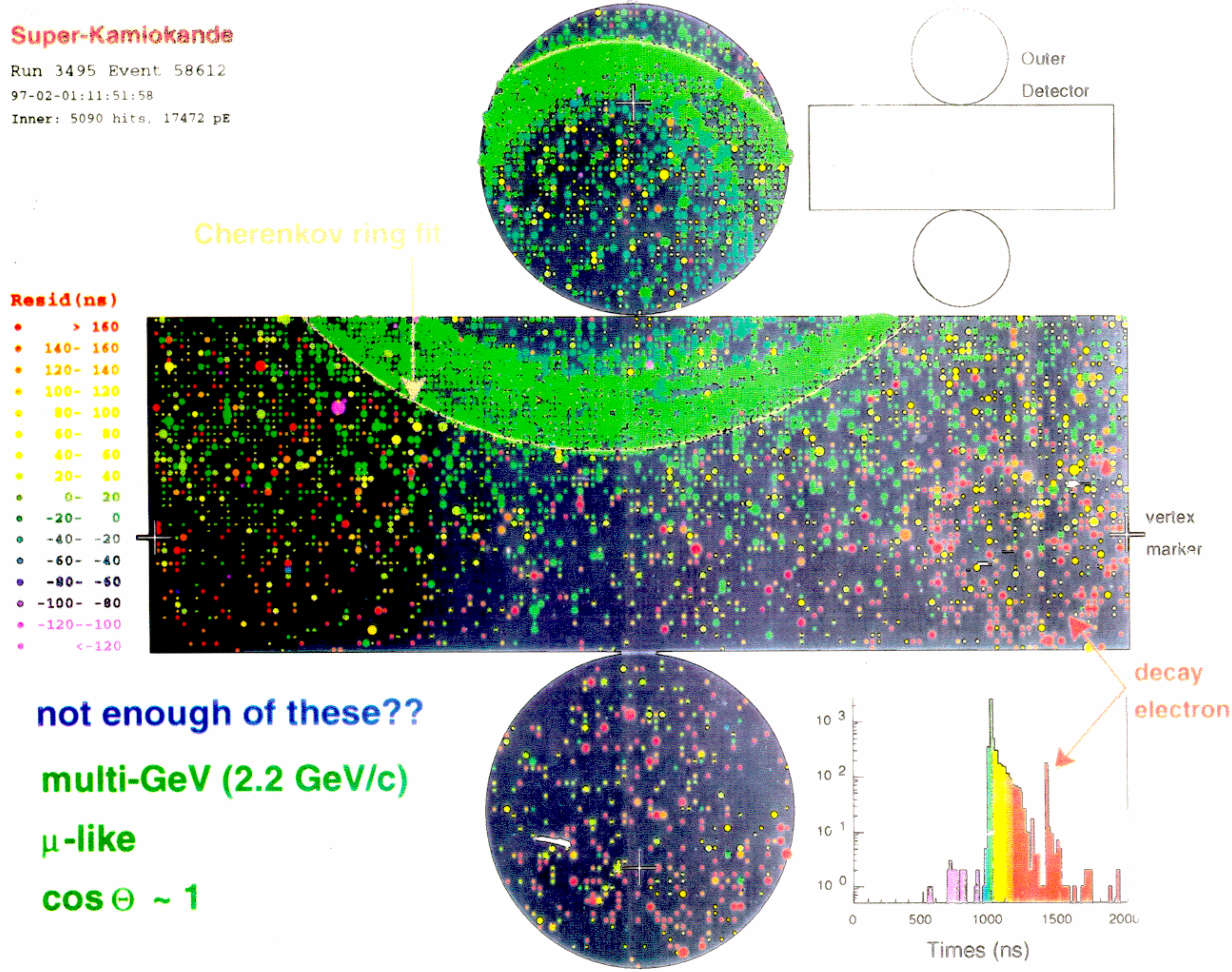
R = 0.67 ±0.03 ±0.08

Up-Down Asymmetry

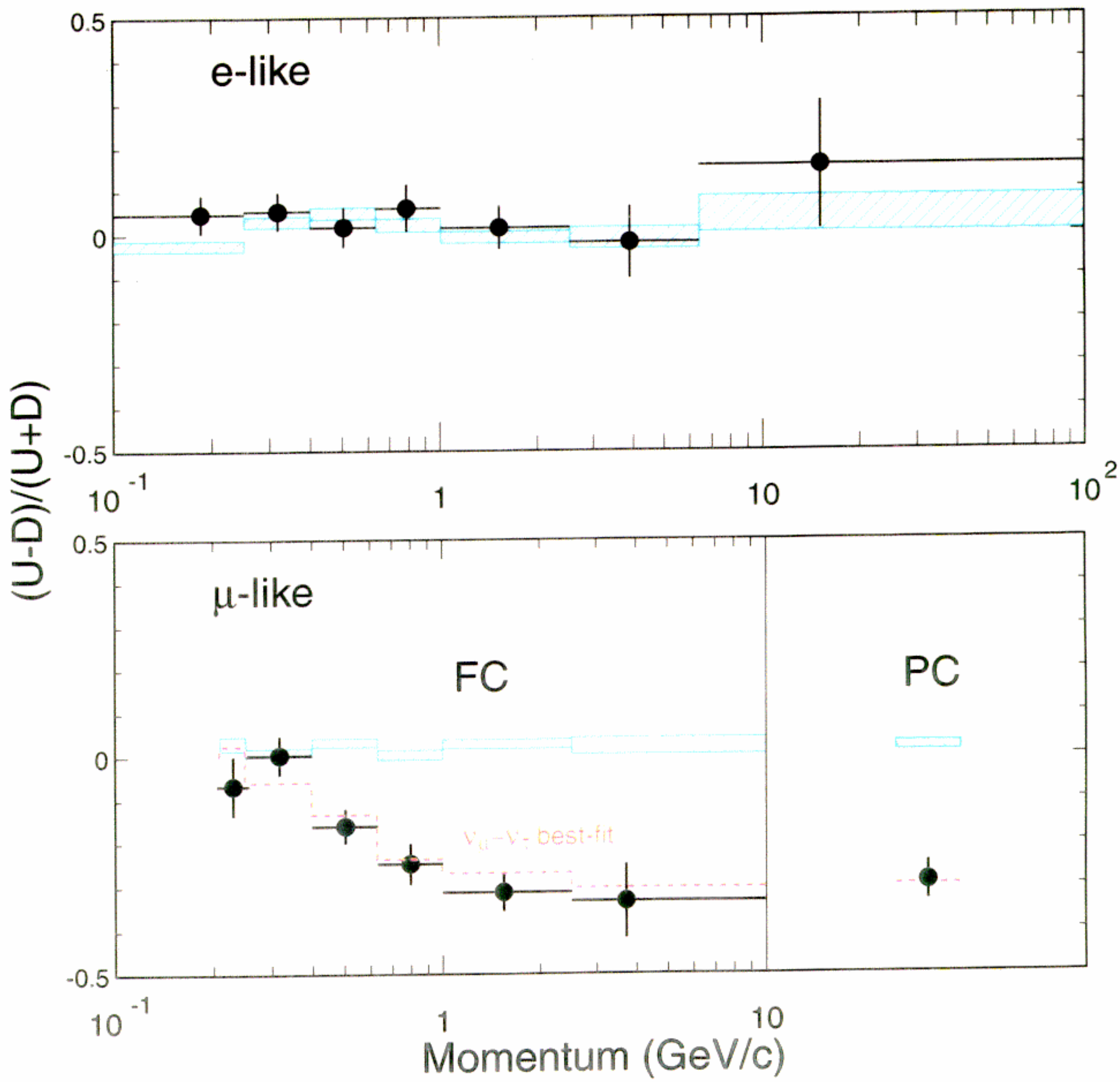


$$\frac{U - D}{U + D}$$

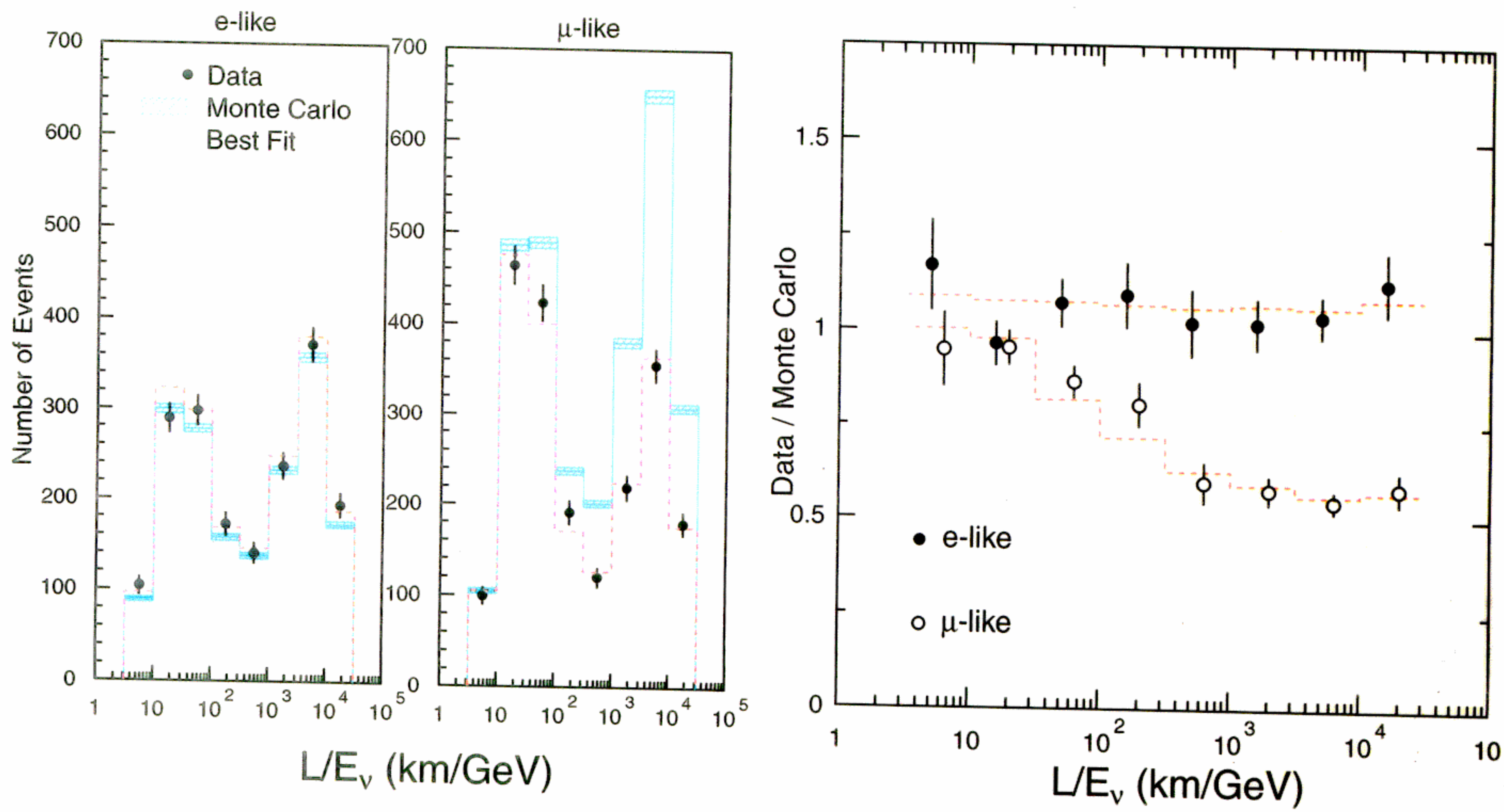
mu-like data	-.296 ±.032 ±.01	>8σ !
mu-like M.C.	-.020 ±.008 ±.01	CONSISTENT WITH 0
e-like data	-.016 ±.048 ±.02	
e-like M.C.	-.024 ±.014 ±.01	


Super-Kamiokande
Run 3495 Event 58612
97-02-01:11:51:58
Inner: 5090 hits, 17472 pE
Outer Detector
Cherenkov ring fit
Resid(ns)
> 160
140- 160
120- 140
100- 120
80- 100
60- 80
40- 60
20- 40
0- 20
-20- 0
-40- -20
-60- -40
-80- -60
-100- -80
-120--100
<-120
vertex marker
decay electron
not enough of these??
multi-GeV (2.2 GeV/c)
μ-like
cos Θ ~ 1
10 3
10 2
10 1
10 0
0
500
1000
1500
2000
Times (ns)

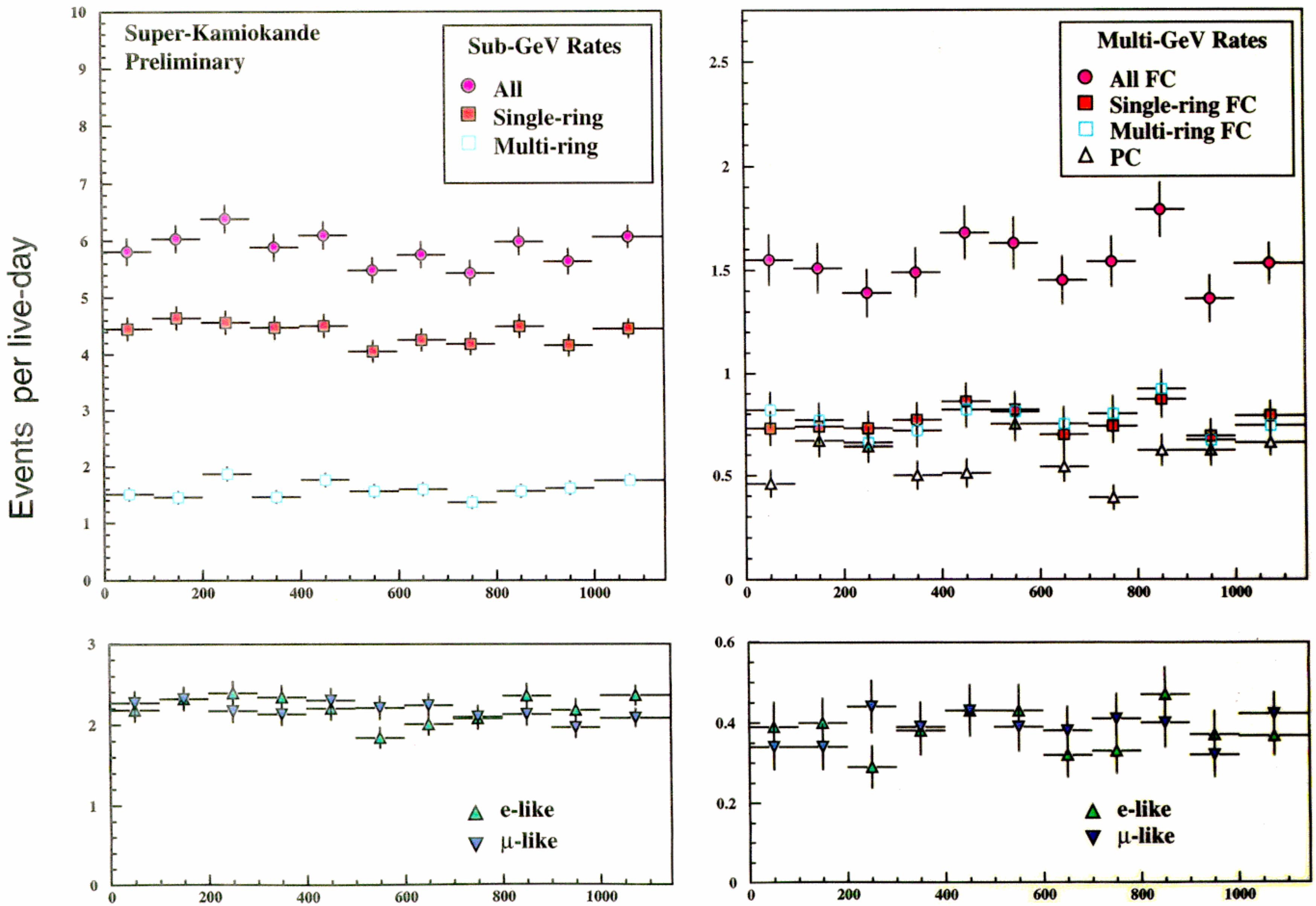
Up-Down Asymmetry versus Momentum



Bin SK data as a function of L/E

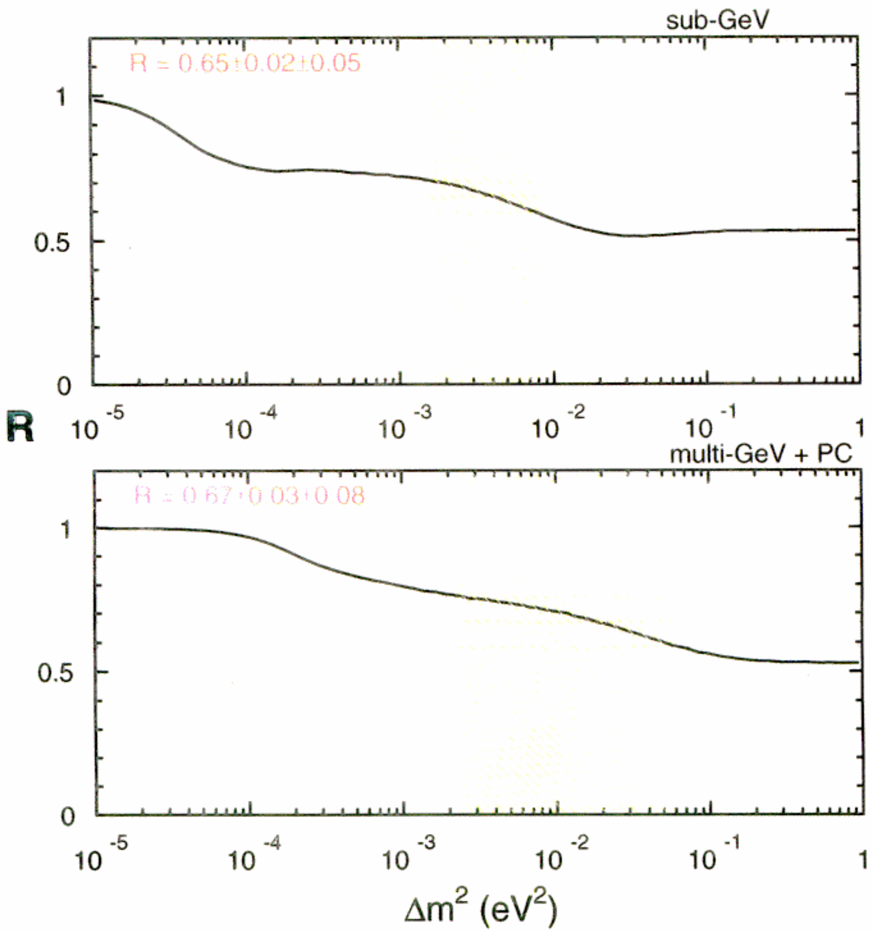


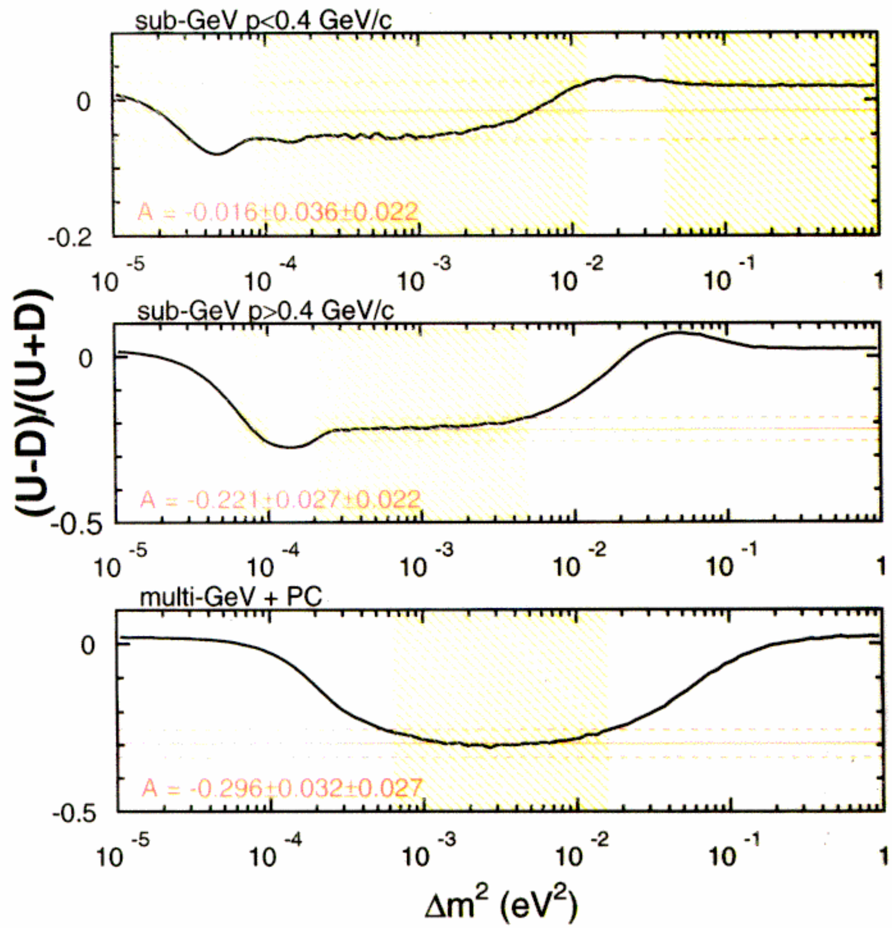
Event Rate Stability



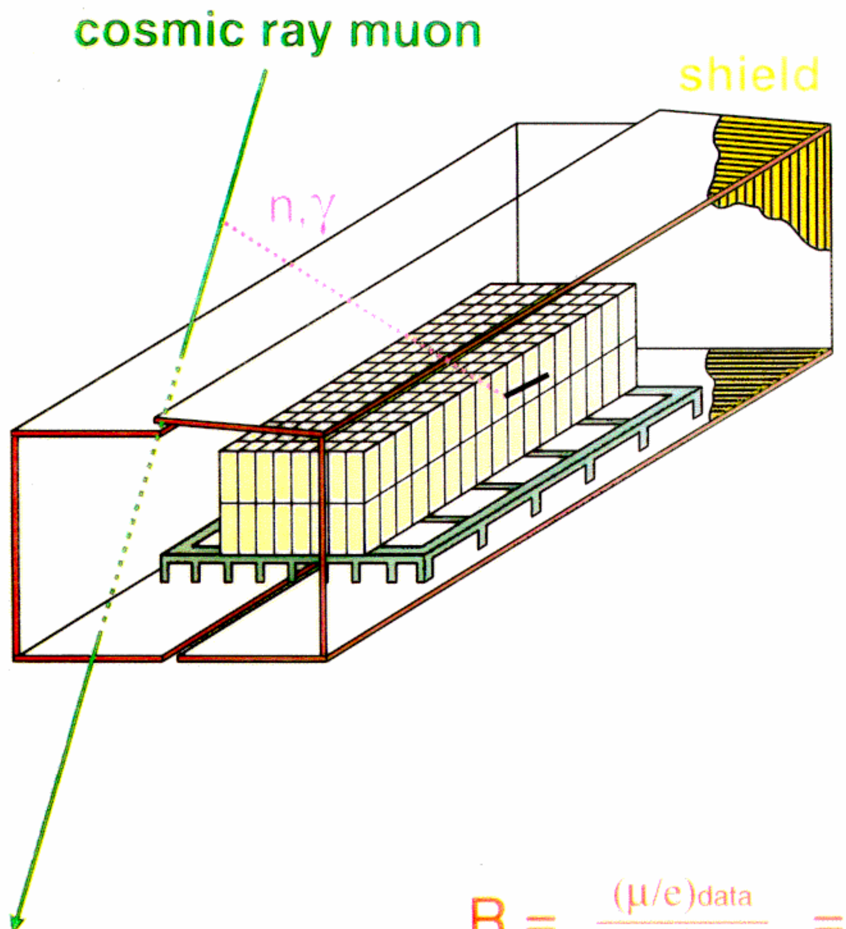
Consistency of Evidence for Δm^2

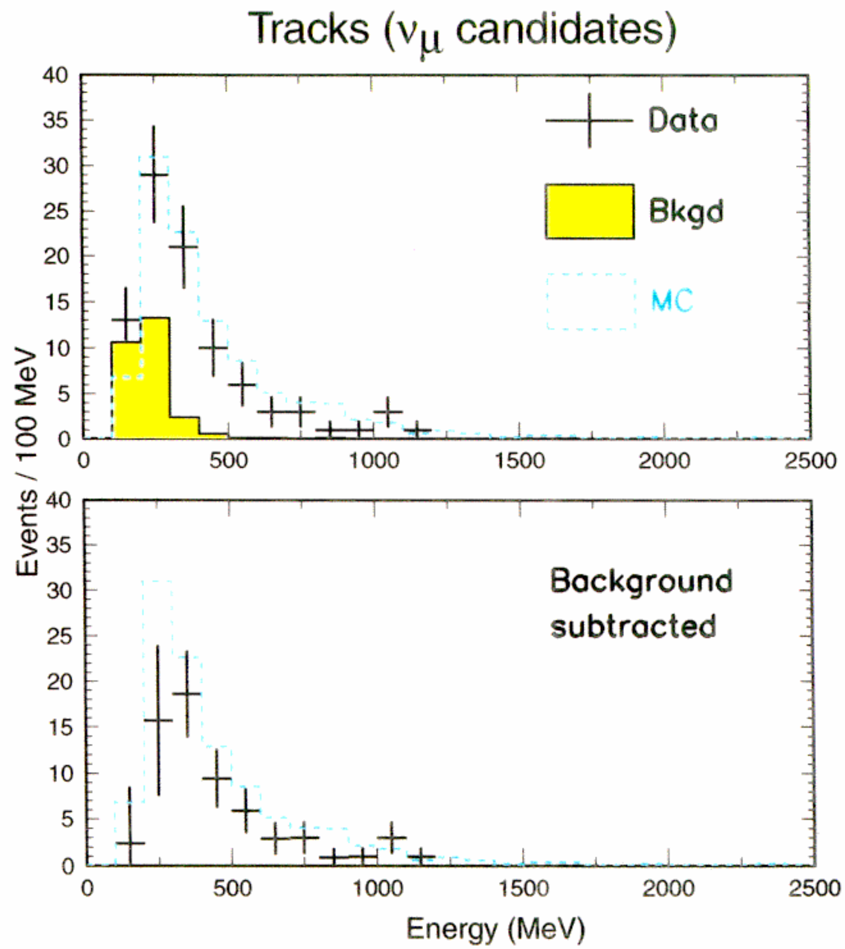
$\sin^2(2\theta)=1$





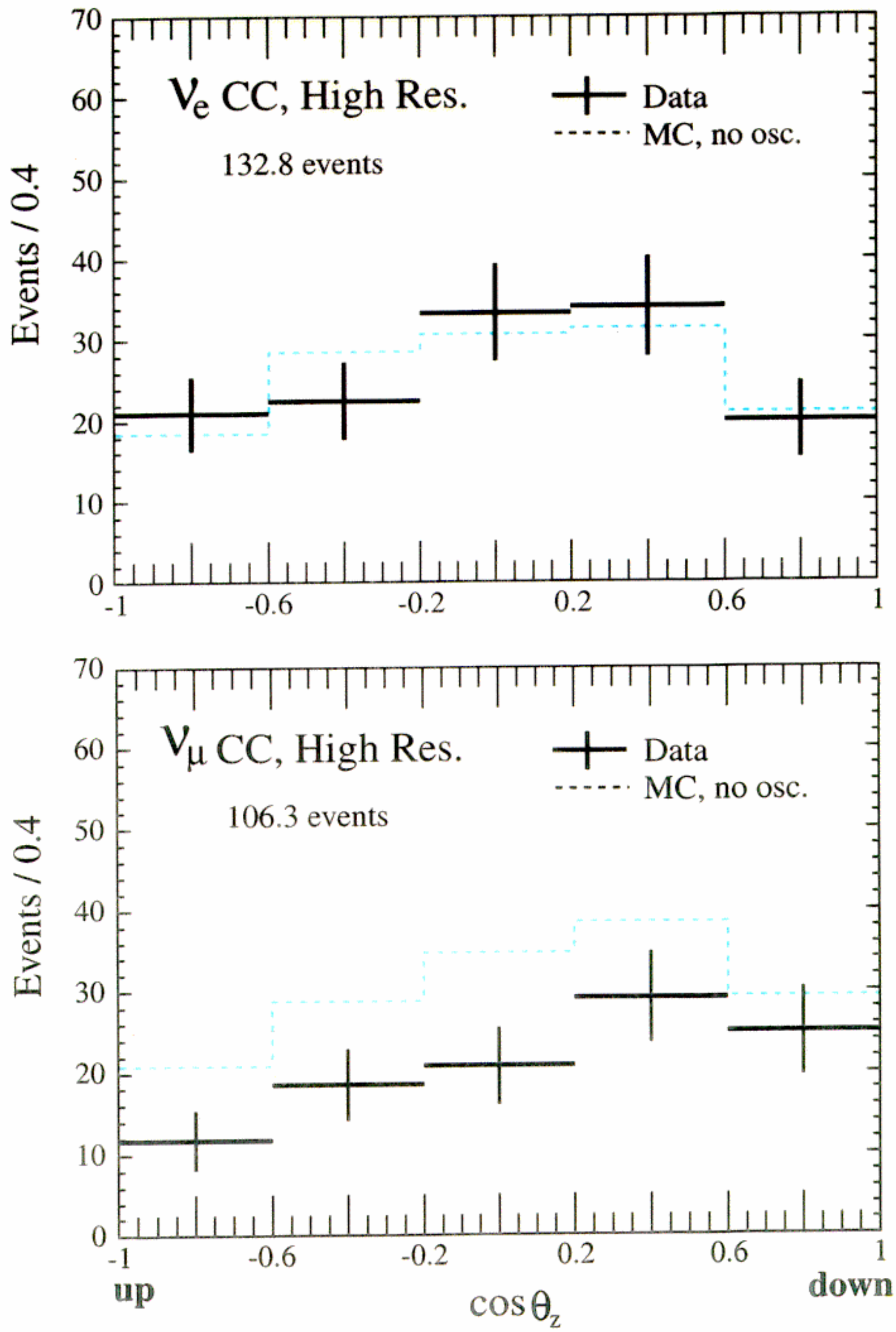
Soudan 2   Fully Contained Events





$$R = \frac{(\mu/e)_{data}}{(\mu/e)_{m.c.}} = 0.66 \pm 0.11 \pm 0.06 \text{ (bg subtracted)}$$

Soudan 2 Zenith Distributions

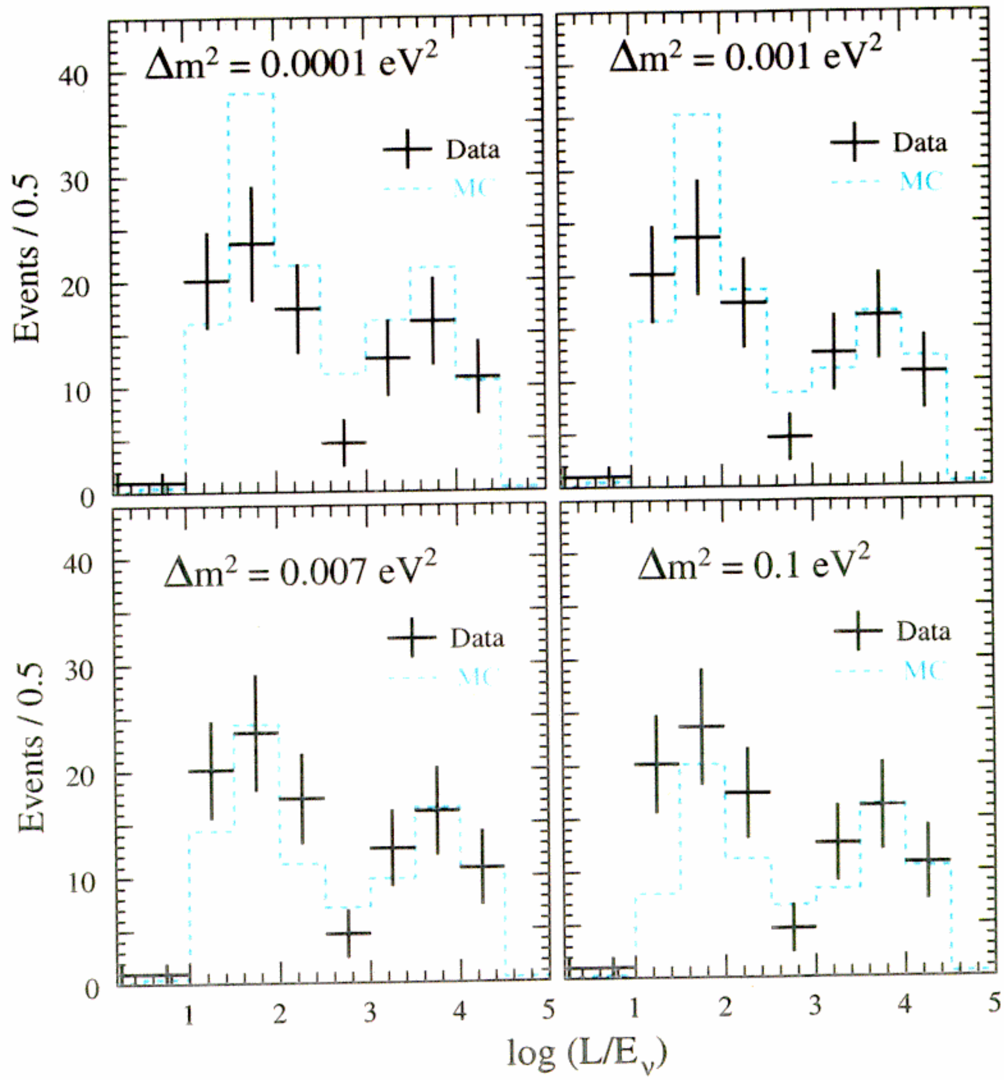


Soudan 2 high resolution analysis

quasi-elastic
- p > 150 MeV/c if recoil present
- Evis > 600 MeV otherwise

high energy multi-prongs

20-30° pointing, log(L/E) resolution ~0.5



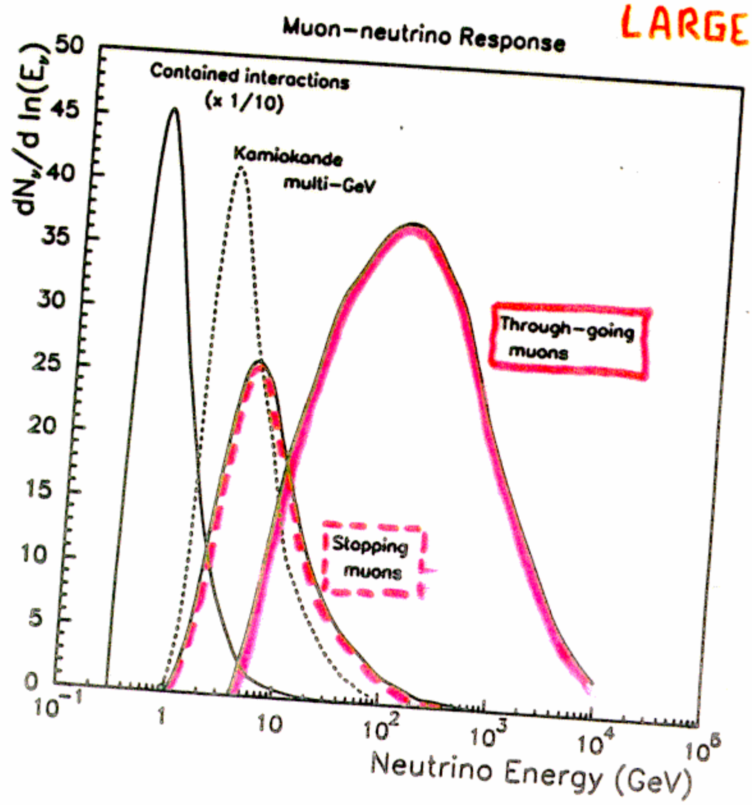
best fit: $\sin^2 2\theta = 0.9$, $\Delta m^2 = 8 \times 10^{-3}\ eV^2$

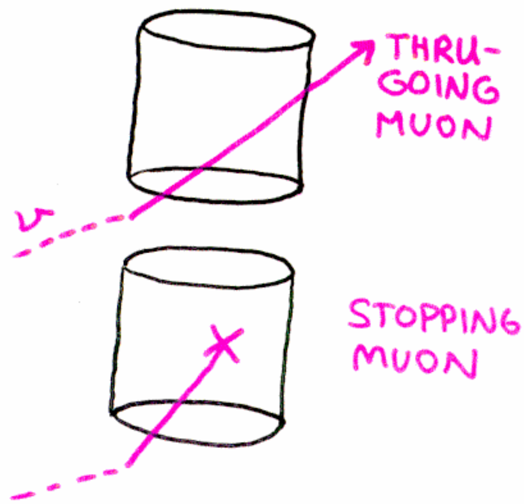
WILL SHOW CONTOUR SHORTLY → ...

Upward-Going Muons

ν-INTERACTIONS IN ROCK BELOW THE DETECTOR

LARGE TARGET MASS



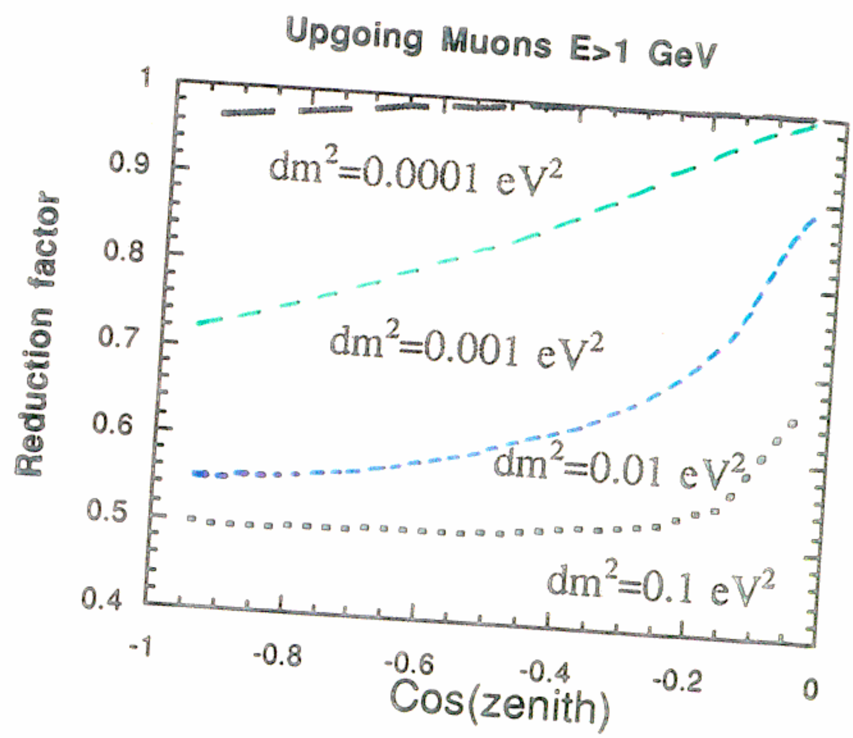


STUDY RATIO N_{STOP} / N_{THRU}

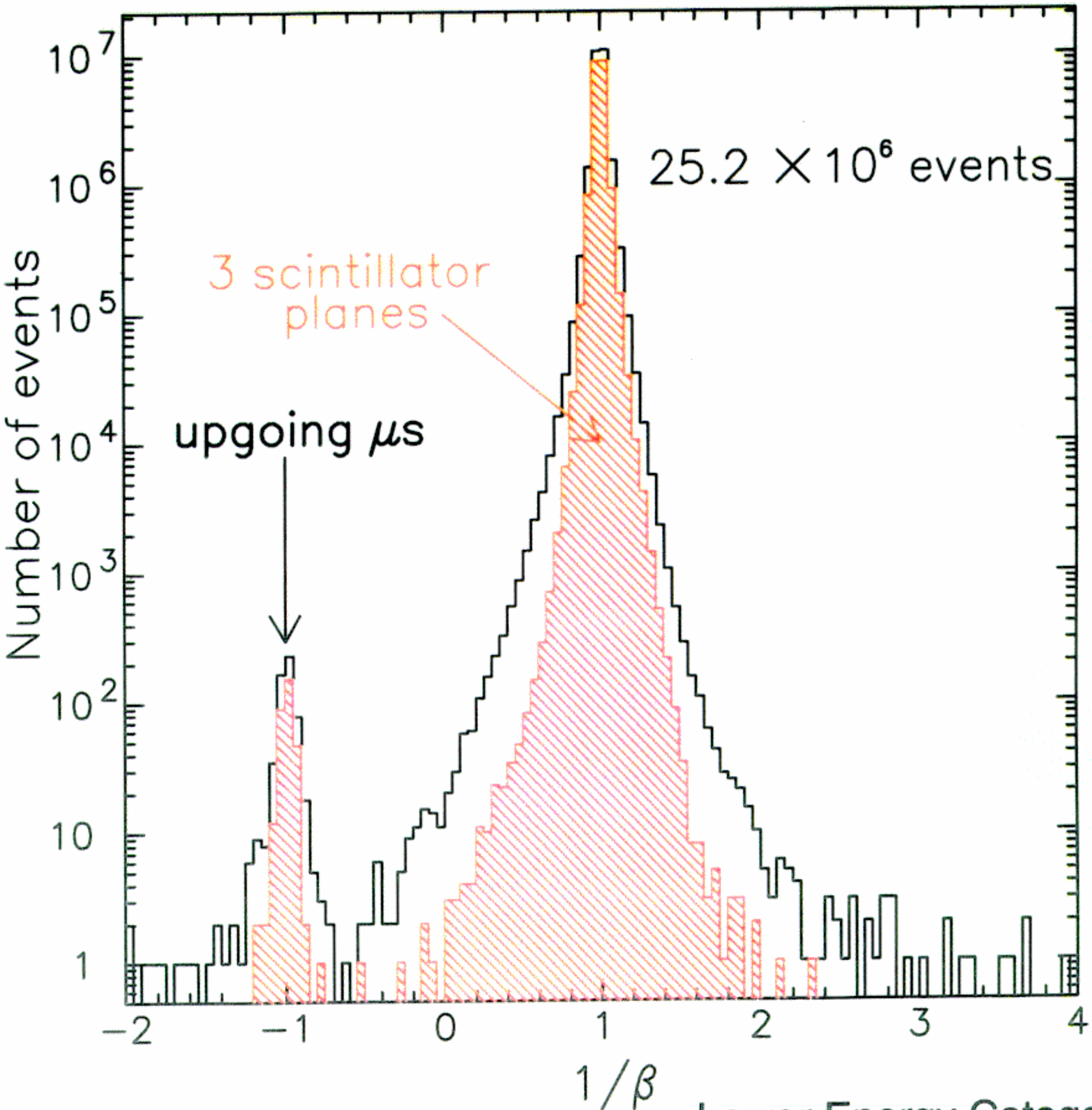
$\cos\theta_z < 0$

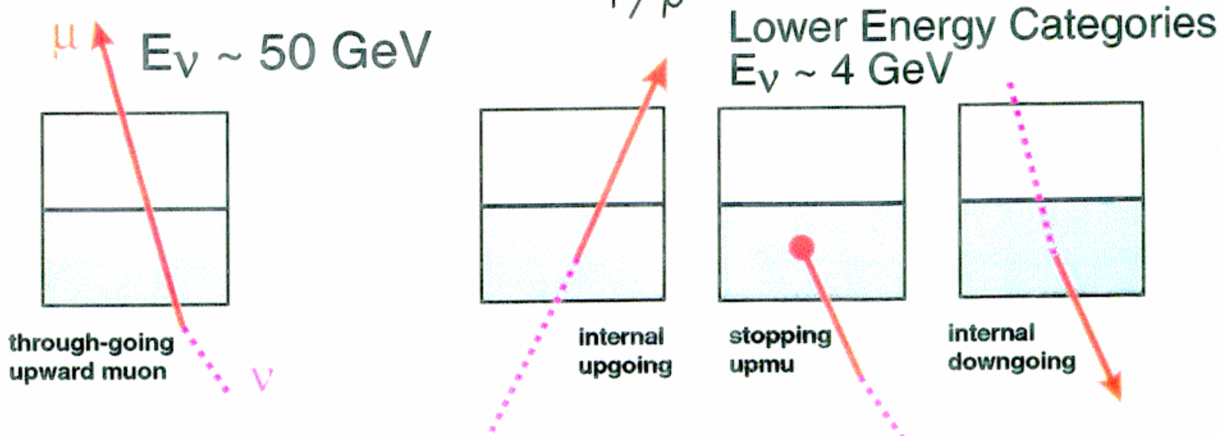
$L = 500 - 10^4$ km

STUDY ZENITH ANGLE SHAPE

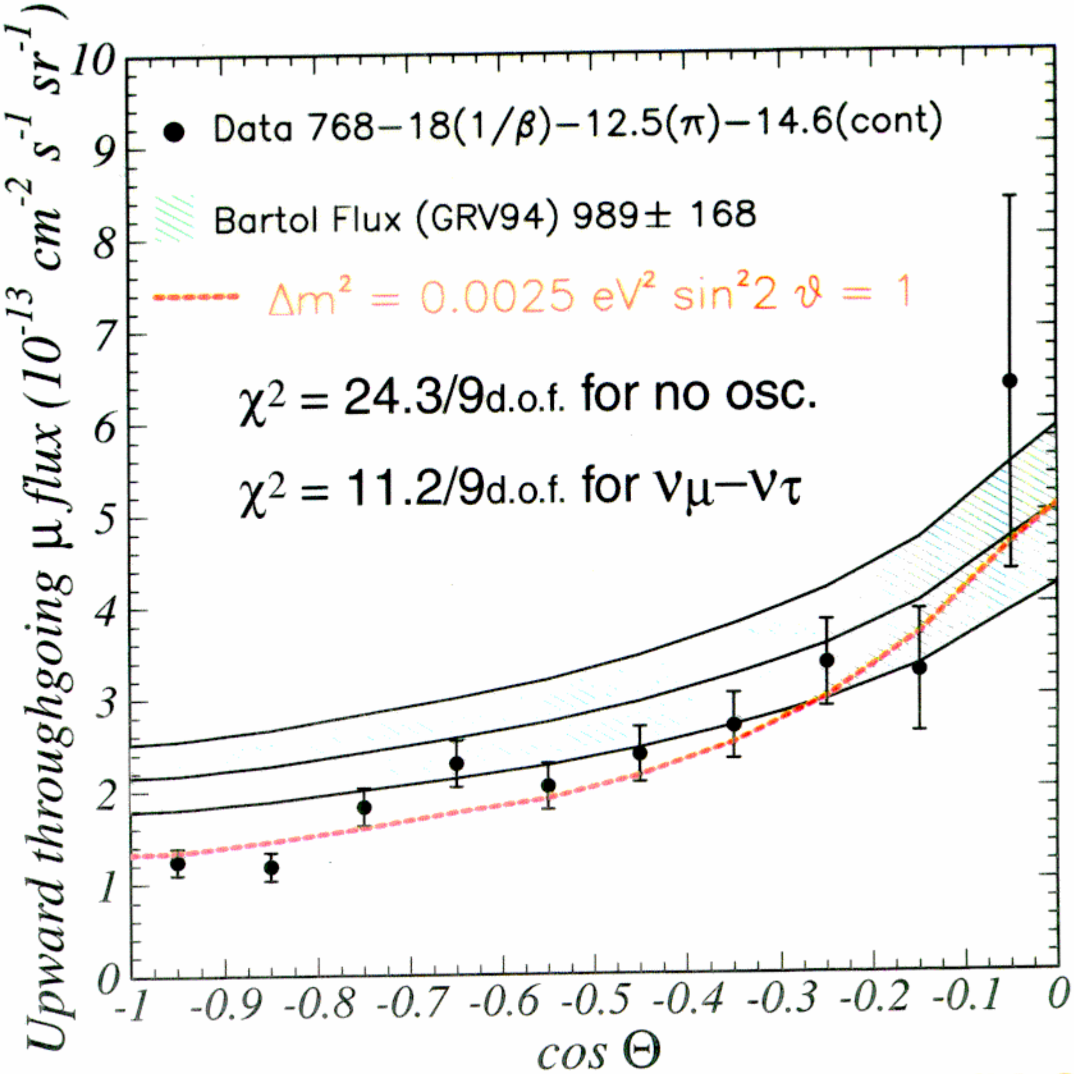


MACRO: Through-going Upward Muons





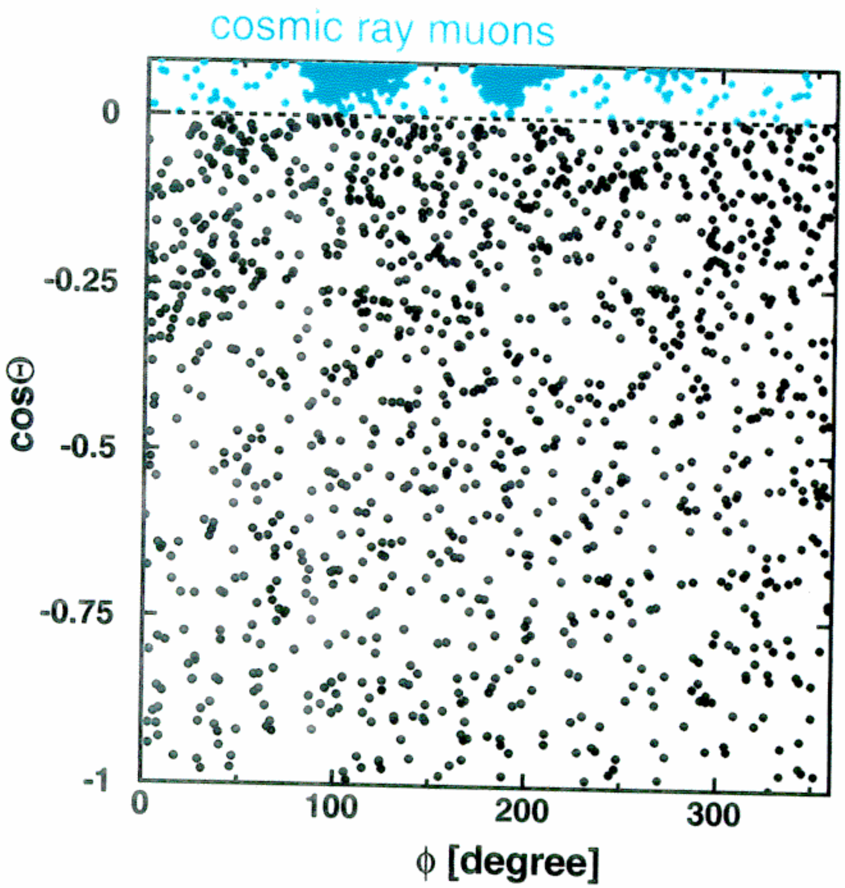
MACRO Up-μ Results

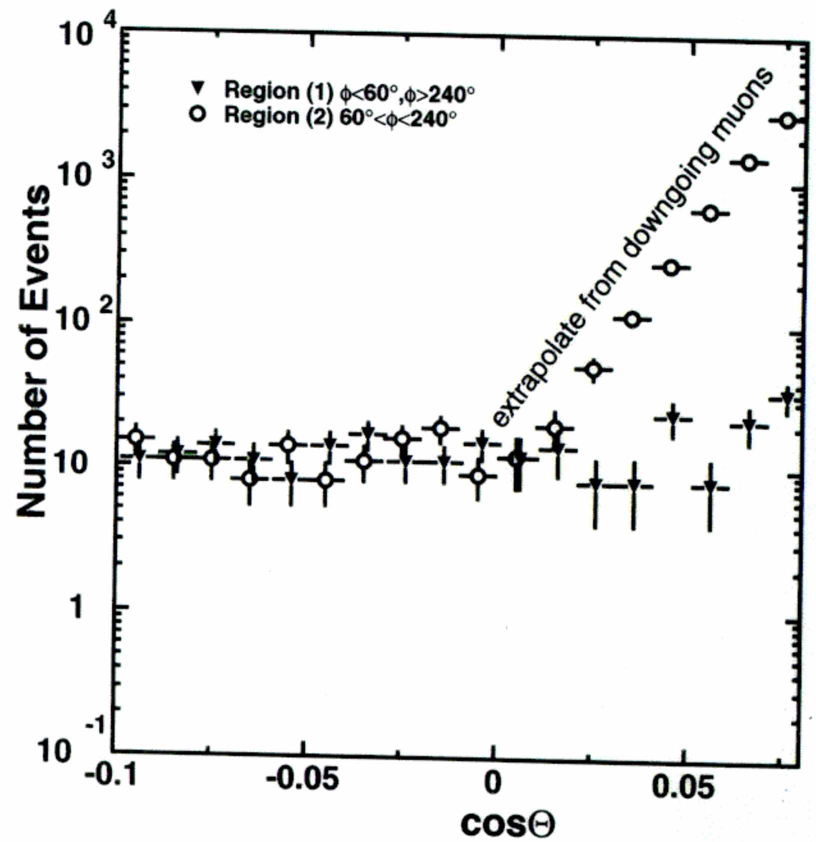


	DATA/M.C.
thru-upmu	0.73 ±0.03 ±0.04 ±0.12
internal upgoing	0.55 ±0.04 ±0.06 ±0.14
int.down+up-stop	0.70 ±0.04 ±0.07 ±0.18
	stat *sys* *theo*

IU/(ID+US) = 0.59 ±0.07 *cf* 0.75 ±0.06 (no osc)

Through-going Upward Muons



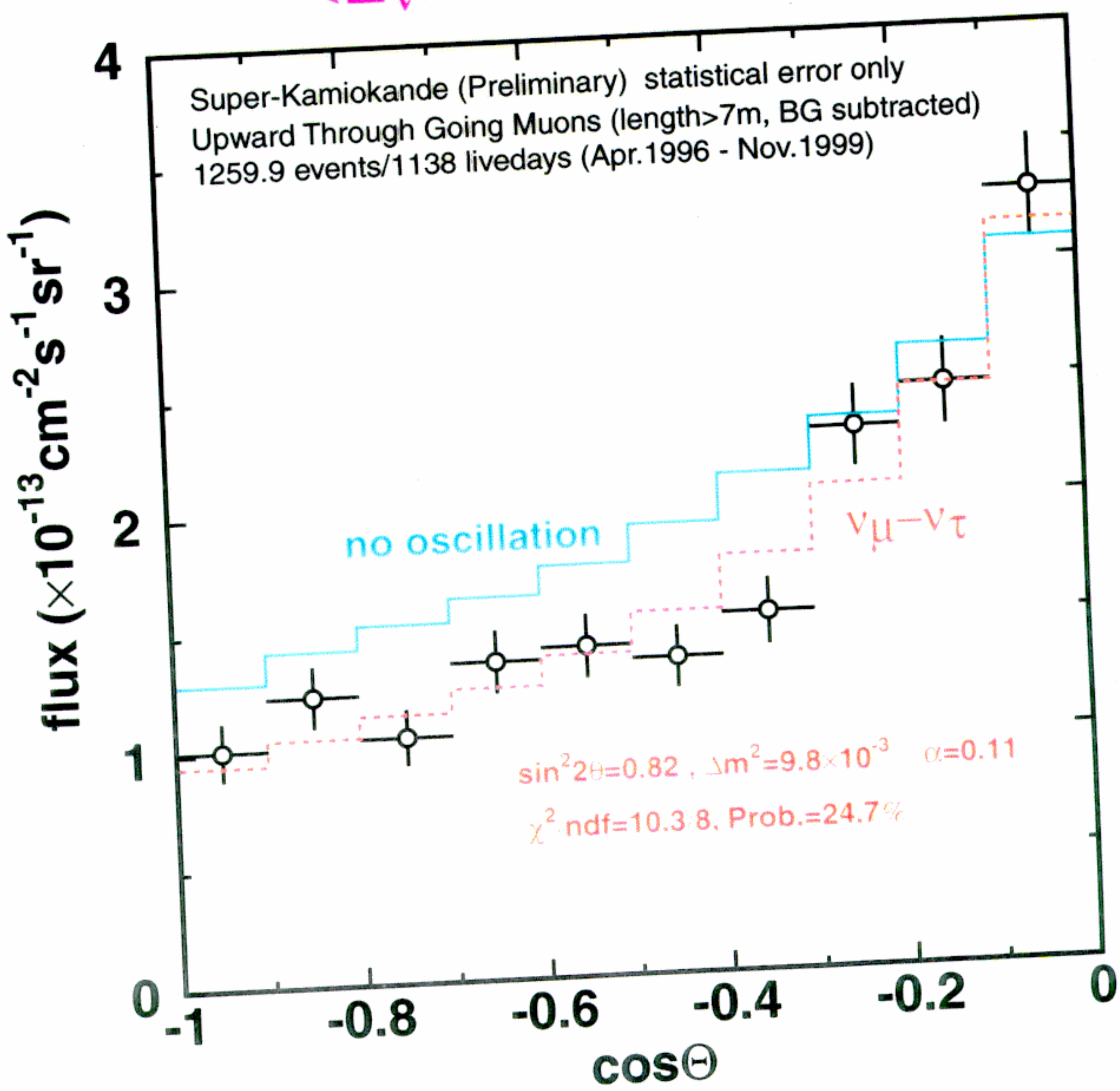


background subtraction (most horizontal bin):

9.1 ±0.8 for through-going
21.2 ±8.6 for stopping

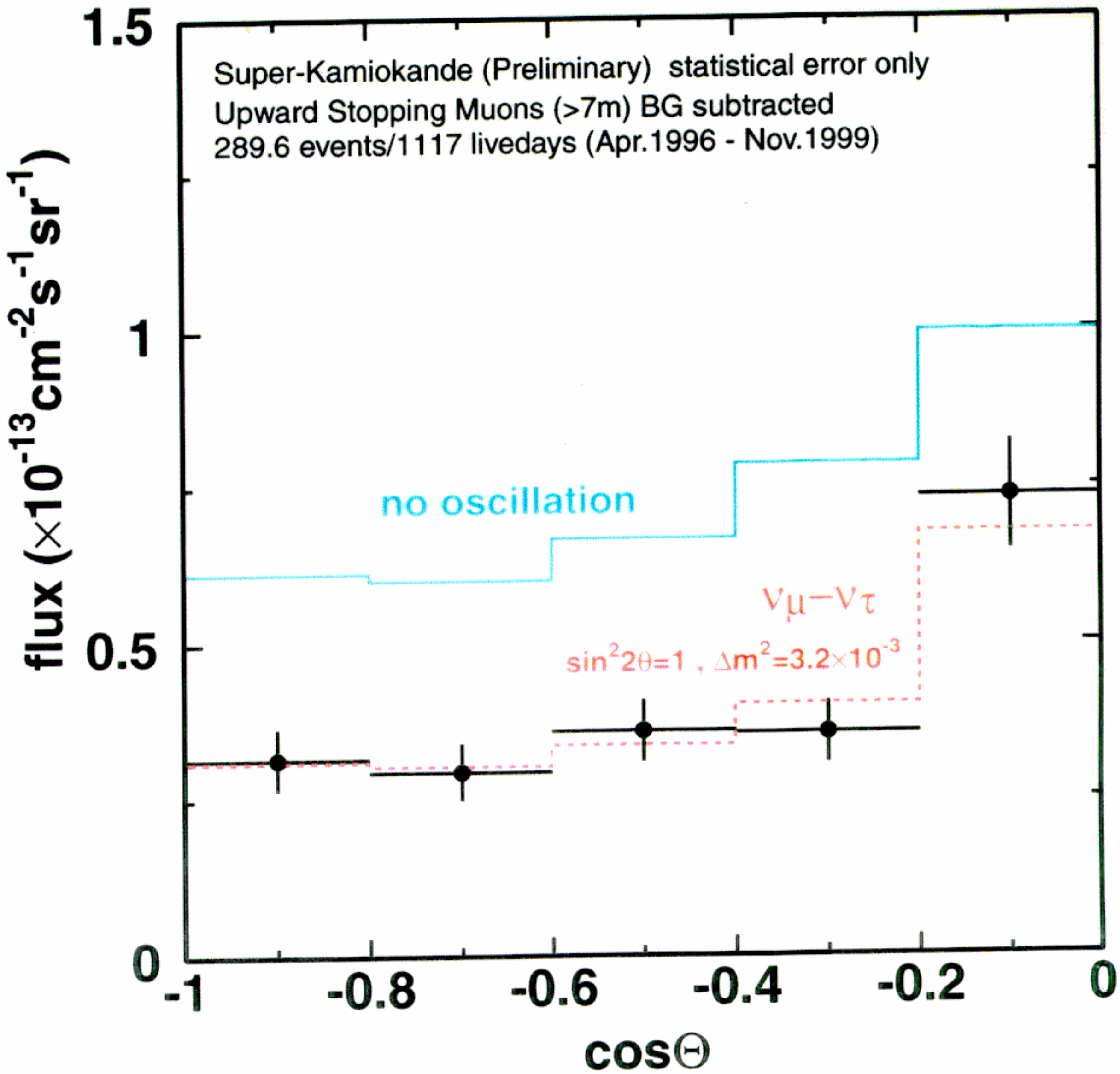
Through-Going Upward Muons

$\langle E_\nu \rangle \sim 100$ GeV



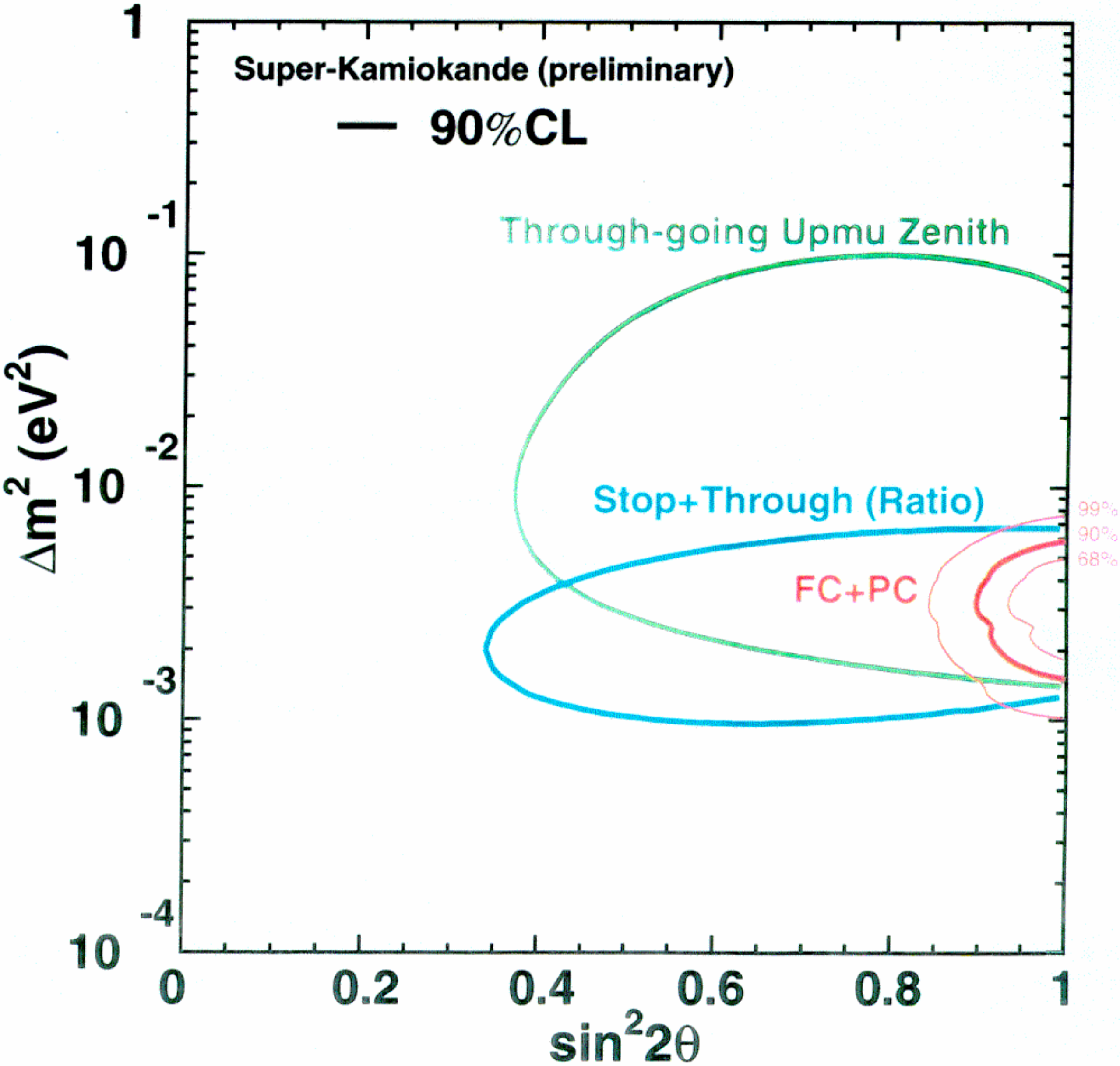
no oscillation - χ^2/ndf=22.6/10, Prob.=1.2%

Stopping Upward Muons



Ratio:	stopping/through-going	
cancel many uncertainties	.24 ±.02 ±.01	(data)
	.37 ±.05	(M.C.)

Super-K Contours



Fitting Technique

$$\chi^2 = \sum_{\substack{\cos\theta \\ p \\ e,\mu}} \frac{(N_{DATA} - N_{MC})}{\sigma^2} + \sum_j \frac{\epsilon_j^2}{\sigma_j}$$

$\cos\theta$, p, e,μ } 155 bins total

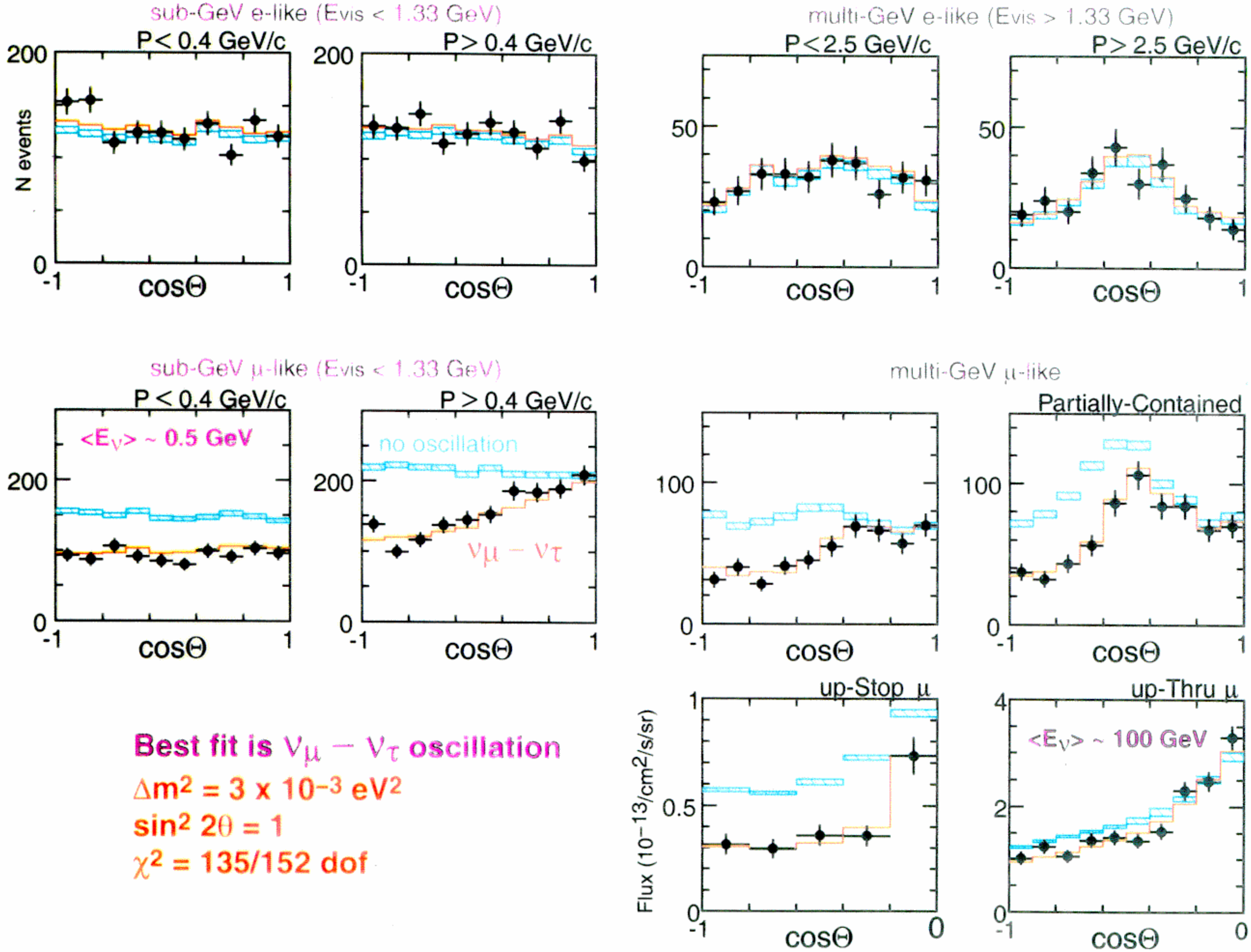
+12 SYSTEMATIC TERMS

$$N_{MC} = \frac{\mathcal{L}_{DATA}}{\mathcal{L}_{M.C.}} \sum_{\substack{MC \\ EVTS}} \text{weight}$$

weight is a function of $\{\sin^2 2\theta, \Delta m^2, \epsilon_j$

systematic uncertainty	σ	best fit
Primary flux (α)	Free	+5.2%
Eν spectrum index	0.05	-0.08
Sub-GeV m/e ratio	8%	-1.0%
Multi-GeV m/e ratio	12%	-11%
FC/PC normalization	8%	-0.6%
Sub-GeV up/down	2.4%	-1.3%
Multi-GeV up/down	2.7%	-1.3%
FC+PC/stop normalization	7%	-0.2%
Upthru/upstop normalization	7%	+7%
Horizontal/Vertical FC+PC	4%	-1.1%
Horizontal/Vertical upmu	3%	-0.4%
Uncertainty in L/E	15%	+8.7%

Fit to Super–K Atmospheric Neutrinos over 3 Decades in Energy



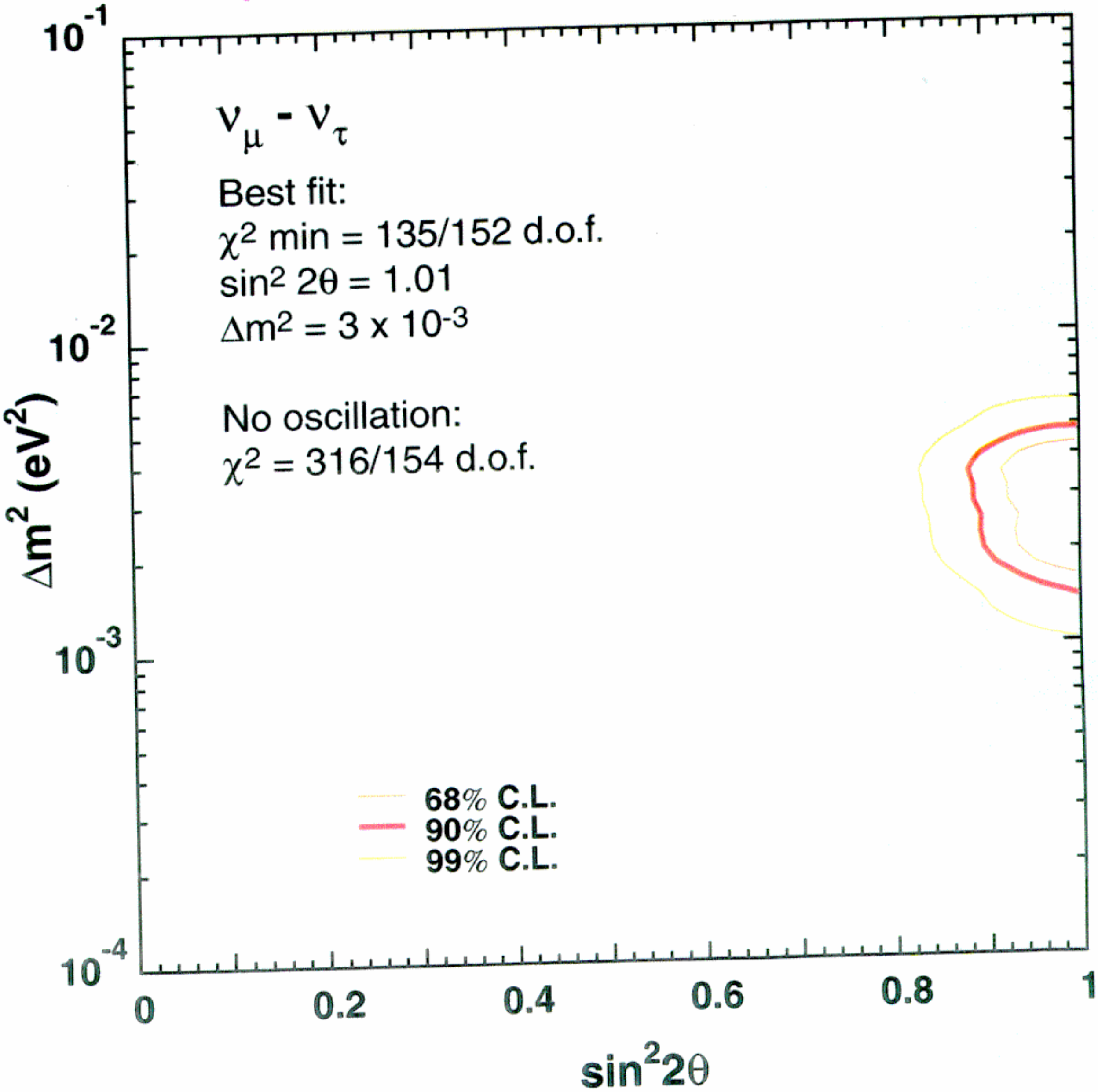
Best fit is $\nu_\mu - \nu_\tau$ oscillation

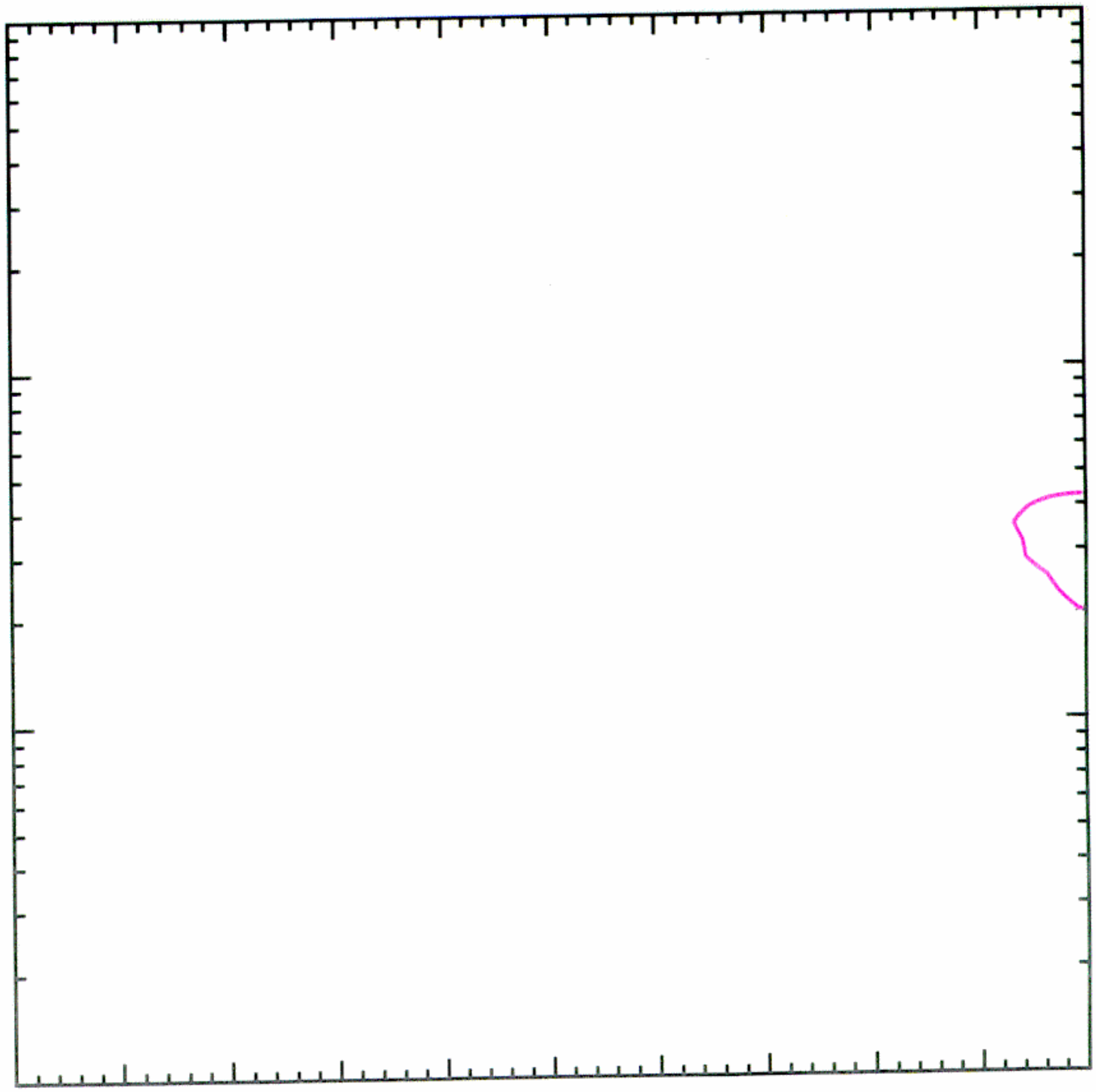
$\Delta m^2 = 3 \times 10^{-3}$ eV^2

$\sin^2 2\theta = 1$

$\chi^2 = 135/152$ dof

Super-K Simultaneous Best Fit to all Atmospheric νs (FC+PC+upstop+upthru)

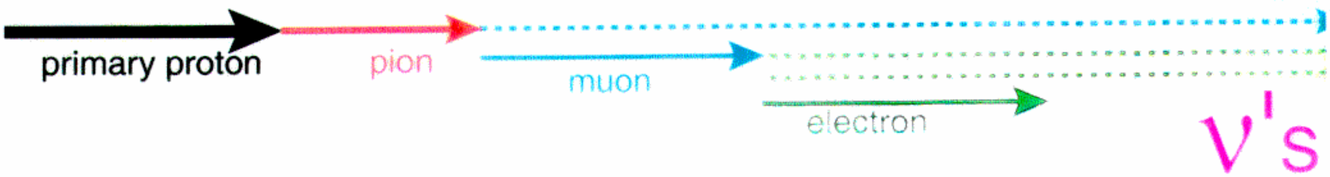




Contour with all systematic terms turned off

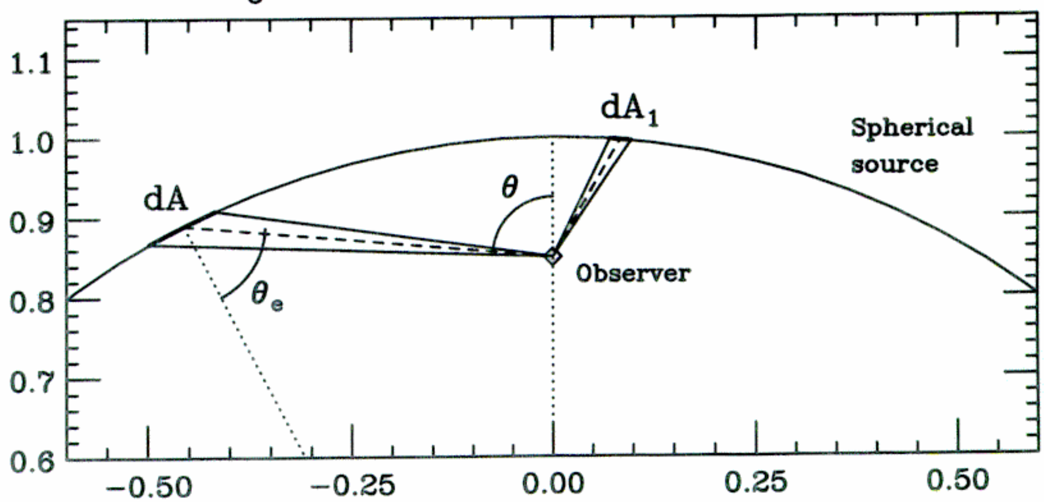
1D versus 3D Flux calculations

until recently, all atmospheric neutrino flux calculations have used the **1D approximation:**



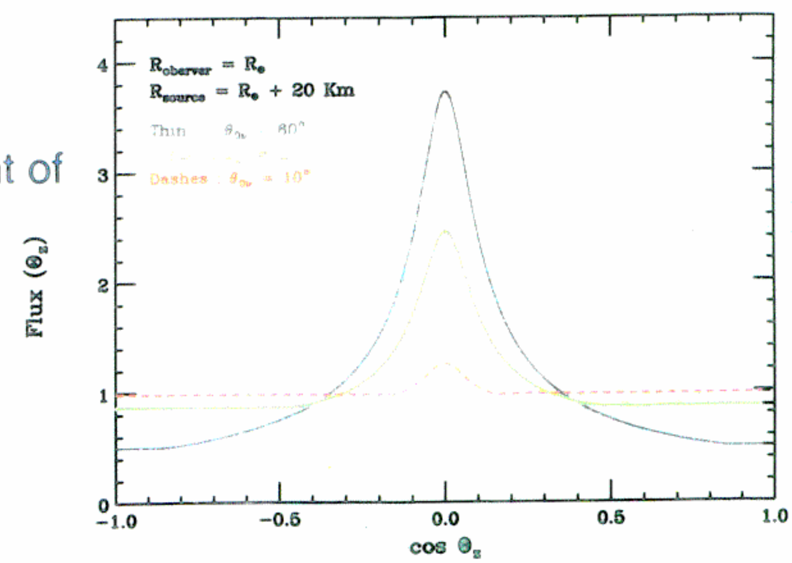
neglect transverse momentum, scattering, bending of secondaries in Earth's B-field

First attempts at 3D calculation (P.Battistoni et al. hep-ph/9907408)
uncovered geometric effect (P.Lipari hep-ph/0002282)



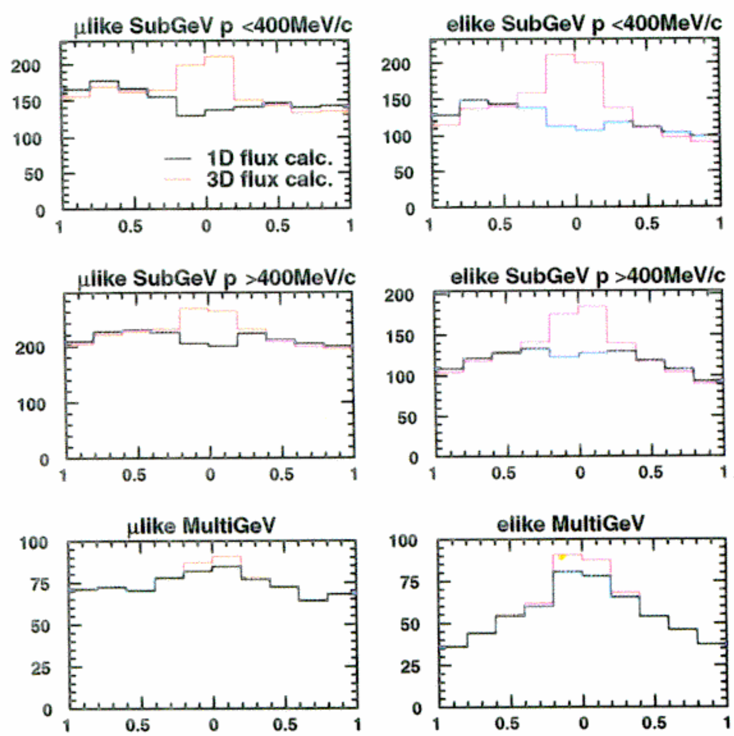
Net effect:

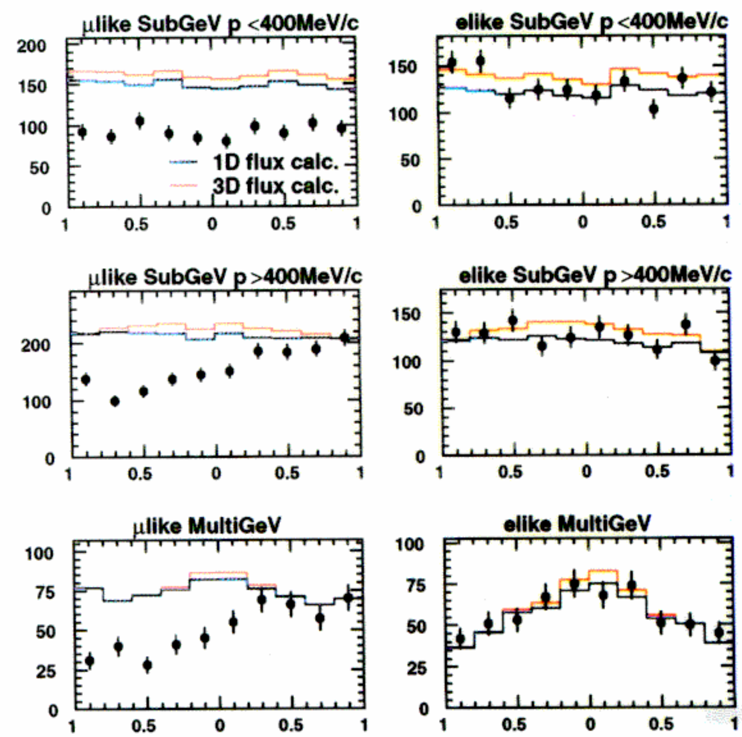
horizontal enhancement of neutrino flux



3D Calculations of Atmospheric Neutrino

Neutrino Direction → Lepton Direction



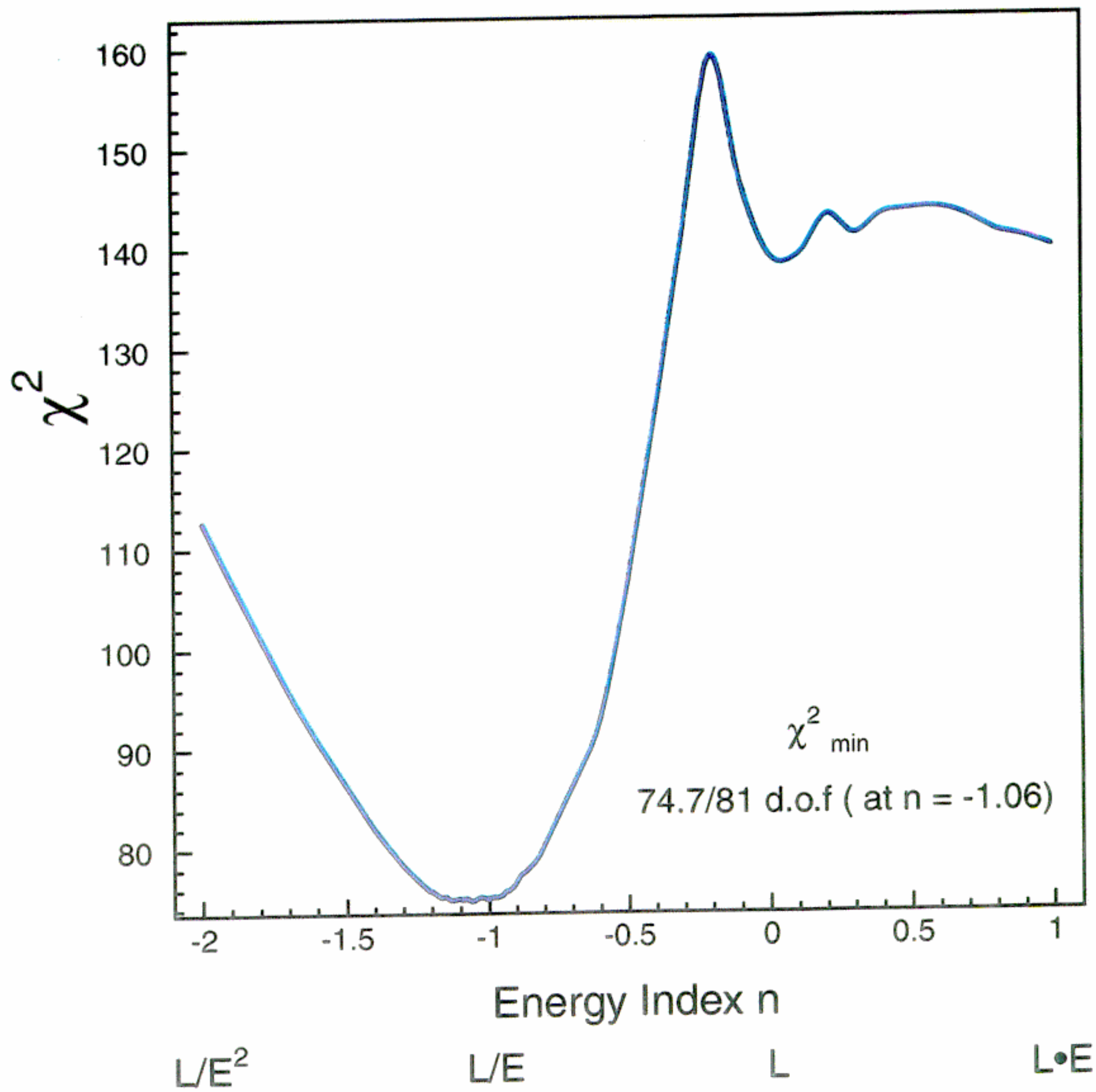


- Increase flux at low energies (P<400 MeV/c)
- 4% change in vertical/horizontal ratio (P>400 MeV/c)
- Included in oscillation fits
- Preliminary! final calculations expected soon

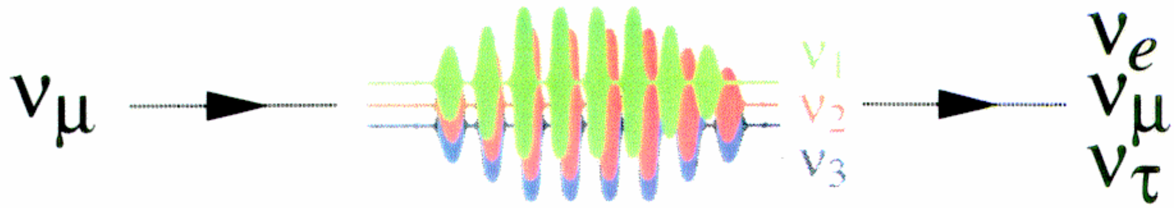
Battistoni et al. hepph/9907408
Tserkovnyak et al. hep-ph/9907450
Lipari hepph/0002282

Exotic Oscillation Forms

$$\propto \sin^2 X \frac{L}{E^n}$$

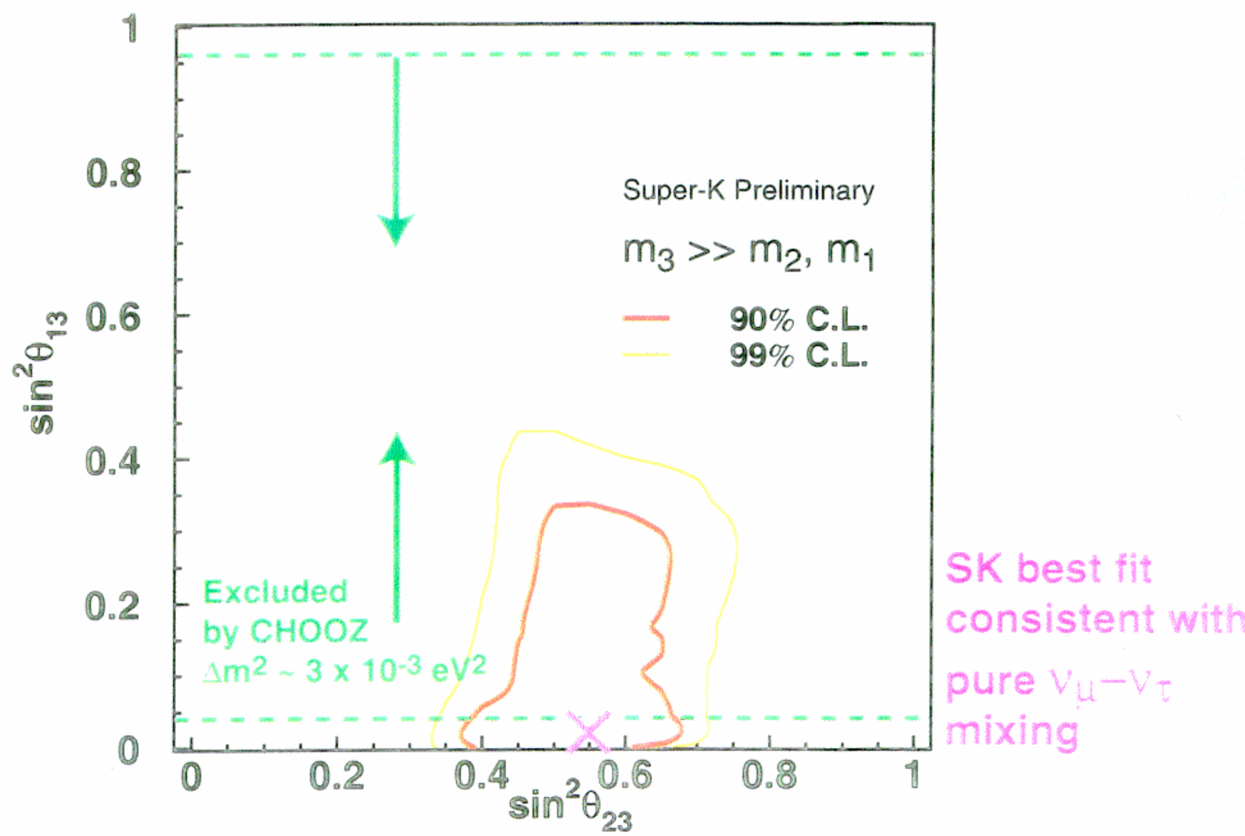


3 Flavor Oscillations



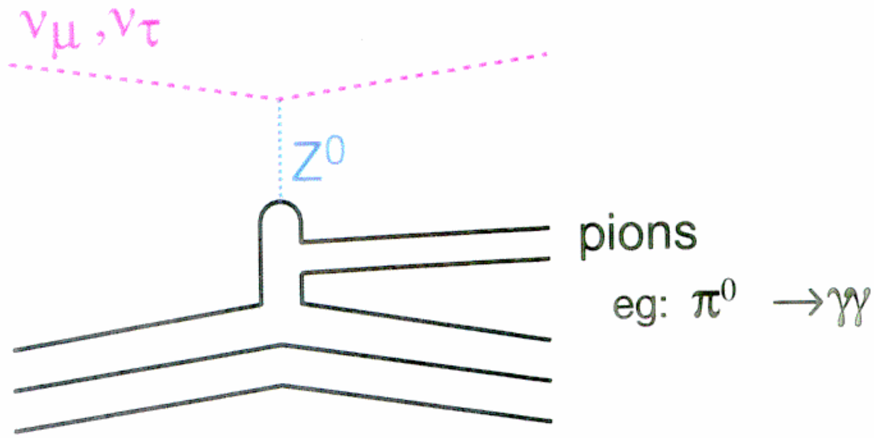
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$P_{ab} = \delta_{ab} - 4\sum_{i<j} U_{ai} U_{bj} U^*_{aj} U^*_{bi} \sin^2 \frac{1.27\, \Delta m^2_{ij} L}{E}$$

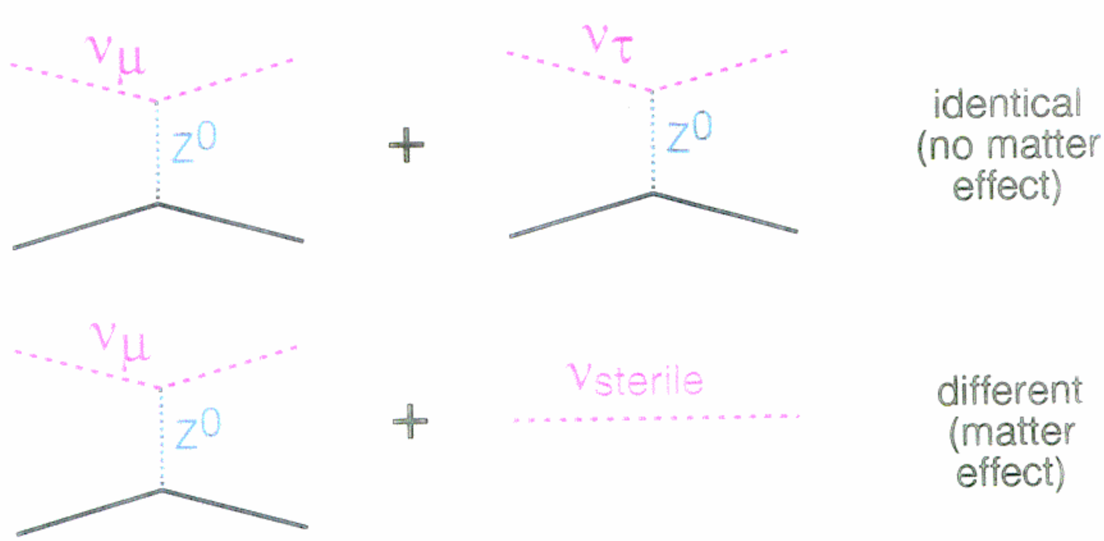


Experimental signatures to resolve ν_μ- ν_τ versus ν_μ- $\nu_{sterile}$

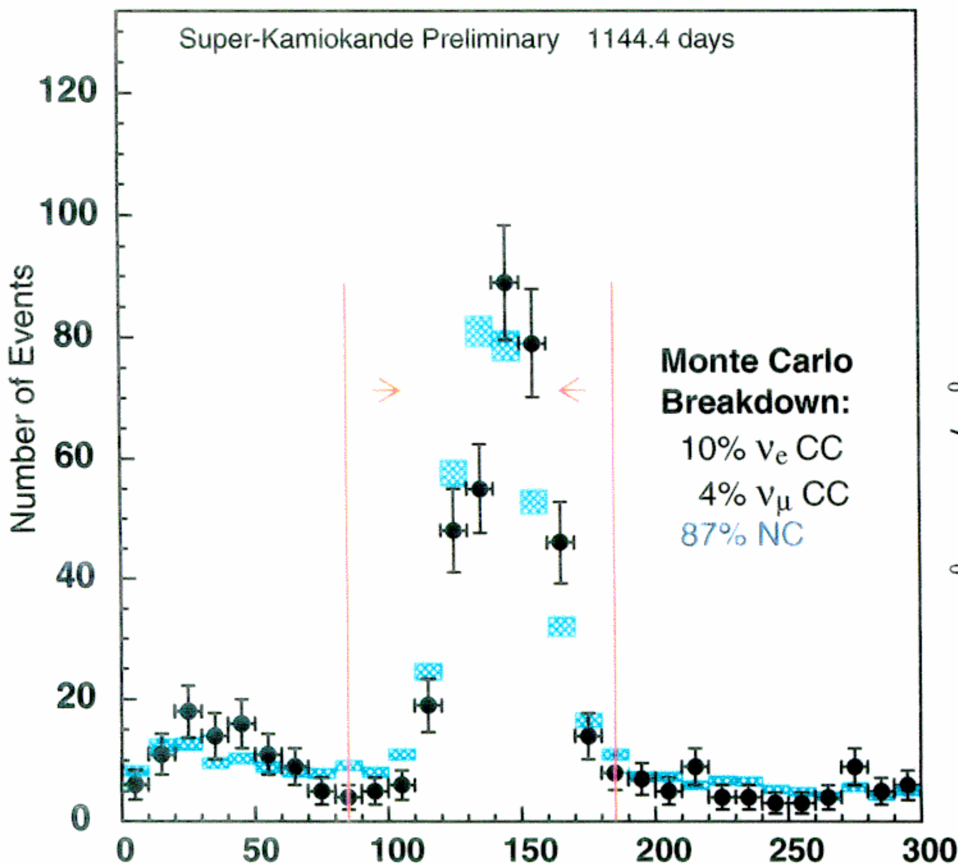
① Neutral Current: missing for ν_μ- $\nu_{sterile}$



② Matter effects: present for ν_μ- $\nu_{sterile}$



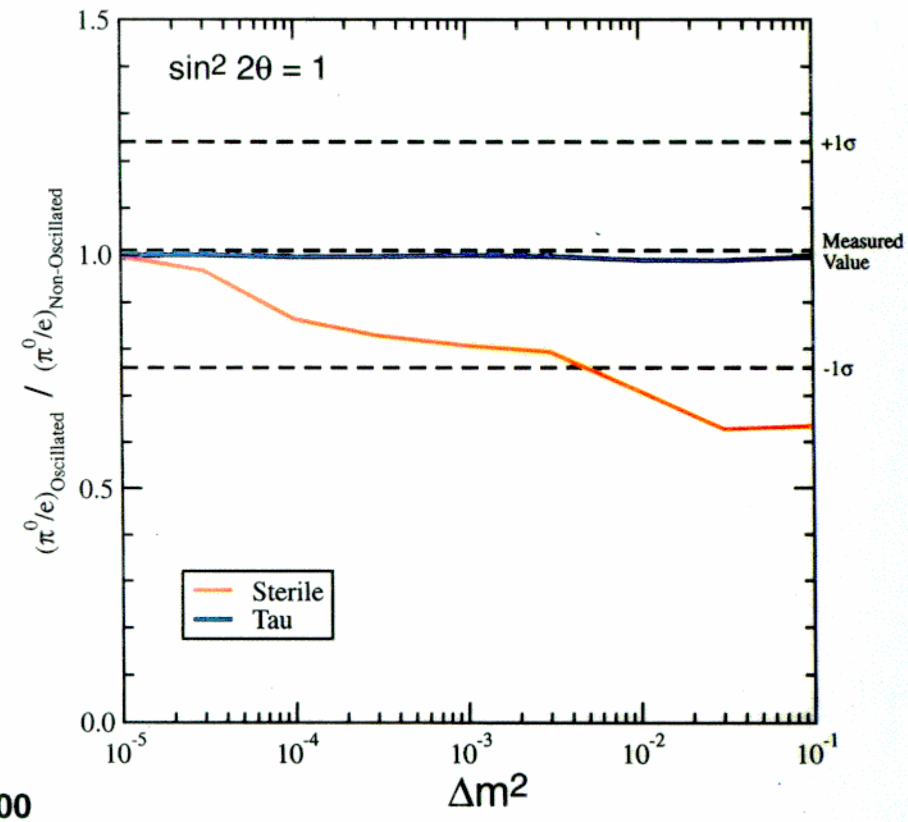
Pi-zero Events



- Two e-like rings
- no muon decay

Not used in ν_τ / ν_s ANALYSIS (yet)

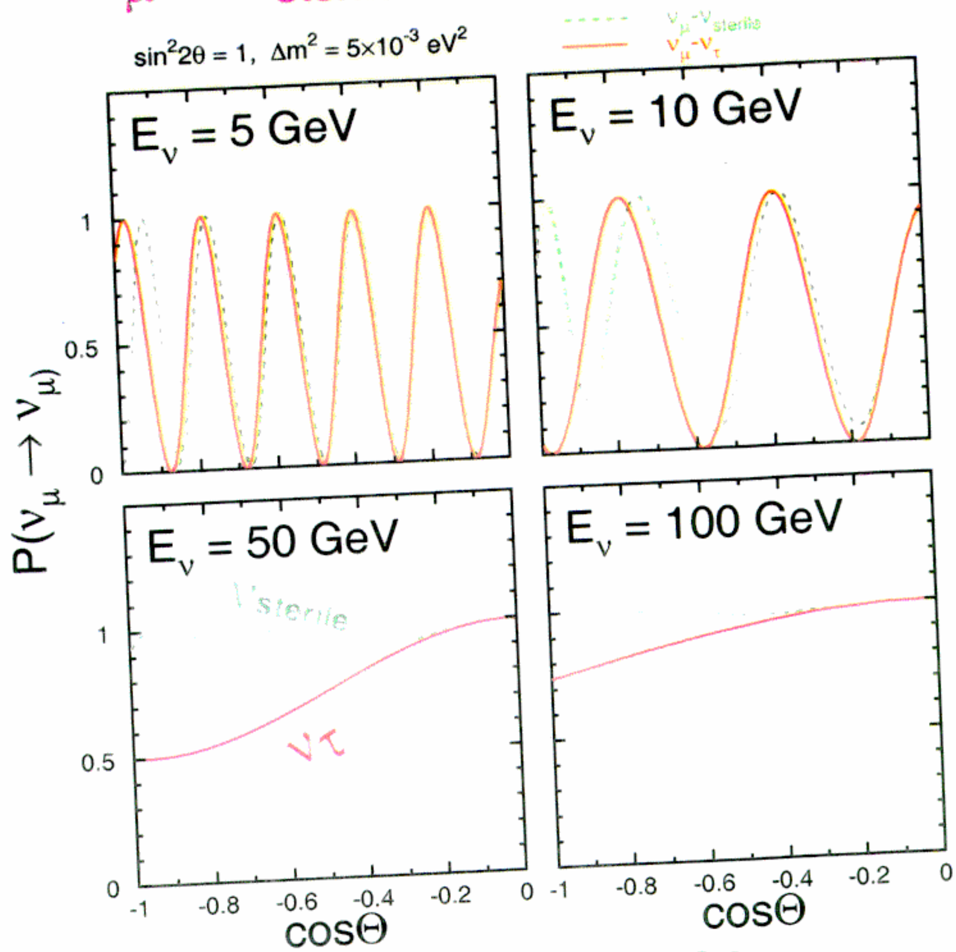
$$\frac{\pi 0}{\text{e-like}} = 1.01 \pm 0.06 \pm 0.23$$



systematic uncertainty dominated by ~20% in σ

MEASURE at K2K NEAR DETECTOR

$\nu_\mu - \nu_{sterile}$ Matter Effects



$$\sin^2 2\theta \longrightarrow \frac{\sin^2 2\theta}{(A-\cos 2\theta)^2 + \sin^2 2\theta}$$

$$\Delta m^2 \longrightarrow \frac{\Delta m^2}{\sqrt{(A-\cos 2\theta)^2 + \sin^2 2\theta}}$$

$$A = \mp \frac{\sqrt{2}\, E_\nu \cdot G_F\, n}{\Delta m^2}$$

small E_ν, $|A| \ll 1$ no matter effects → vacuum oscillation

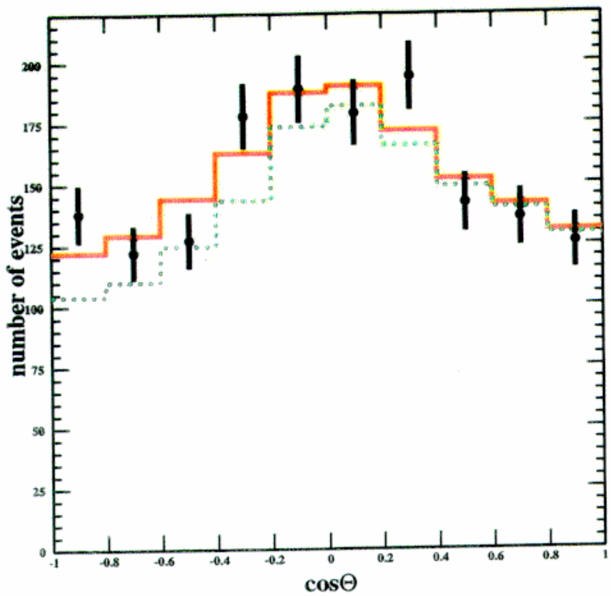
large E_ν, $|A| \gg 1$ oscillation is suppressed

$|A| \sim 1$ in earth for $E_\nu = 5$ GeV x $\Delta m^2 (10^{-3}$ eV$^2)$

Evidence that atmospheric ν oscillation is $\nu_\mu - \nu_\tau$ (solid line), not $\nu_\mu - \nu_{sterile}$ (dotted line)

T.Toshito

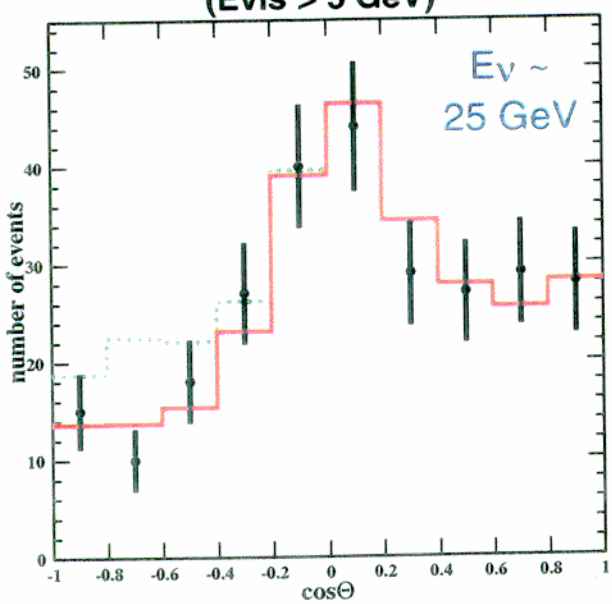
N.C. enriched multi-ring



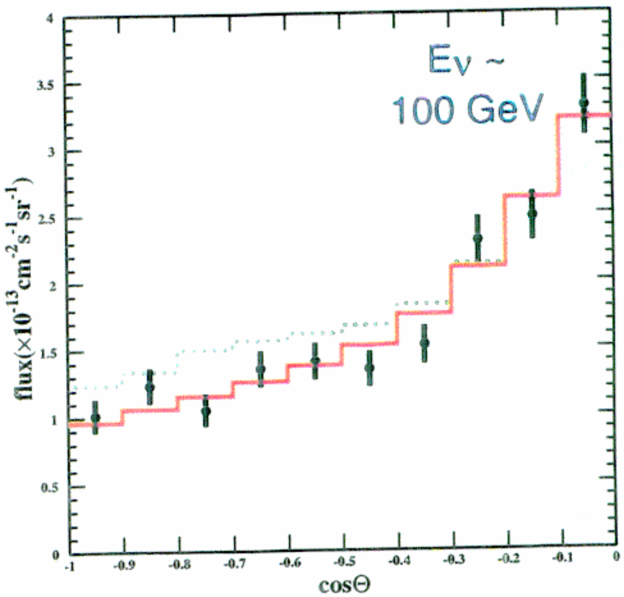
① Neutral Current Enhanced Sample

② High Energy Events with Matter Effects

Partially Contained
(Evis > 5 GeV)

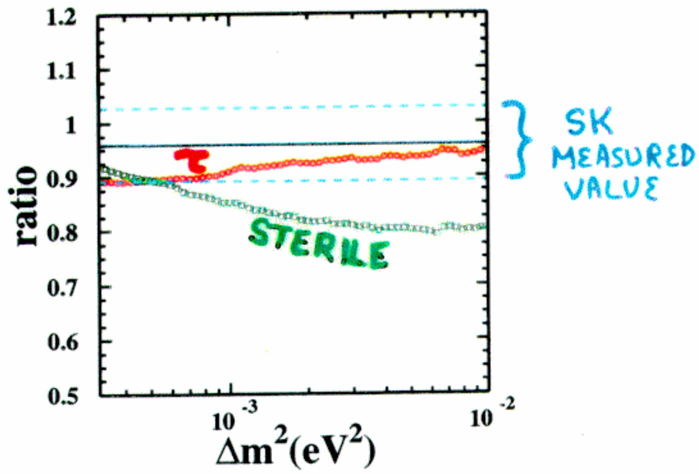


Throughgoing Up-μ

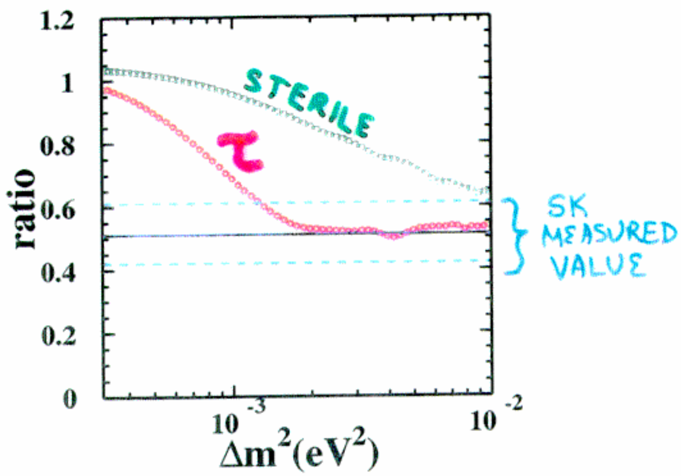


upgoing direction

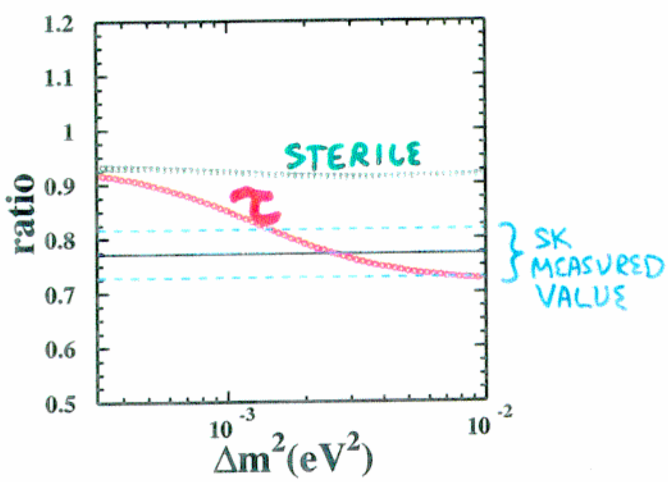
Delta-m2 Scans of test ratios



up/down multiring (N.C.)



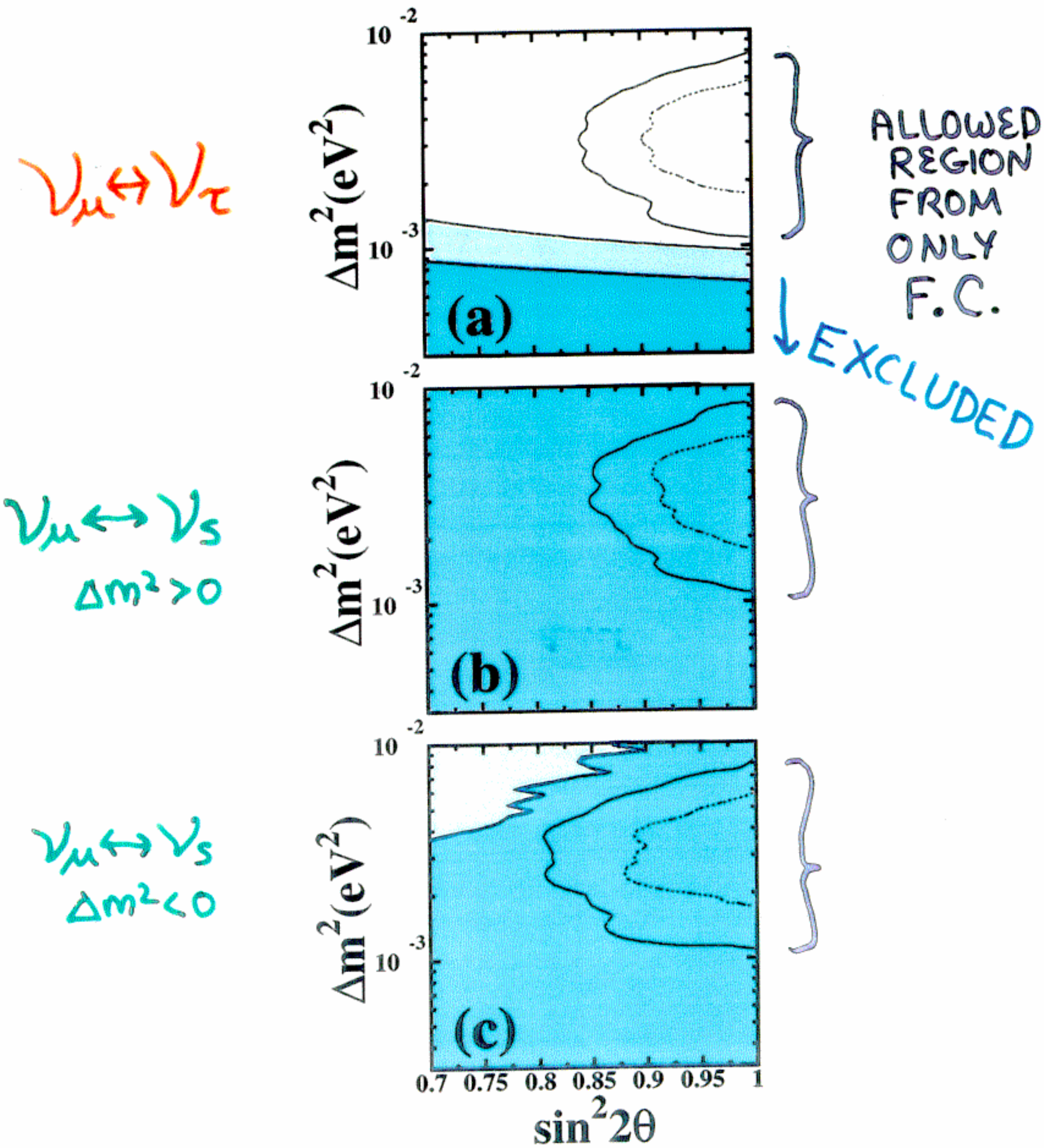
up/down P.C. (high energy)



up/horizontal through-going upmu

Ed Kearns, SSI 2000

COMBINED TEST



SUMMARY

Atmospheric ν's "scooped"
solar ν's for first solid evidence
of ν-oscillations

CROSS CHECKS
INDEPENDENT DATA SAMPLES
INDEPENDENT EXPERIMENTS
HIGH STATISTICS + LOW SYSTEMATICS

what you want in an EXPERIMENT
SOLAR HAS THEM TOO but $L_\oplus$ & E_ν
are cooperating with Δm^2 and $\sin^2 2\theta$

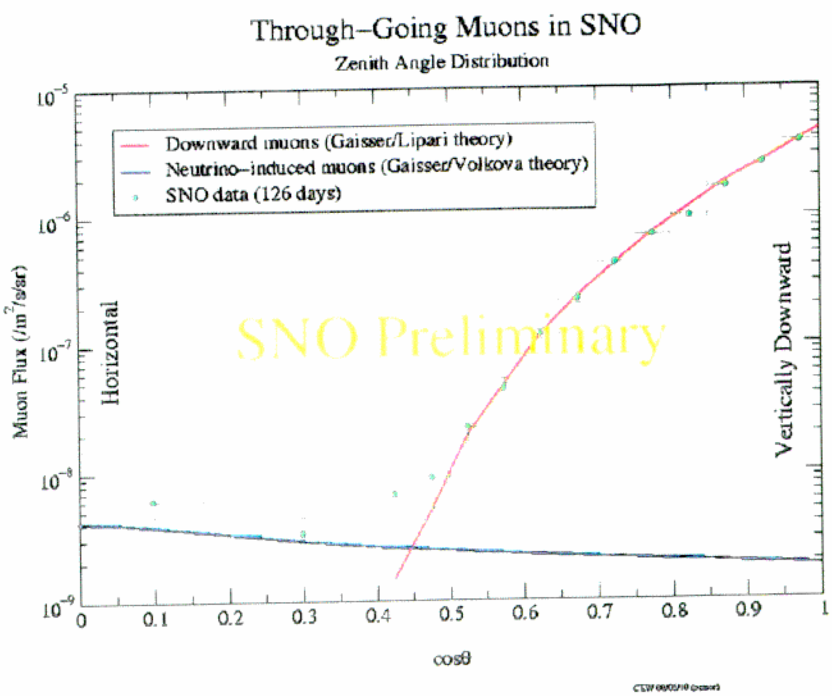
Future

- squeeze current data dry
- long baseline experiments
- future experiments

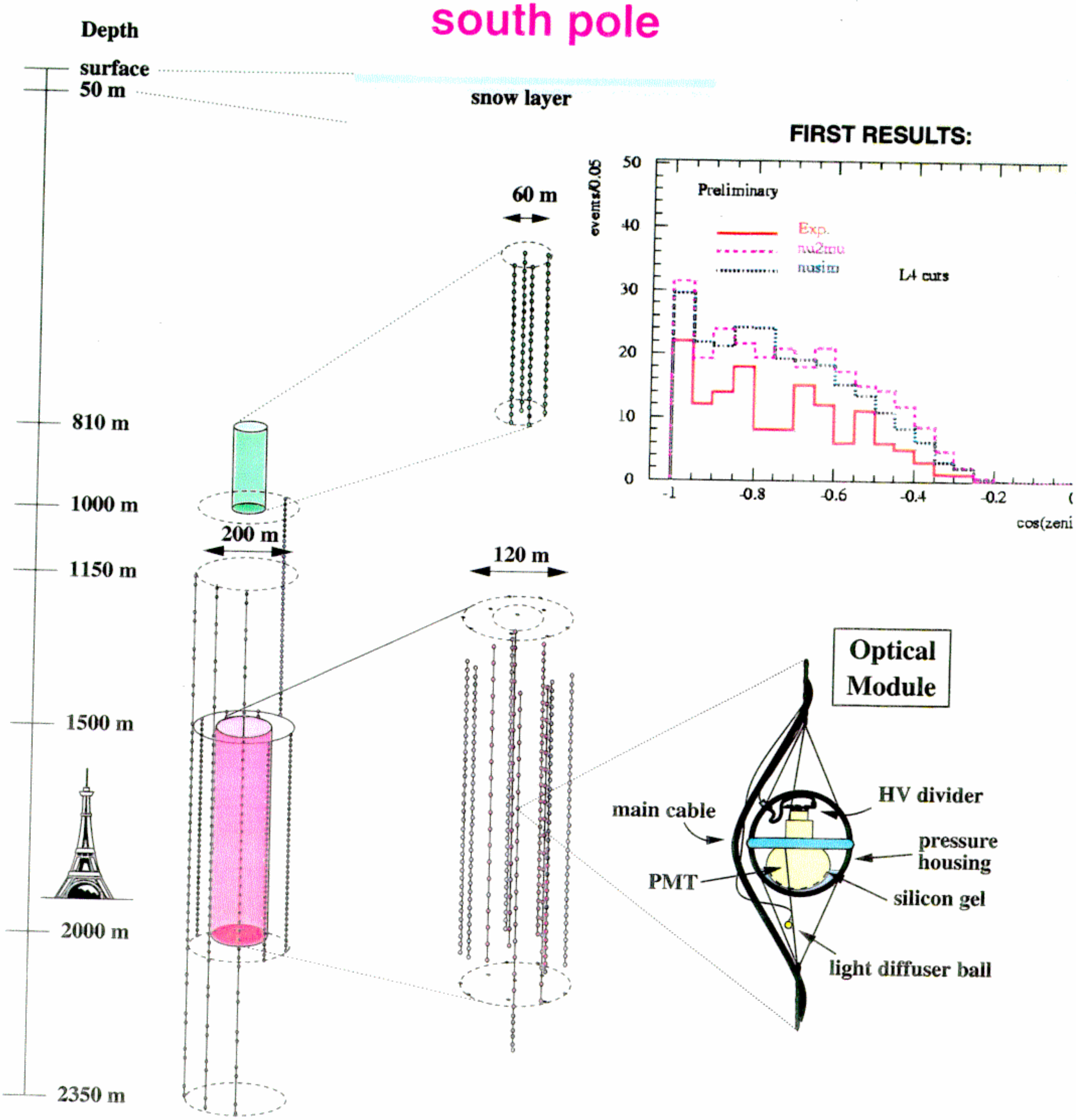
SNO

~250 atmospheric neutrino interactions per year
~200 upward-going muons per year
possibility of neutron tag

Extreme depth (2073 m) allows measurement of neutrino-induced "upward" muons above the horizon:



AMANDA
south pole

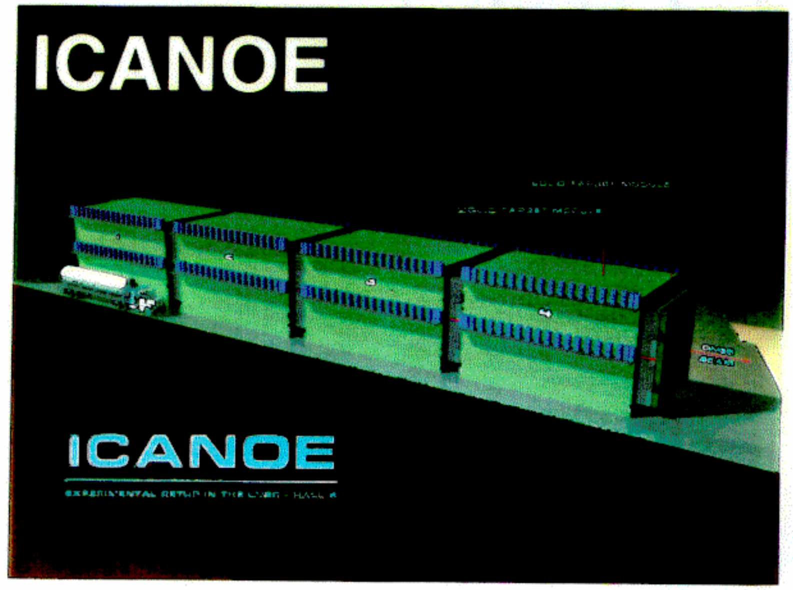


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

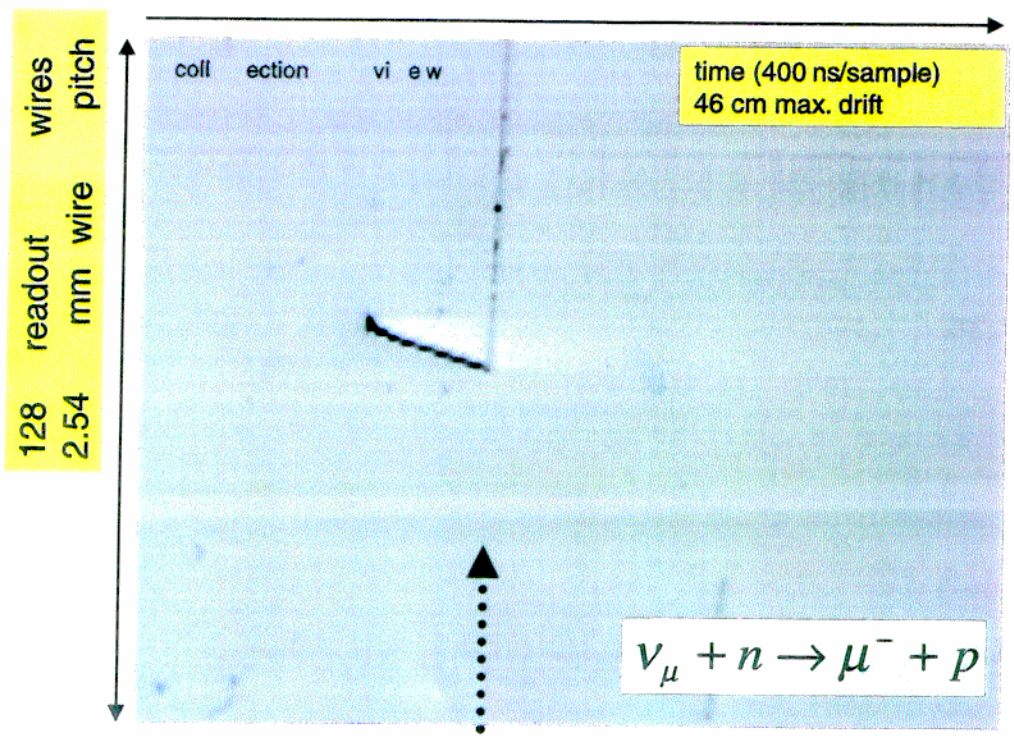
ICARUS ... ICANOE



Liquid Argon TPC

600 ton module under construction

very fine resolution
dE/dx allows K^+ identification (proton decay)

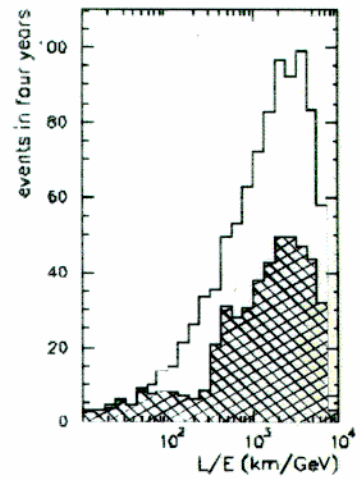


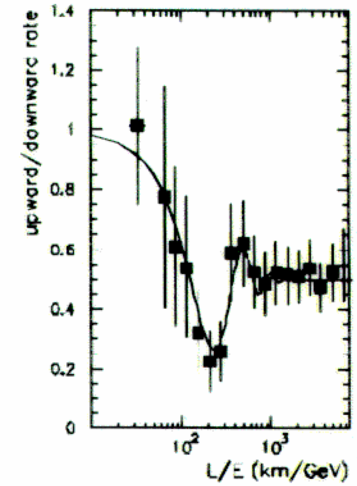
CERN ν-beam

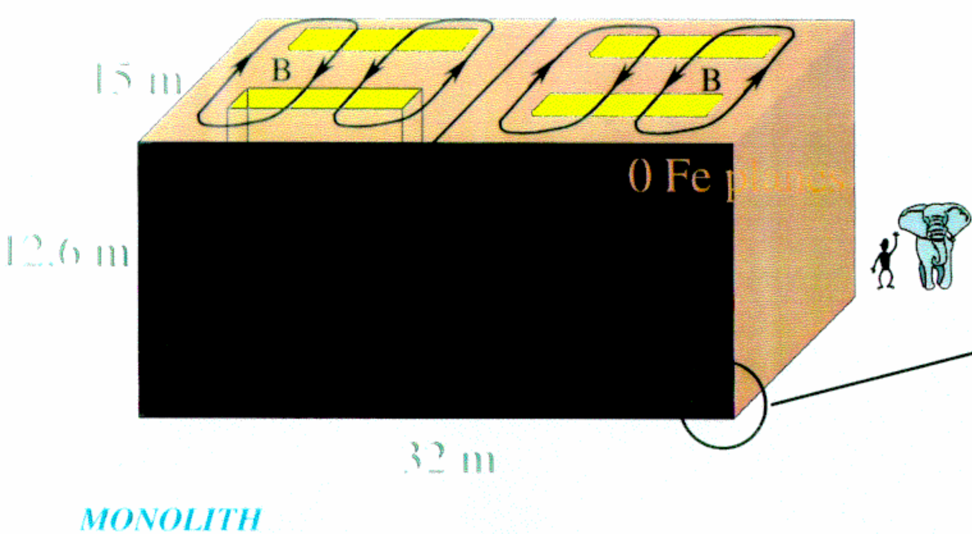
André Rubbia, ETH/Zürich, 21/6/00, Neutrino 2000

MONOLITH

Massive detector ~ 35 kton
Momentum resolution $\sigma_p/p \sim 15\%$
with B=1.3 Tesla







~58000 m^2 of detector
Glass Spark Counters