大気ニュートリノによるニュートリノ振動の測定

16-May-2001

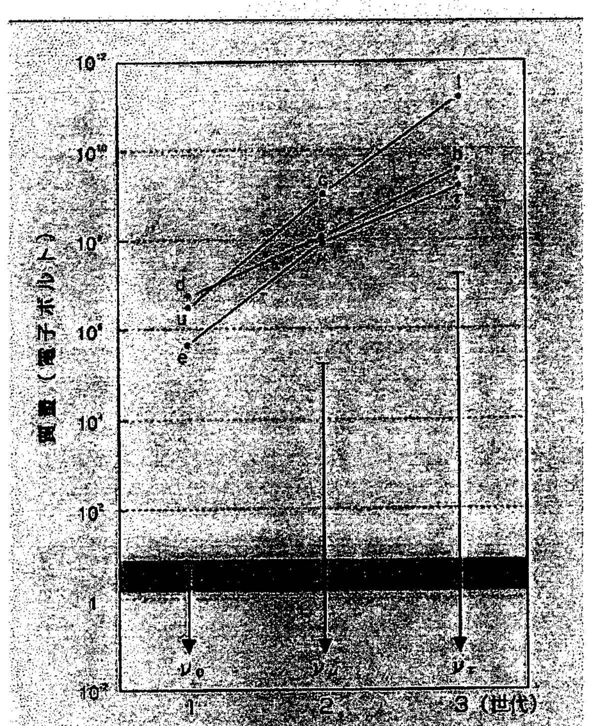
東大宇宙線研(ICRR)
奥村公宏

Outline

- Super-Kamiokande atmospheric neutrino 1289days data
- Neutrino oscillation analysis
  - two flavor $\nu_\mu \Leftrightarrow \nu_\tau$
  - three flavor analysis
  - Sterile neutrino
  - Exotic neutrino oscillation
  - Tau neutrino search

Introduction to neutrino

- One of the fundamental particles
- Three flavor exist （ν_e, ν_μ, ν_τ）
- Interacts only through weak current
  possible detection with large matter
- Characteristics do not well known
  Dirac or Majorana type ?
- Very light and existence of mass had not been confirmed



レプトンとクォークの質量を世代毎に示した図。ニュートリノの質量は、直接測定実験から上限だけがわかっています。宇宙論からもニュートリノの質量の上限が与えられています。

Neutrino oscillation

- If neutrinos are massive…

$$|\nu_l\rangle = \sum U_{lm} |\nu_m\rangle \qquad |\nu_l\rangle \; : \nu_e, \nu_\mu, \nu_\tau$$

$$|\nu_m(t)\rangle = e^{-i\frac{M_m^2}{2E_\nu}t} |\nu_m(0)\rangle \qquad |\nu_m\rangle \; : \nu_1, \nu_2, \nu_3$$

flavor oscillation occurs

- Oscillation probability (2 flavor case)

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

θ : mixing angle

$\Delta m^2 = m_3^2 - m_2^2$

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

Neutrino oscillation experiments

- Accelerator

  $P \rightarrow \pi \rightarrow \mu + \nu_\mu \cdots \nu_x, \nu_e$

  LSND, Karmen2, K2K

- Reactor

  anti-$\nu_e \rightarrow \nu_x$ $\langle E\nu \rangle \sim 3$MeV

  CHOOZ, Palo Verde

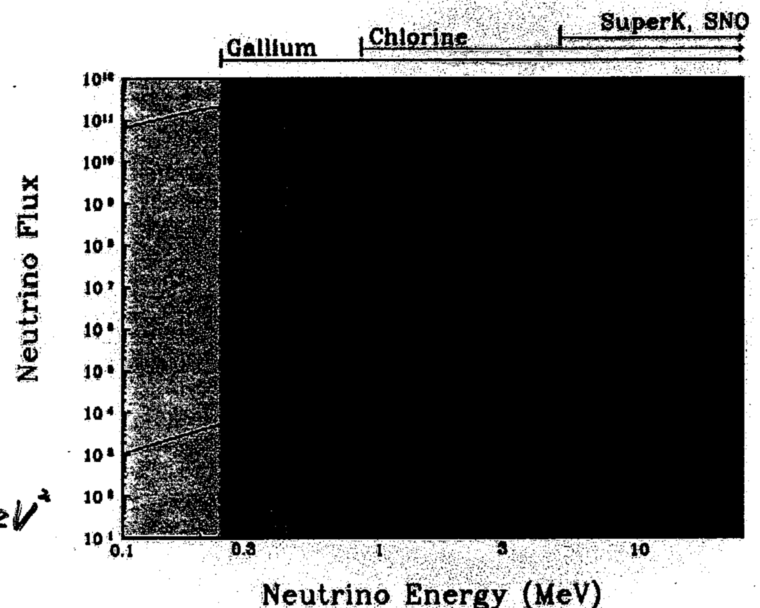
- Solar neutrino

  $\nu_e \rightarrow \nu_x$ $E_\nu < 10$MeV

  Homestake, Gallex, Super-K, SNO

  $E_\nu < 10$MeV $L \sim 10^8$km $10^{-10} < \Delta m^2 < 10^{-4}$eV^2

- Atmospheric neutrino

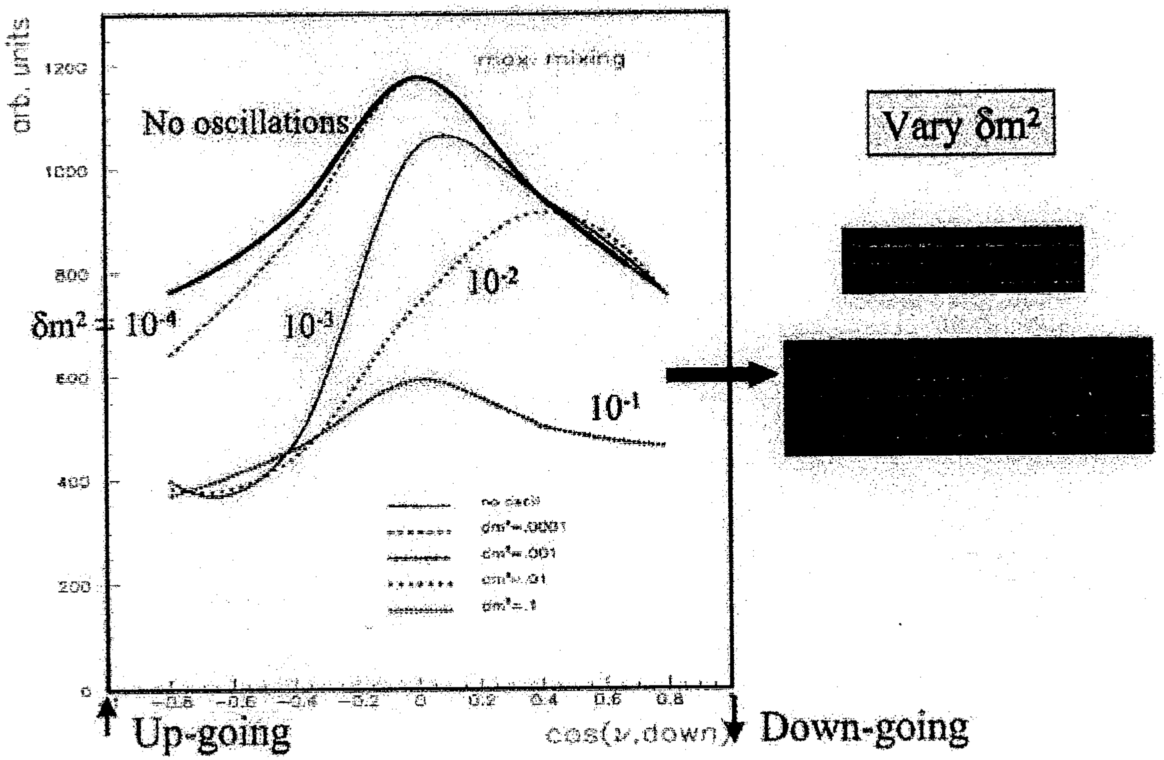


Energy spectrum of solar ν

J.N.Barcall http://www.sns.ias.edu/jnb/

If neutrino oscillation exists

- ν_μ/ν_e flux ratio and zenith angle distribution will differ from expected



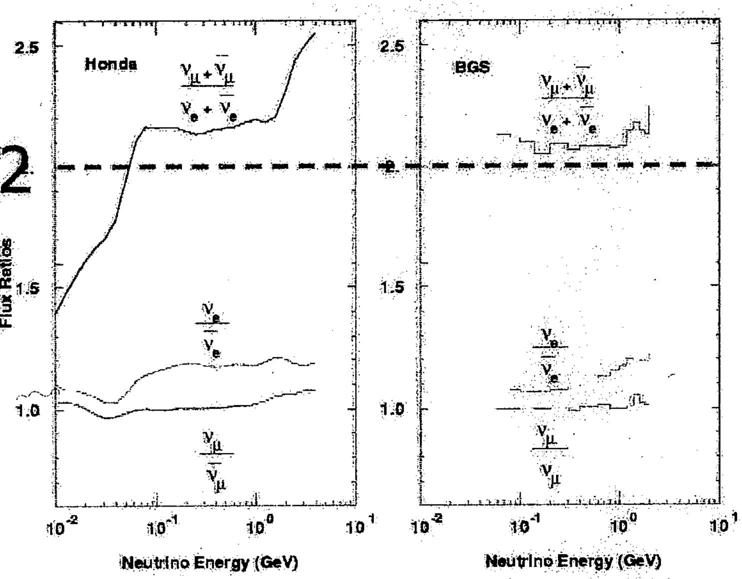
Atmospheric neutrino

Pr[redacted]here
[redacted]klet

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow \; e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow \; e^- + \bar{\nu}_e + \nu_\mu$$

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

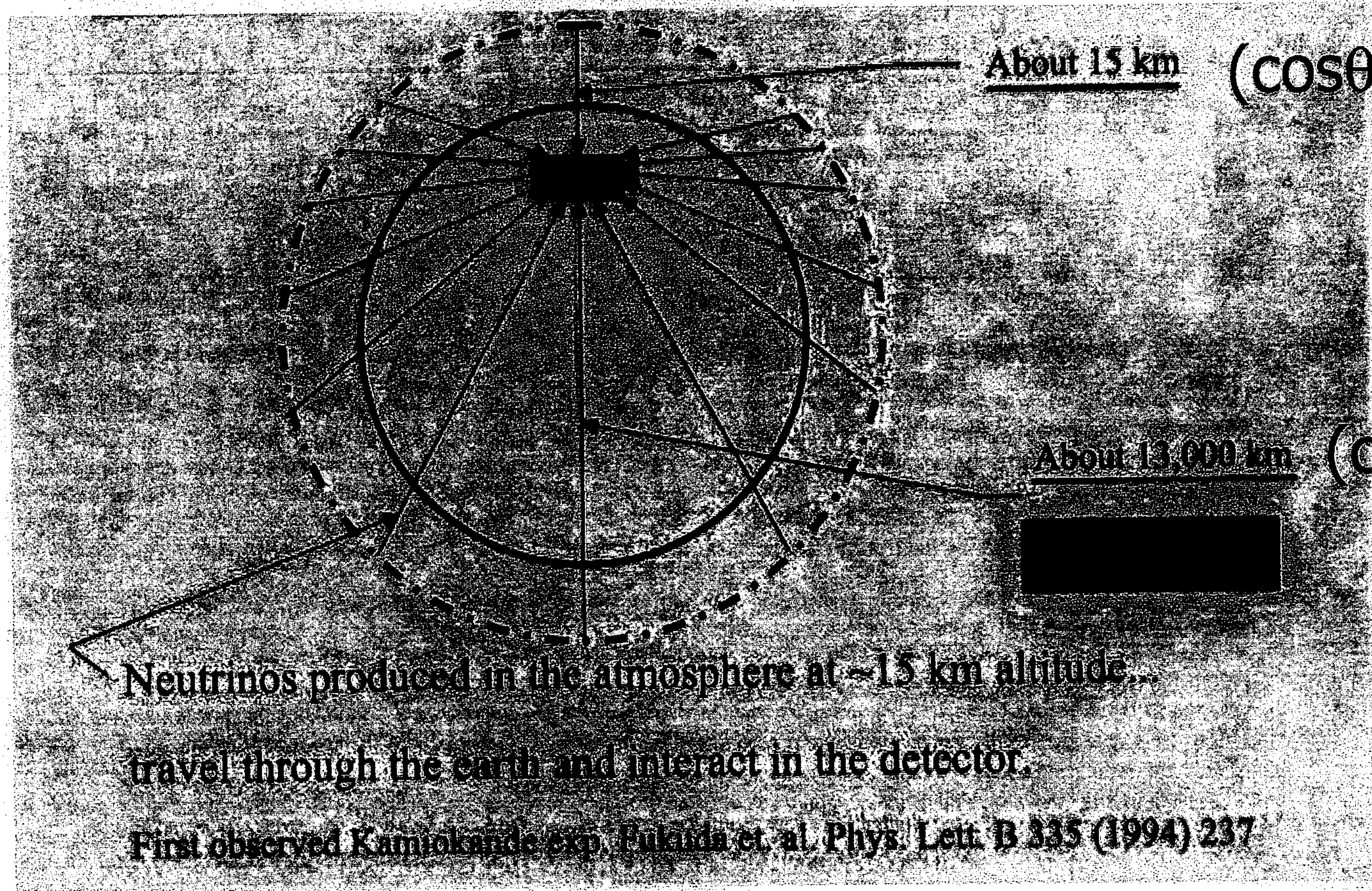
ν_μ/ν_e ratio



M.Honda et al., Phys.Lett. (1990)

- Secondaries from interaction of primary cosmic ray and atmosphere
- $<E_\nu>$~1GeV   flux $\propto E_\nu^{-\gamma}$ $\gamma \sim 2.7$
- ν_μ/ν_e flux ratio ~ 2
  - uncertainty ~5%
  - ratio increase at Eν>1GeV

Zenith angle of atmospheric ν

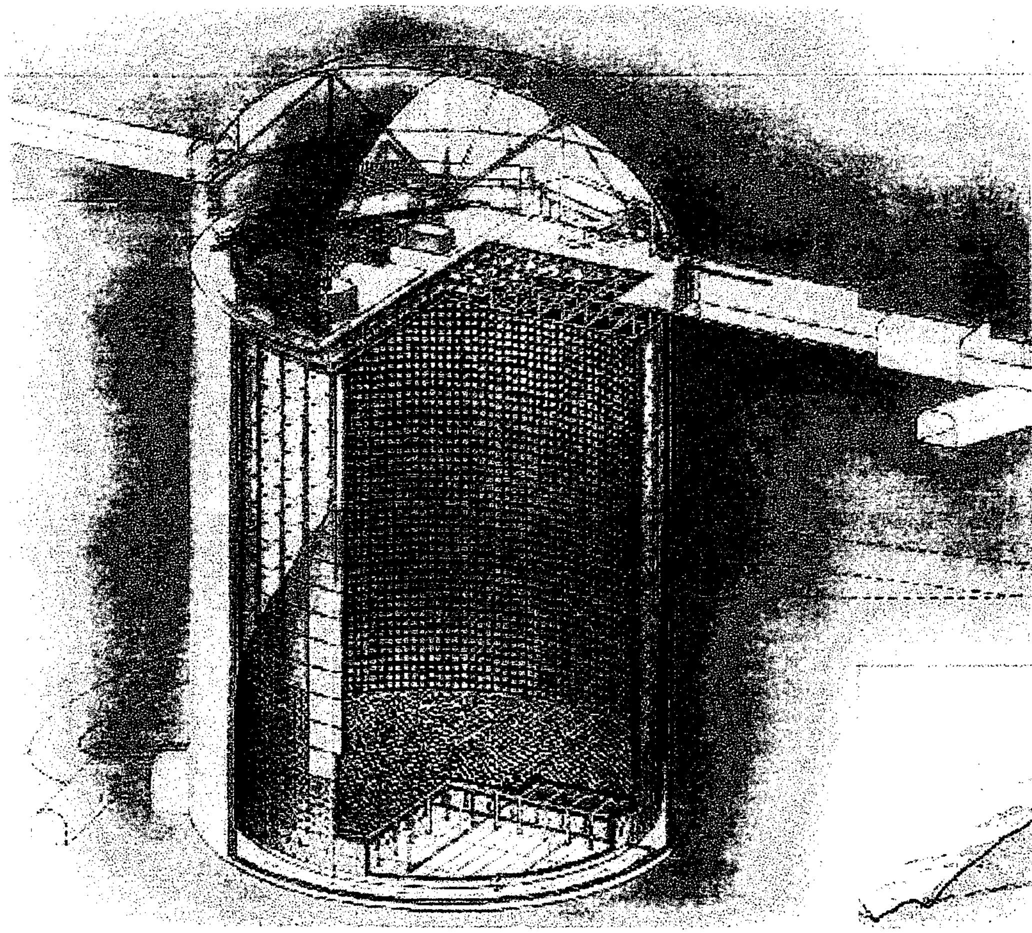


(cosθ=1)

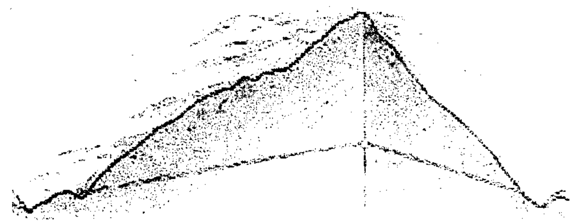
θ：天頂角

(cosθ=-1)

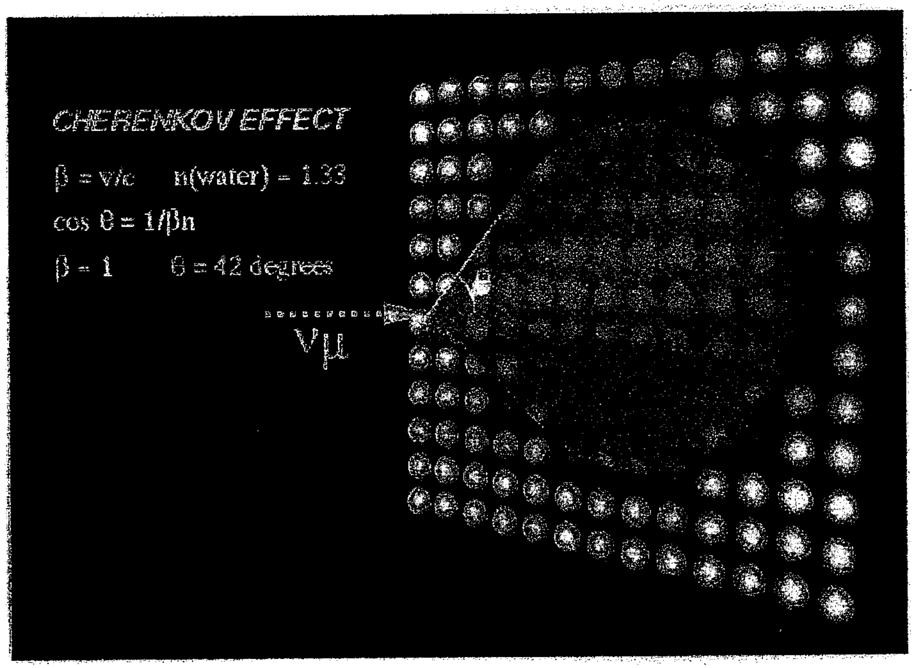
Super-Kamiokande detector



- Water cherenkov detector
- ~40m in height and diameter
- 50.0kt Pure Water
- 22.5kt Fid.Vol.
- 11146 PMTs for ID
- 1885 PMTs for OD
- 1000m UnderGround (2700m.w.e.)
- Operation started in Apr. 1996

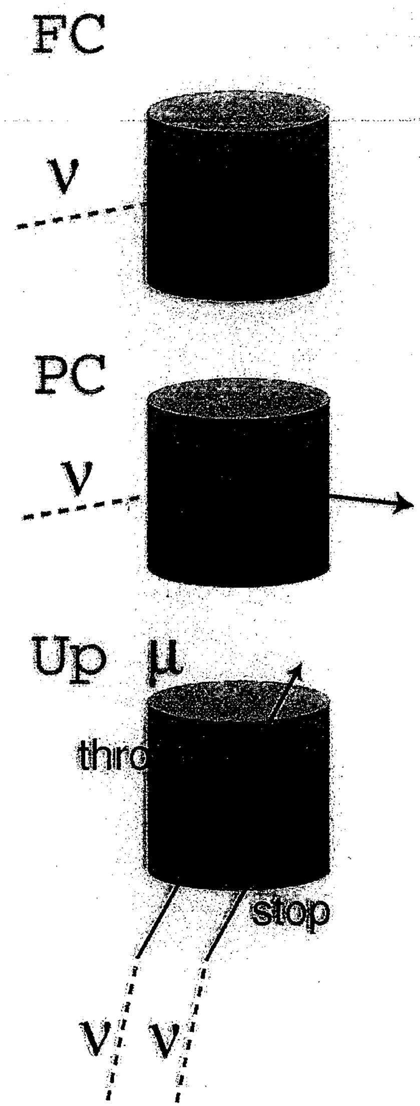


Detection method



- Charged particle emits cherenkov light in water and produce ring image
- Cherenkov opening angle
  42° for β=1
- Cherenkov image gives
  - energy from charge
  - vertex from timing and ring shape
  - particle ID from image pattern

Event Categories

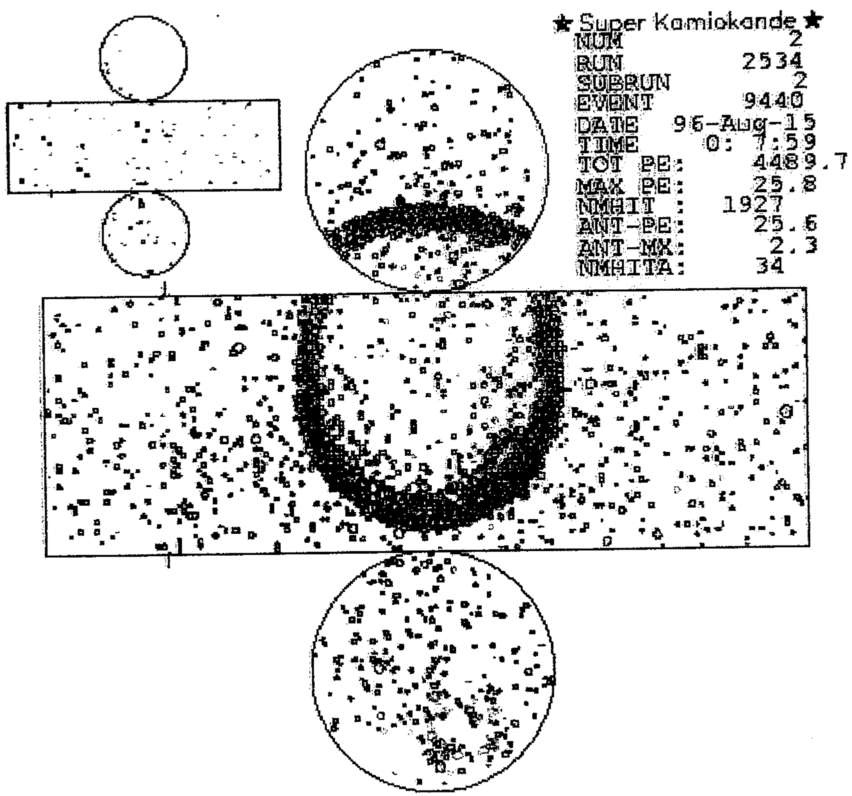


- Fully Contained (FC)
  - ν_μ CC, ν_e CC, NC
  - $\langle E_\nu \rangle \sim 1$GeV
- Partially Contained (PC)
  - ν_μ CC
  - $\langle E_\nu \rangle \sim 10$GeV
- Upward Going Muon (Upμ)
  - ν_μ CC
  - $\langle E_\nu \rangle \sim 10$GeV (Stop μ)

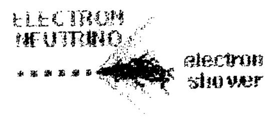
    ~ 100GeV (Through μ)

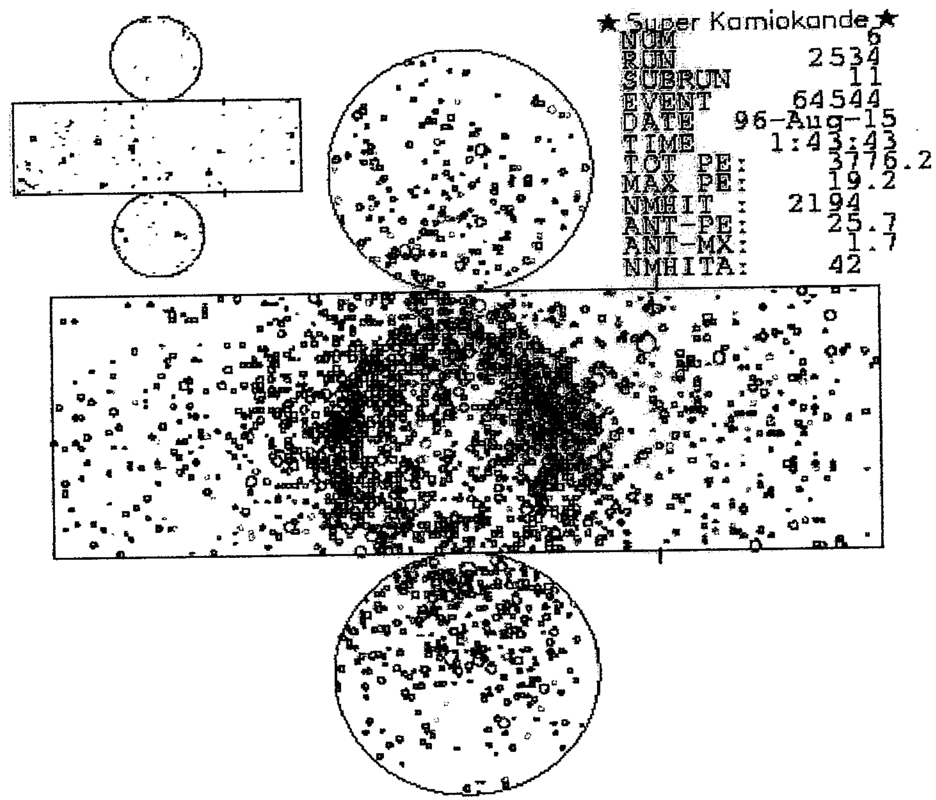
Fully-contained (FC) events

FC μ-like
(Non-EM shower)

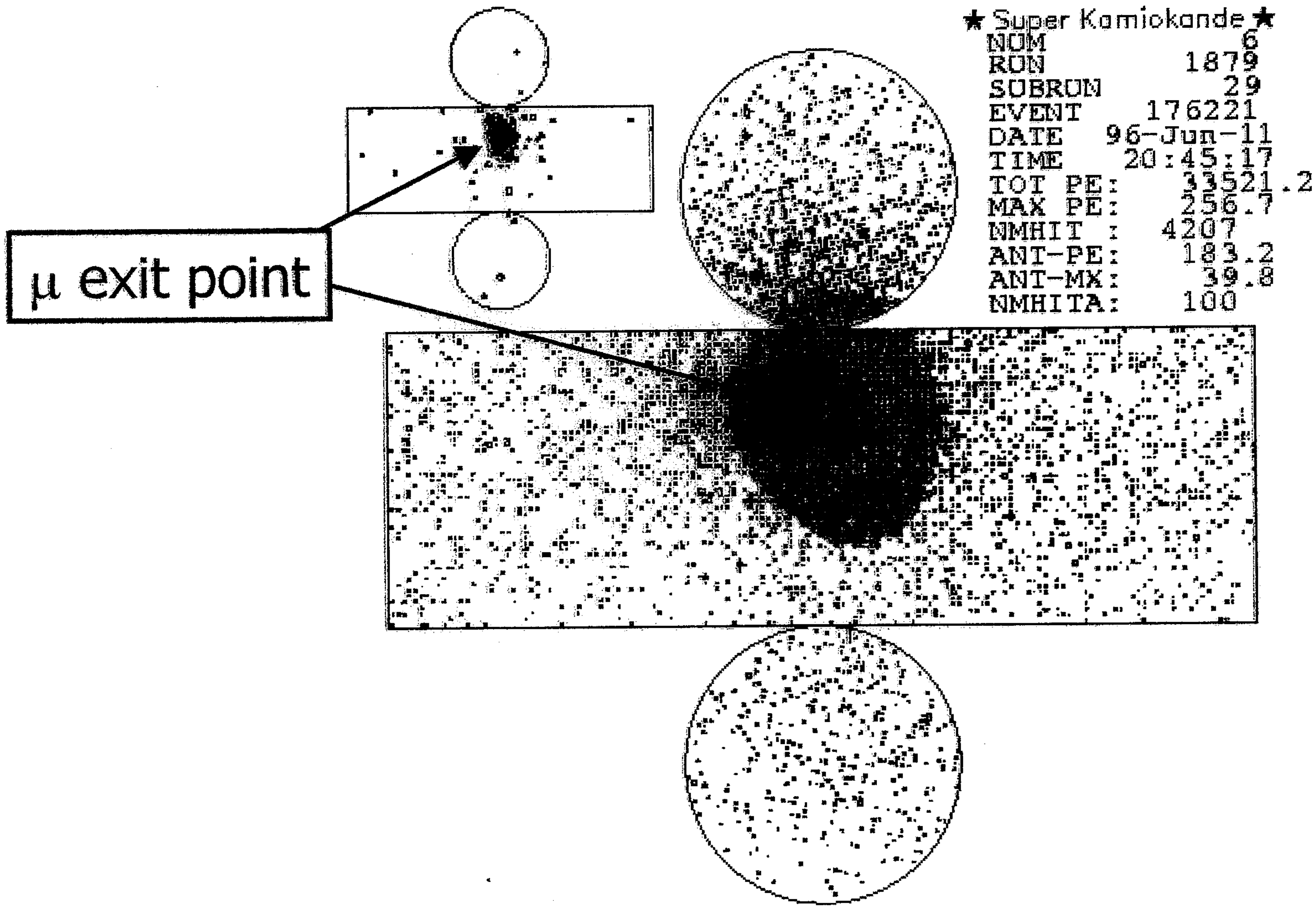


FC e-like
(EM shower)

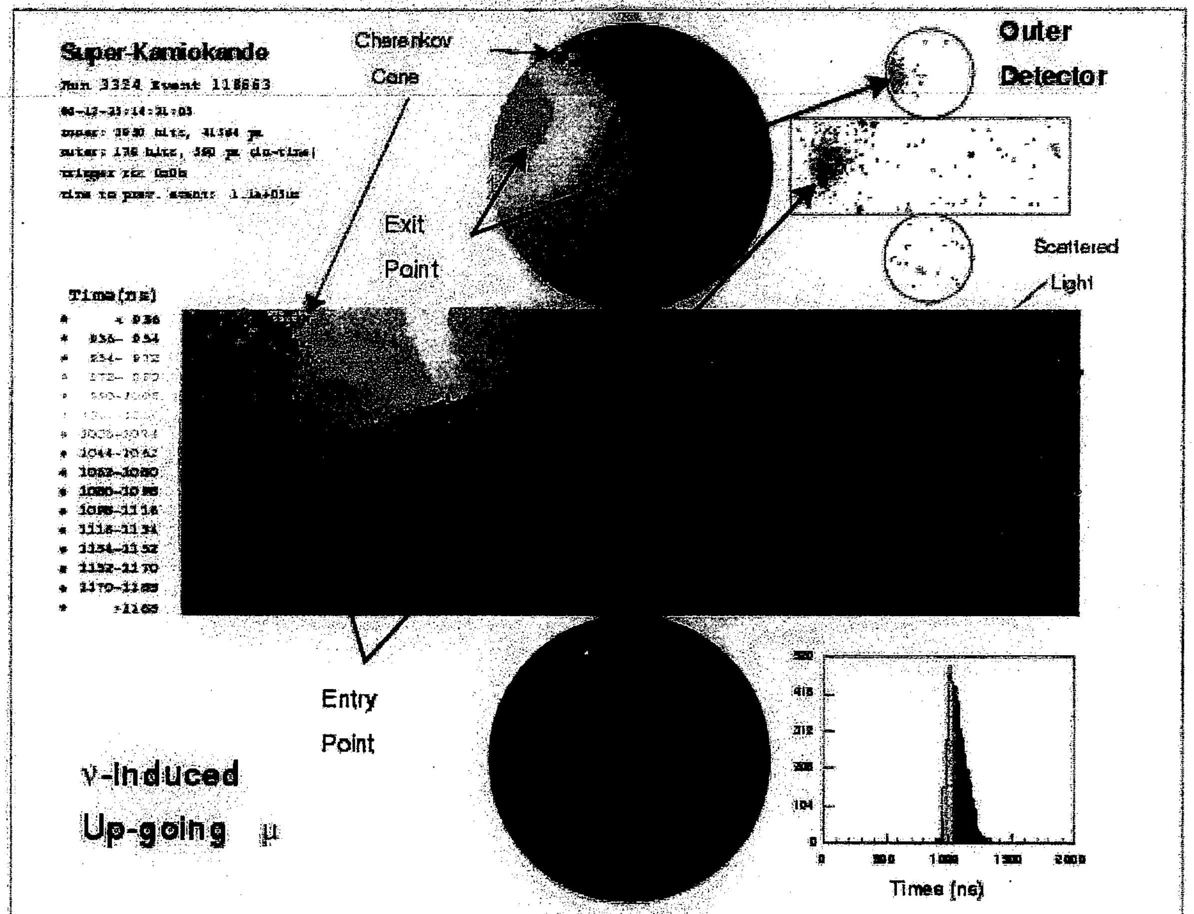




Partially-contained (PC) event



Upward-going muon event



Observed Events (SK 1289day)

- Sub-GeV (Evis<1.33GeV)

FC	DATA	MC
single ring	5652	6740.4
e-like	[illegible]	[illegible]
μ-like	[illegible]	[illegible]
multi ring	2159	2585.1
TOTAL	7811	9325.5

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.638 \; {}^{+0.017}_{-0.017}\,{}^{\text{stat.}} \; \pm 0.050\,{}^{\text{syst.}}$$

- Multi-GeV (Evis>1.33GeV)

FC	DATA	MC
single ring	1184	1451.1
e-like	626	612.8
μ-like	[illegible]	838.0
multi ring	1318	1648.1
TOTAL	2502	3099.1
PC	754	1065.0

$$\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.675 \; {}^{+0.034}_{-0.032}\,{}^{\text{stat.}} \; \pm 0.080\,{}^{\text{syst.}}$$

Up μ observed events

- Upward-Thru μ (Livetime 1138days) *(flux unit : $cm^{-2}s^{-1}sr^{-1}$)*

Events	1269
Observed flux	$(1.70 \pm 0.05 \pm 0.02) \times 10^{-13}$
Expected flux	$(1.81 \pm 0.44) \times 10^{-13}$

- Upward-Stop μ (Livetime 1117days)

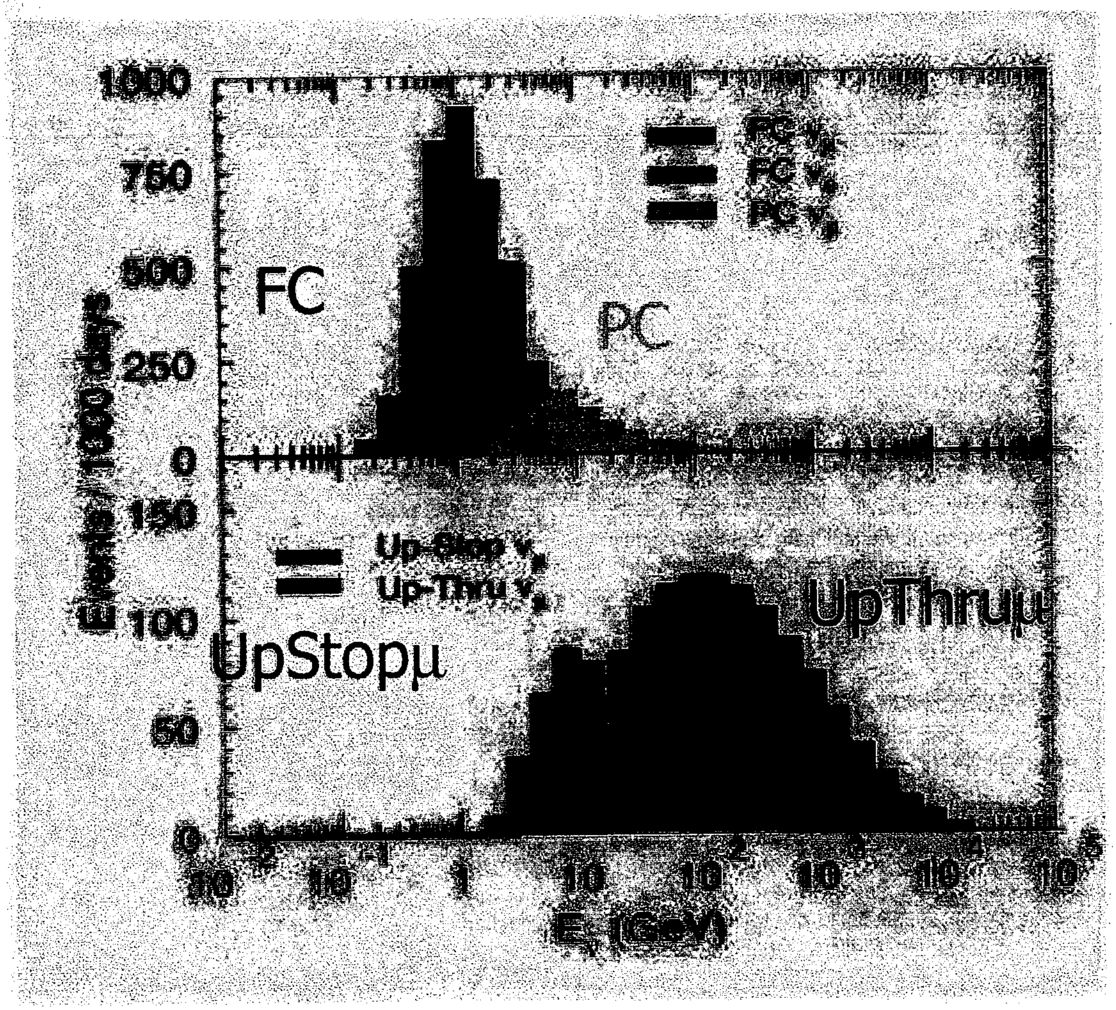
Events	311
Observed flux	(0.41 ± 0.0[illegible] ± 0.02) x10^-13
Expected flux	$(0.68 \pm 0.15) \times 10^{-13}$

- Stopμ/Thruμ Ratio

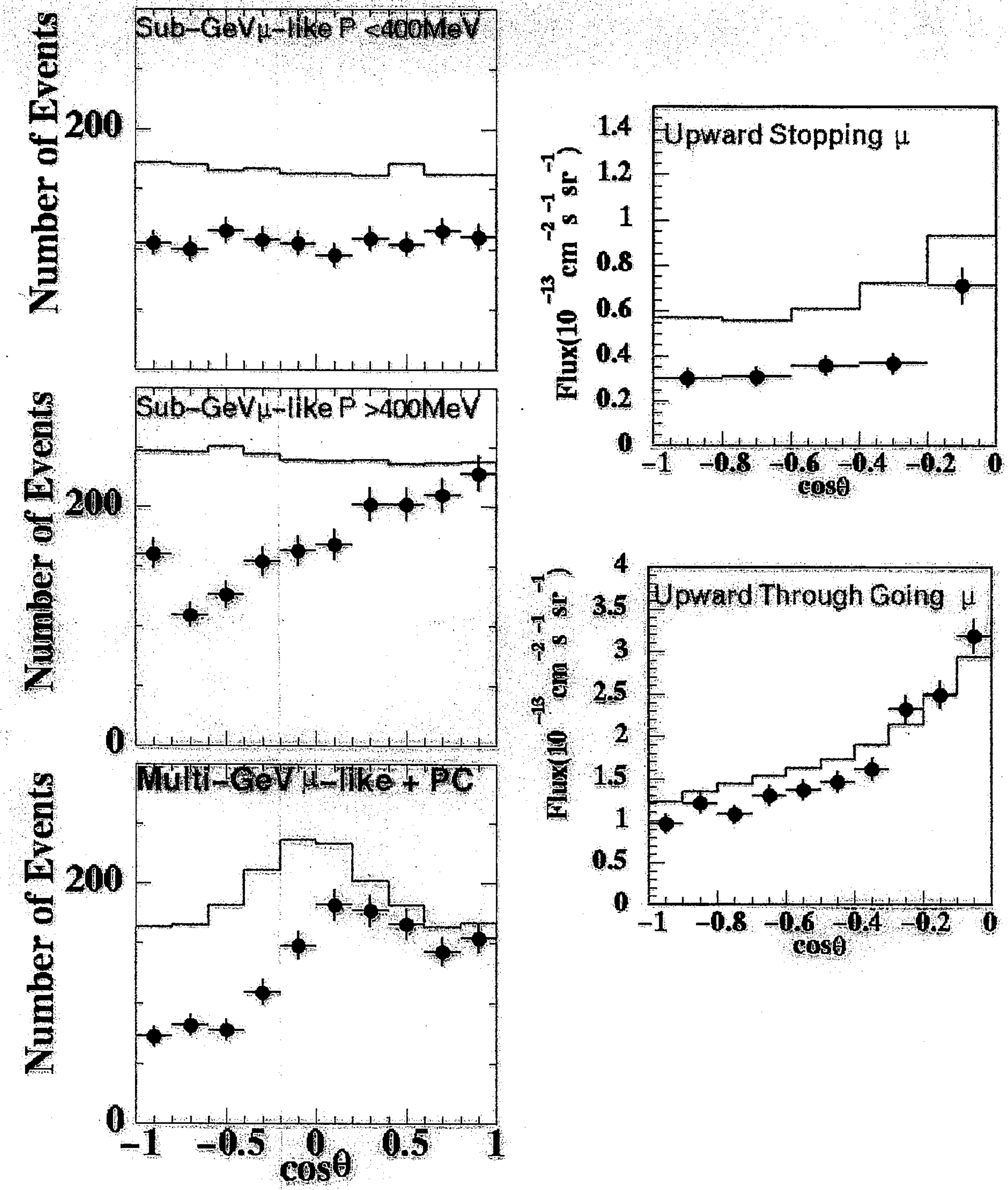
$$0.242 \pm 0.017^{stat.} {}^{+0.013}_{-0.011}{}^{syst.}$$ (Observed)

$$0.368 {}^{+0.049}_{-0.044}{}^{theo.}$$ (Expected)

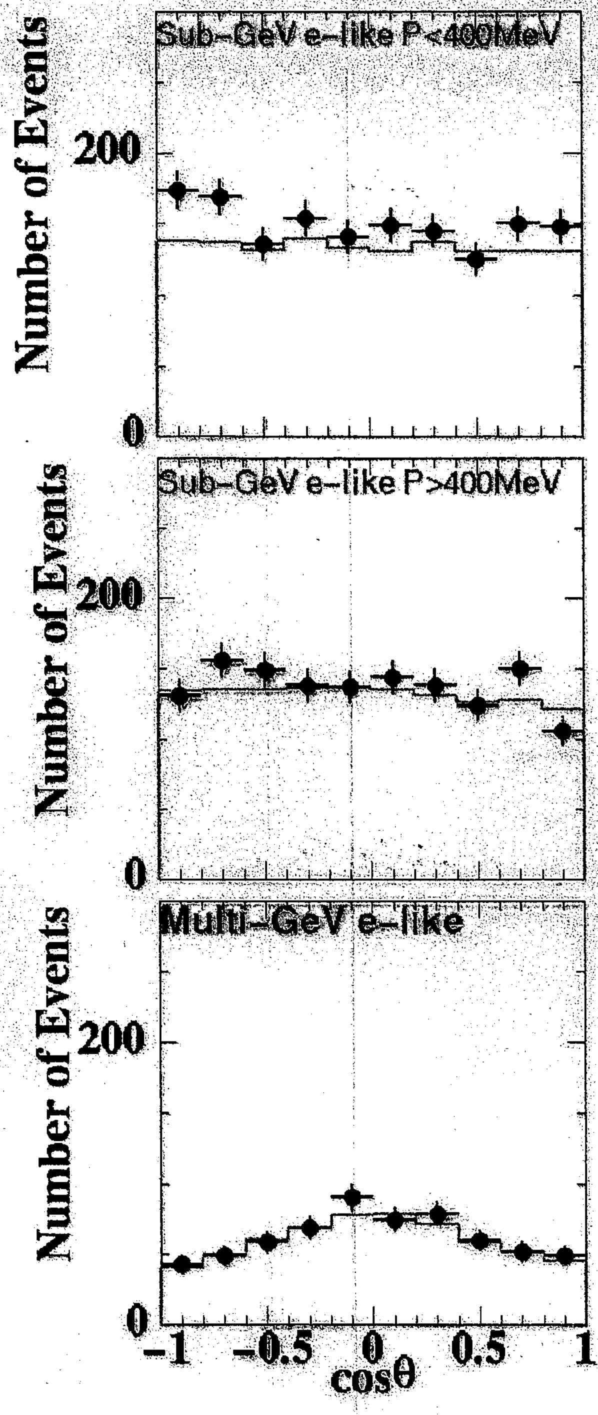
Energy distribution of neutrino events



ν_μ zenith angle



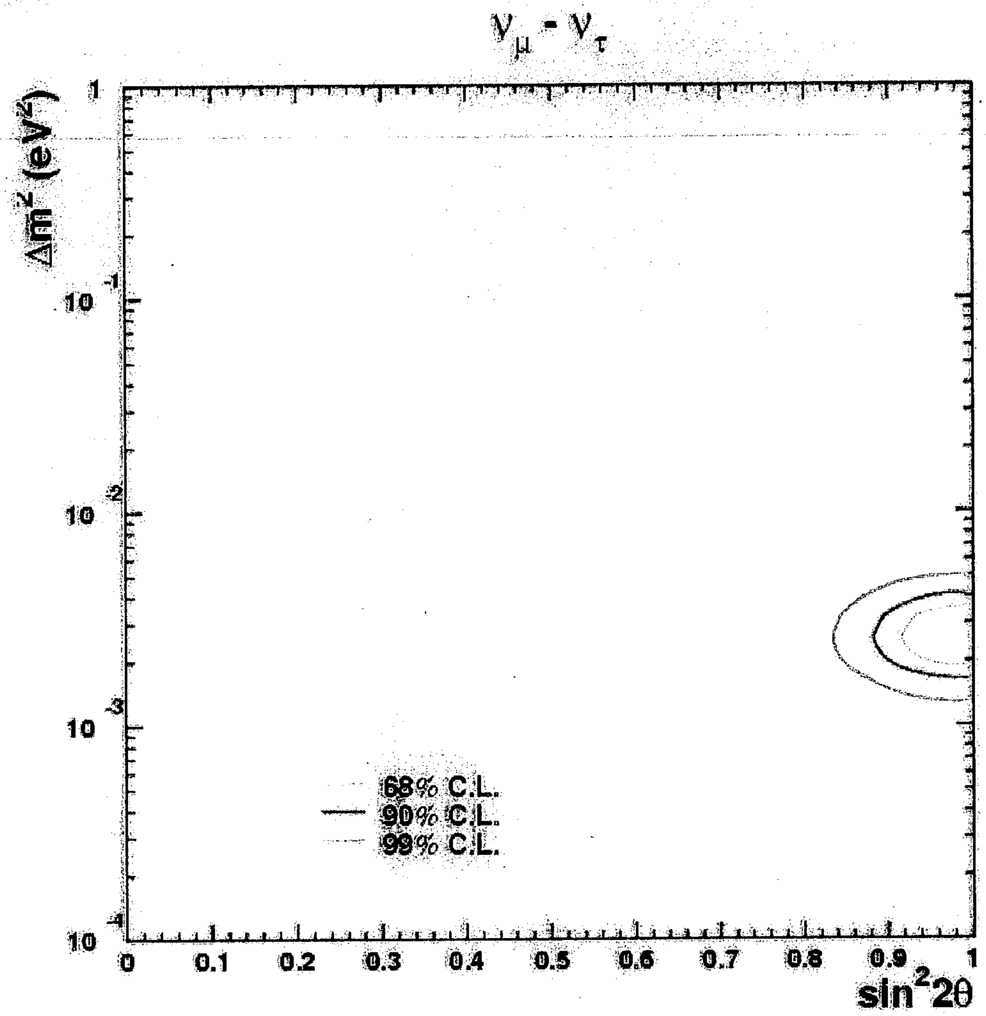
ν_e zenith angle



ν_e seems not to be oscillated

$\nu_\mu \Leftrightarrow \nu_\tau$ likely

$\nu_\mu \Leftrightarrow \nu_\tau$ allowed region



- Oscillation Analysis by FC + PC + Upmu
- Best Fit: χ^2_{min}=142.1/152d.o.f

  @ $\sin^2 2\theta$=1.00

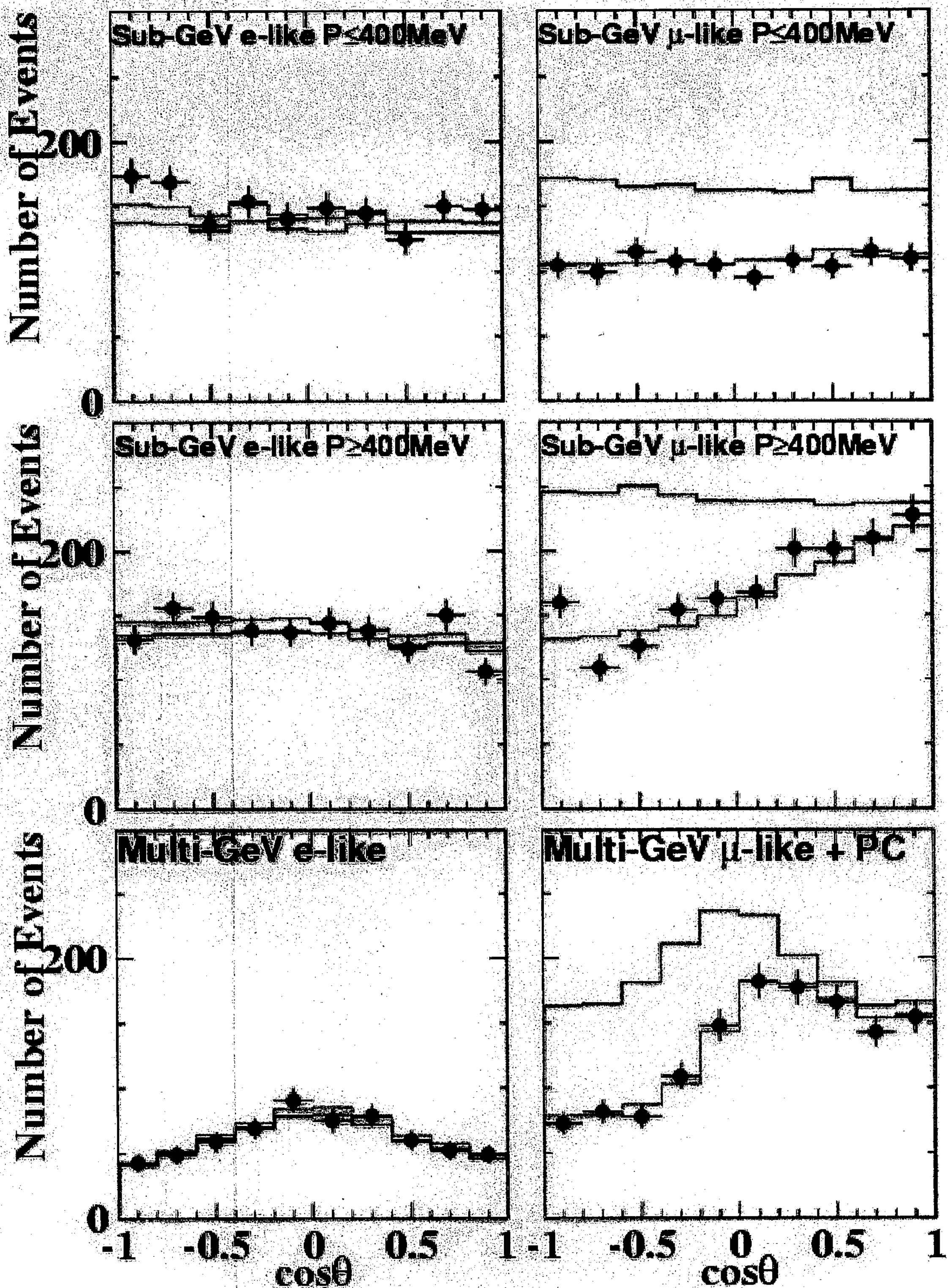
  Δm^2=2.5x10^{-3}eV^2
- Assuming null osc.:

  χ^2_{min}=344.1/154d.o.f
- Allowed region @90%C.L.:

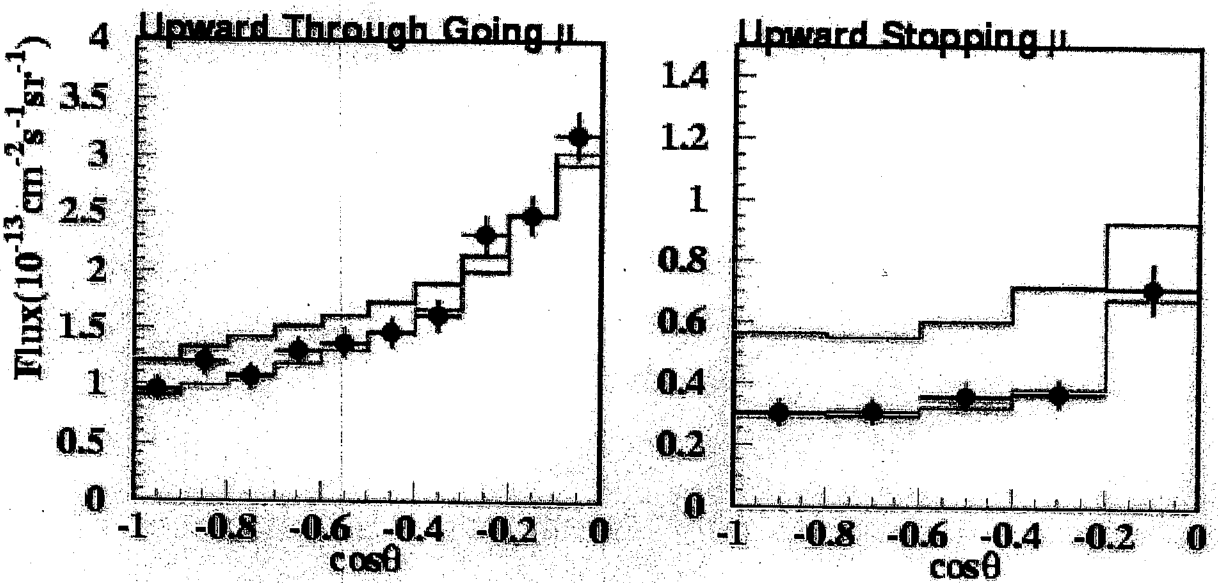
  0.88<$\sin^2 2\theta$

  1.5x10^{-3}<Δm^2<4x10^{-3} (eV^2)

FC/PC with $\nu_\mu \Leftrightarrow \nu_\tau$

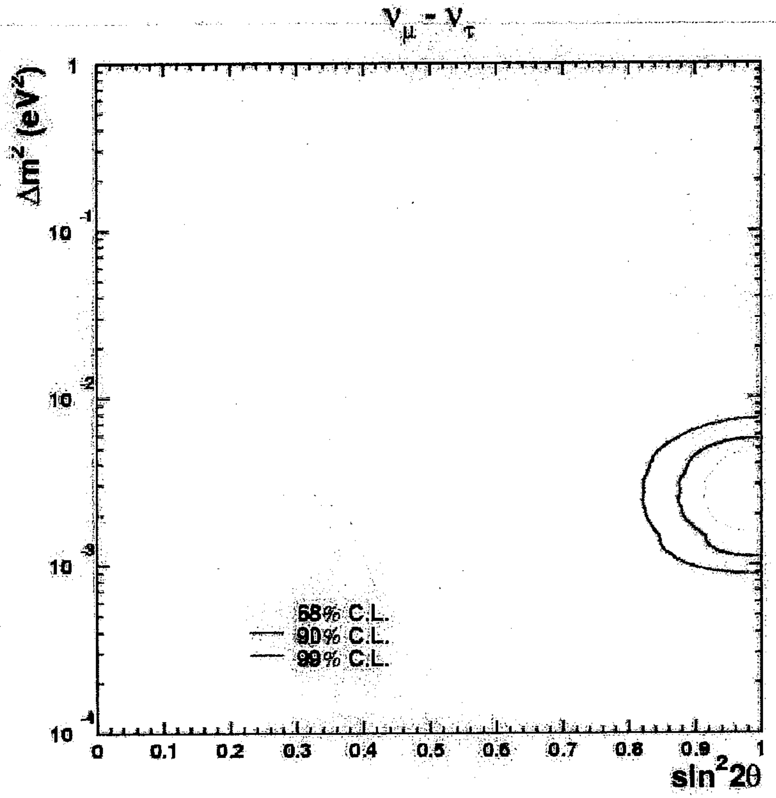


Upward μ with $\nu_\mu \Leftrightarrow \nu_\tau$

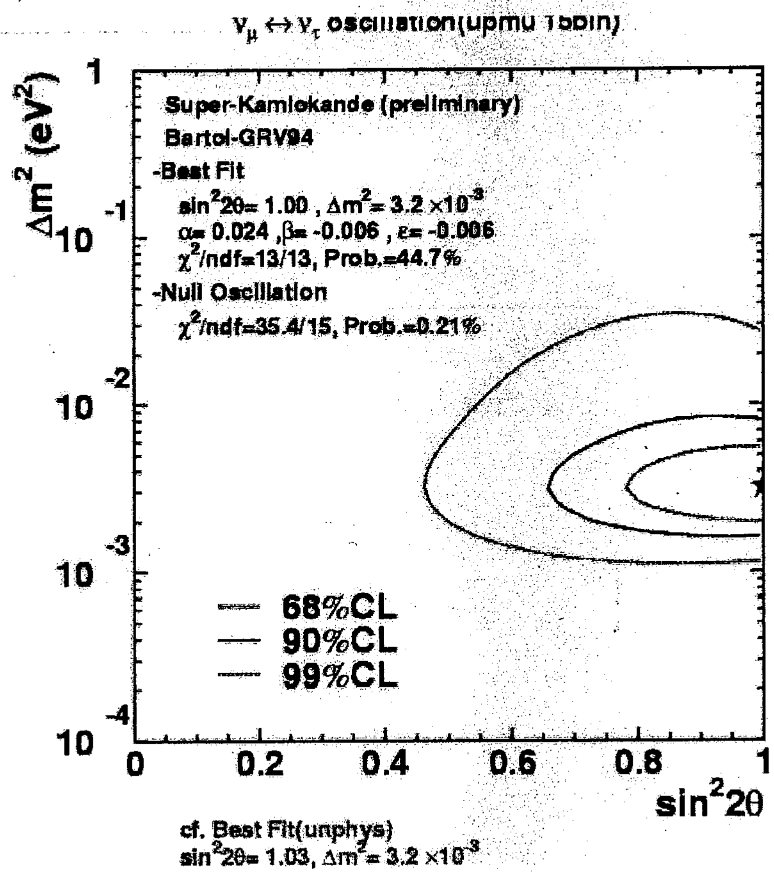


$\nu_\mu \Leftrightarrow \nu_\tau$ allowed region

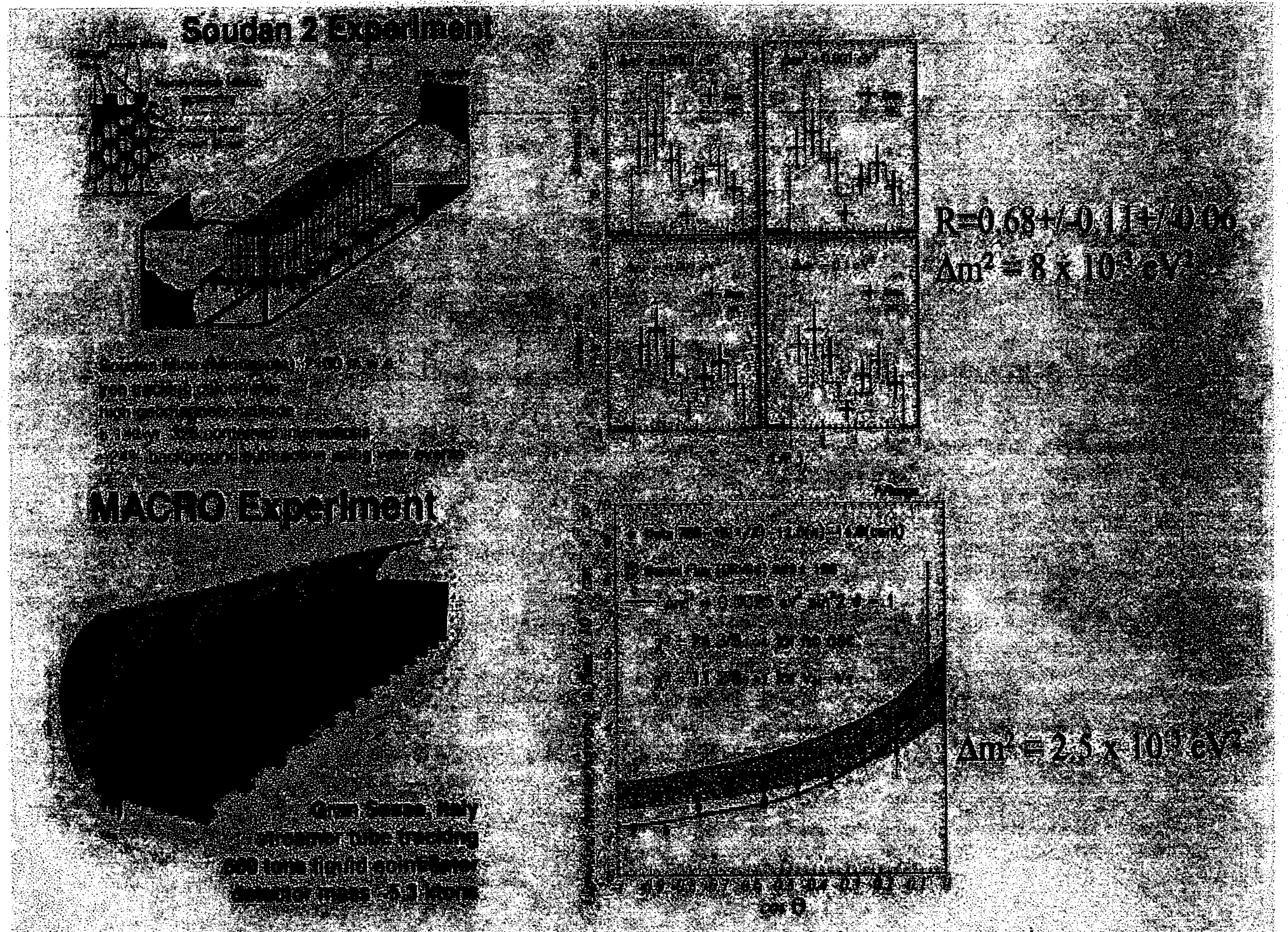
FC+PC



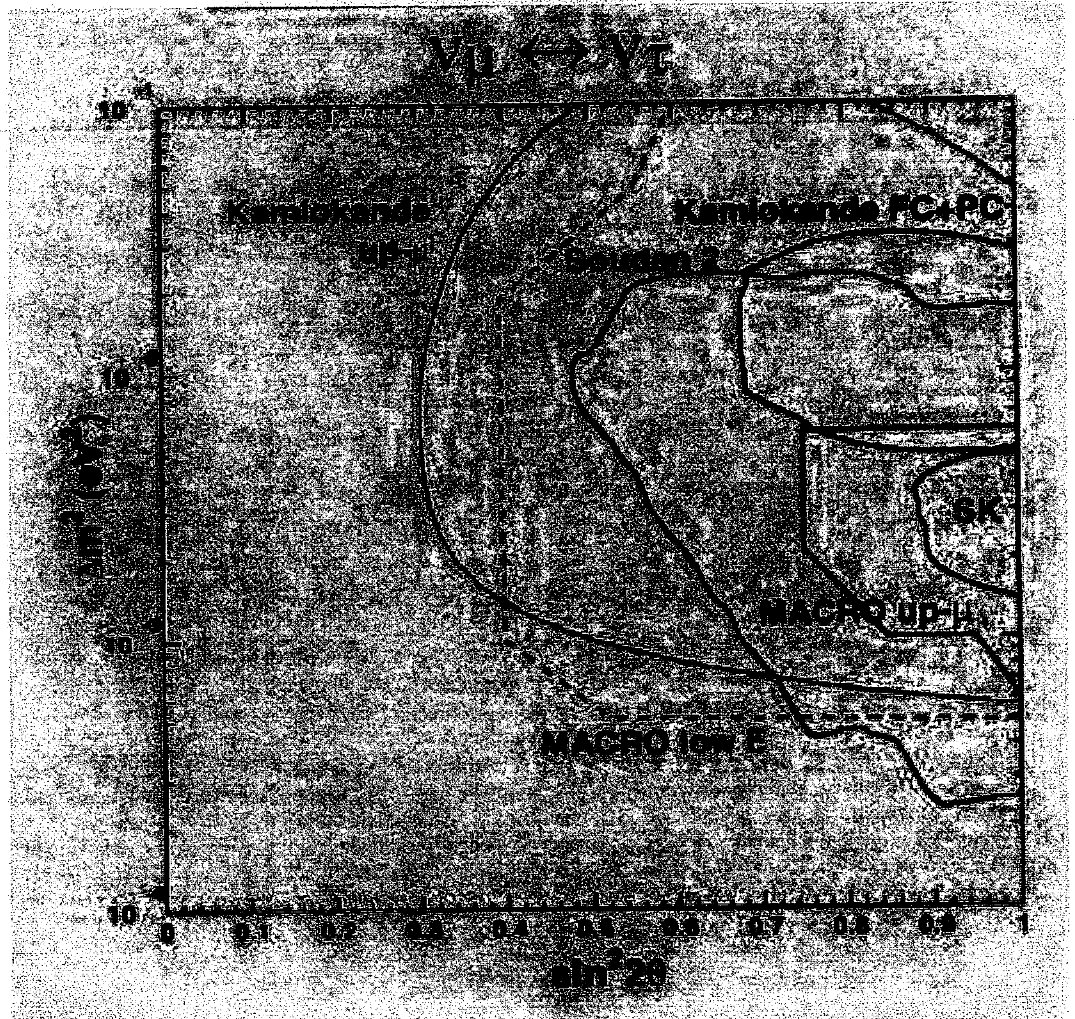
upward-going μ



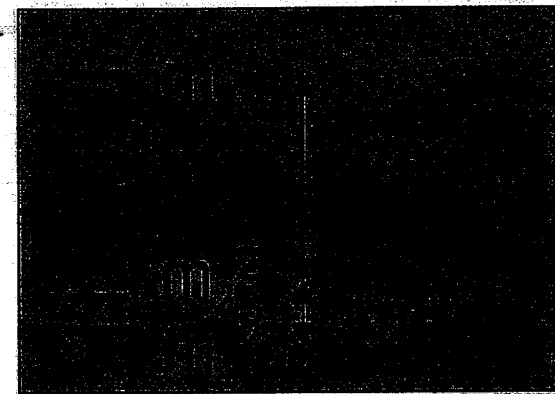
Supporting experiments



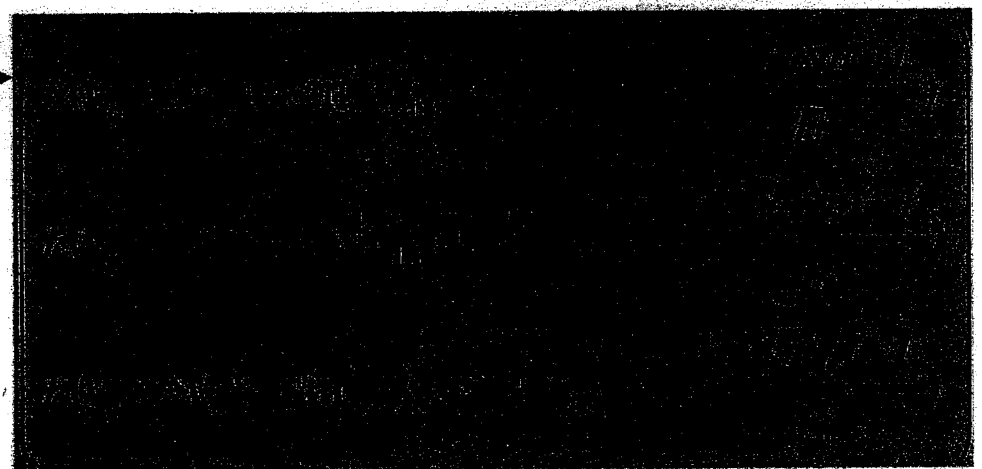
Comparison with other experiments



3 Flavor Oscillation Analysis (ν_μ-ν_τ-ν_e)

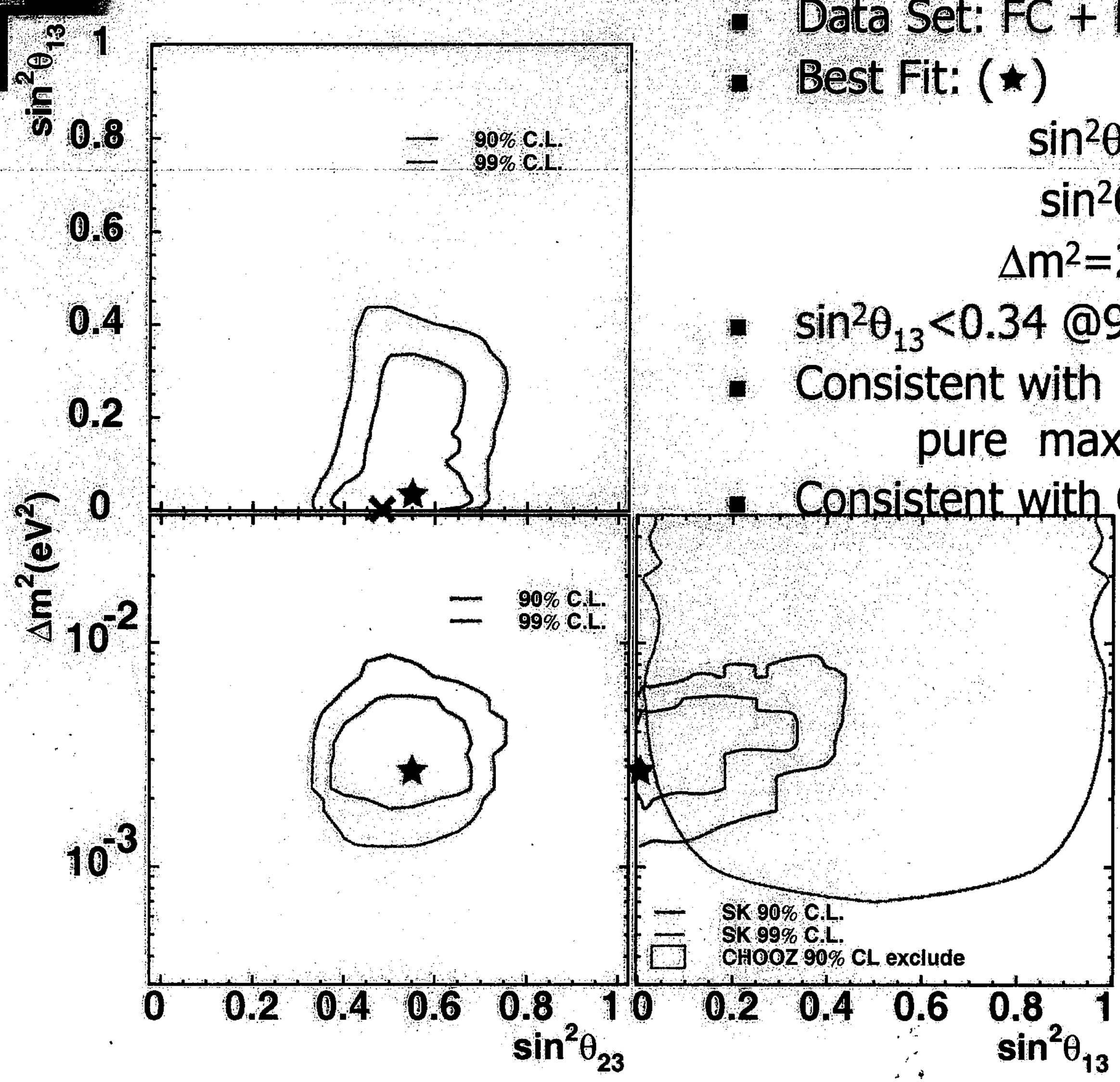


- Approximation:
  - $\Delta m^2_{23} >> \Delta m^2_{12}$
    $\left(\begin{array}{c} \Delta m^2_{23} = \Delta m^2_{atm} > 10^{-3} eV^2 \\ \Delta m^2_{12} = \Delta m^2_{sol} < 10^{-4} eV^2 \end{array} \right)$
  - $\Delta m^2_{23} \sim \Delta m^2_{13} \equiv \Delta m^2$
- Osc. Probability:



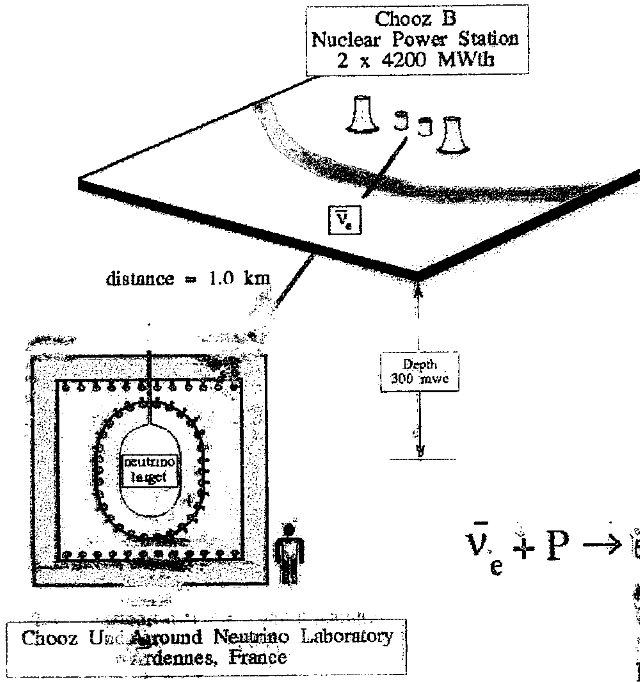
- Parameters:
  $(\sin^2\theta_{13}, \sin^2\theta_{23}, \Delta m^2)$
- Matter effects
  - considered as 5 step density function

3 Flavor Analysis Result



- Data Set: FC + PC
- Best Fit: (★)
  $\sin^2\theta_{13}=0.019$,
  $\sin^2\theta_{23}=0.55$,
  $\Delta m^2=2.5\times10^{-3}eV^2$
- $\sin^2\theta_{13}<0.34$ @90%CL
- Consistent with
  pure maximal $\nu_\mu\rightarrow\nu_\tau$(×)
- Consistent with CHOOZ

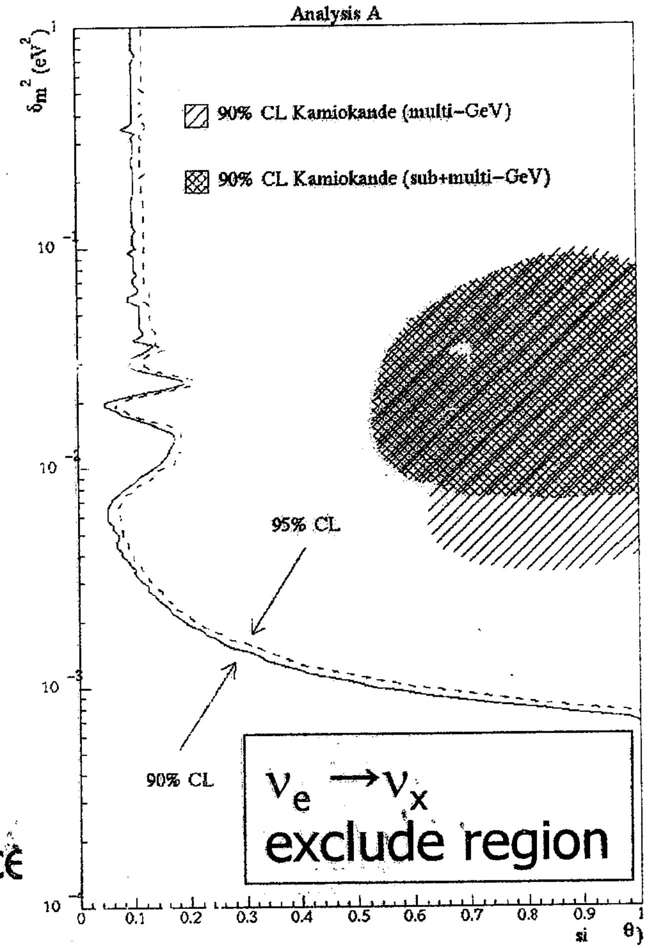
CHOOZ



$\bar{\nu}_e + P \rightarrow e^+ + n$

$e^+ + e^- \rightarrow \gamma\gamma$

$n + \text{nucleus} \rightarrow \gamma_{capture}$



hep-ex/990703

- Search for anti electron neutrino disappearance from reactor
- Detect coincidence signal e^+ and capture γ
- Limit $\nu_e \rightarrow \nu_x$ at $\sin^2 2\theta > 0.1$ and $\Delta m^2 > 10^{-3}\,eV^2$

Sterile neutrino (ν_s) scenario

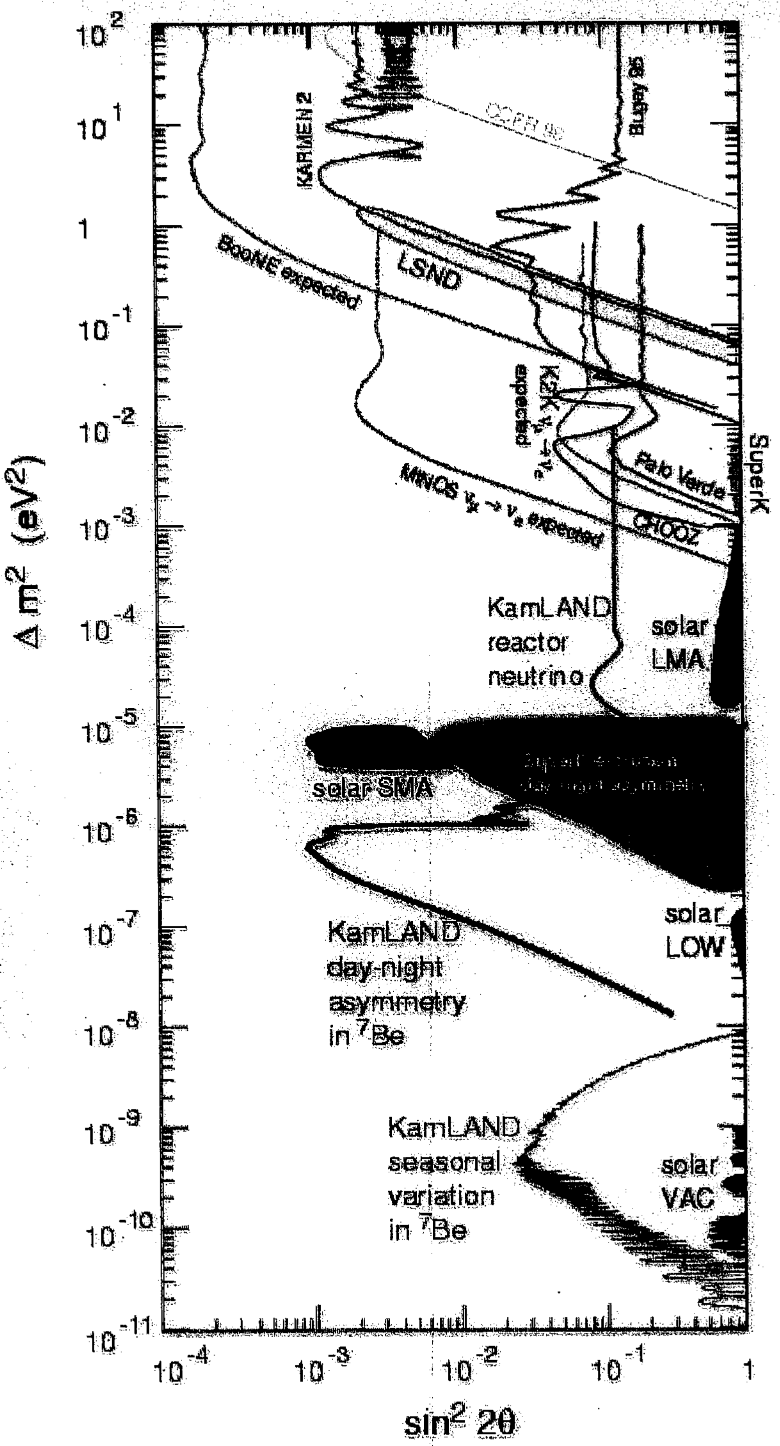
- N_ν limit from Z^0 decay

  $N_\nu = \Gamma_{inv}/\Gamma_{\nu\nu} = 2.994 \pm 0.012$
- Three experiments claims neutrino oscillation
  - LSND
  - Solar ν
  - Atmospheric ν
- Three massive neutrino state can produce only two oscillation signatures

  $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$

Need Sterile neutrino (ν_s) ?

Current status of Neutrino oscillation experiment



- LSND
  $\nu\mu \to \nu e$
  $\Delta m^2 = 10^{-1} \sim 1\ eV^2$
- Atmospheric ν
  $\nu\mu \to \nu x$
  $\Delta m^2 \sim 10^{-3}\ eV^2$
- Solar ν
  $\nu e \to \nu x$
  LMA $\Delta m^2 \sim 10^{-4}\ eV^2$
  SMA $\Delta m^2 \sim 10^{-5}\ eV^2$
  LOW $\Delta m^2 \sim 10^{-7}\ eV^2$
  VAC $\Delta m^2 = 10^{-10} \sim 10^{-9}\ eV^2$

Strategy of ν_s analysis

- Sterile neutrino does not feel either weak CC nor NC

  (ν_τ interacts through only NC at E<3.4GeV)

  ⇒ test with NC enriched multi-ring events

- Matter effect produce difference in oscillation probability with $\nu_\mu \Leftrightarrow \nu_\tau$

$$\sin^2 2\theta_m = \frac{\sin^2 2\vartheta_\nu}{(\varsigma - \cos 2\vartheta_\nu)^2 + \sin^2 2\vartheta_\nu} \qquad l_m = \frac{l_\nu}{\sqrt{(\varsigma - \cos 2\vartheta_\nu)^2 + \sin^2 2\vartheta_\nu}}$$

$$\varsigma = \mp \frac{\sqrt{2} E_\nu G_F N_n}{\Delta m^2} \cong \mp \left(\frac{E_\nu}{5GeV}\right)\left(\frac{\Delta m^2}{10^{-3} eV^2}\right)^{-1}$$

oscillation suppressed at Eν~15GeV for Δm^2~$3\text{x}10^{-3}eV^2$

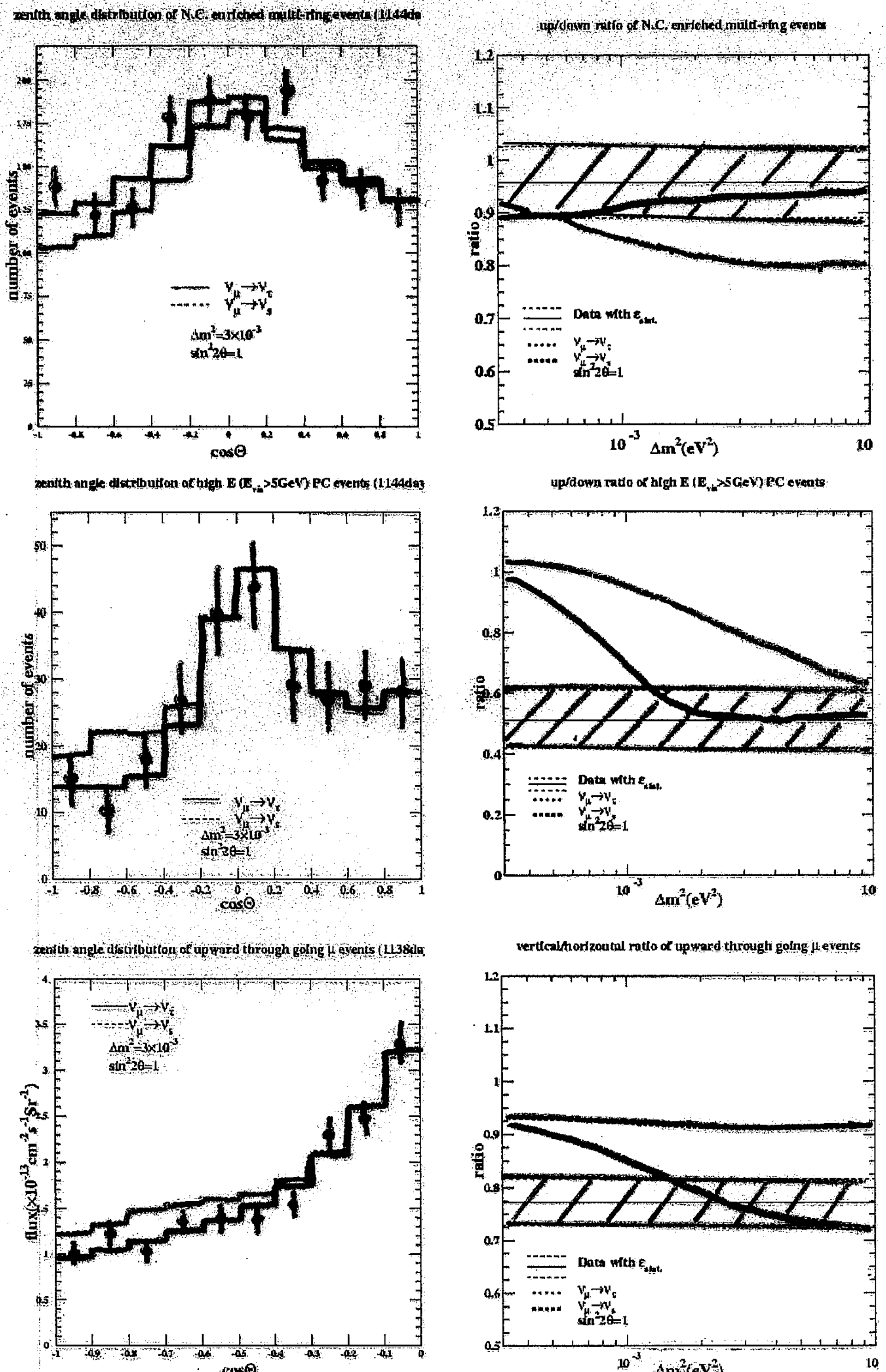
⇒ test with PC and Upward-Thruμ events

$\nu_\mu \Leftrightarrow \nu_\tau$ or $\nu_\mu \Leftrightarrow \nu_s$ analysis

Multi-ring

Partially-contained

Upward-Thru μ



$\nu_\mu \leftrightarrow \nu_\tau$

$\nu_\mu \leftrightarrow \nu_s$

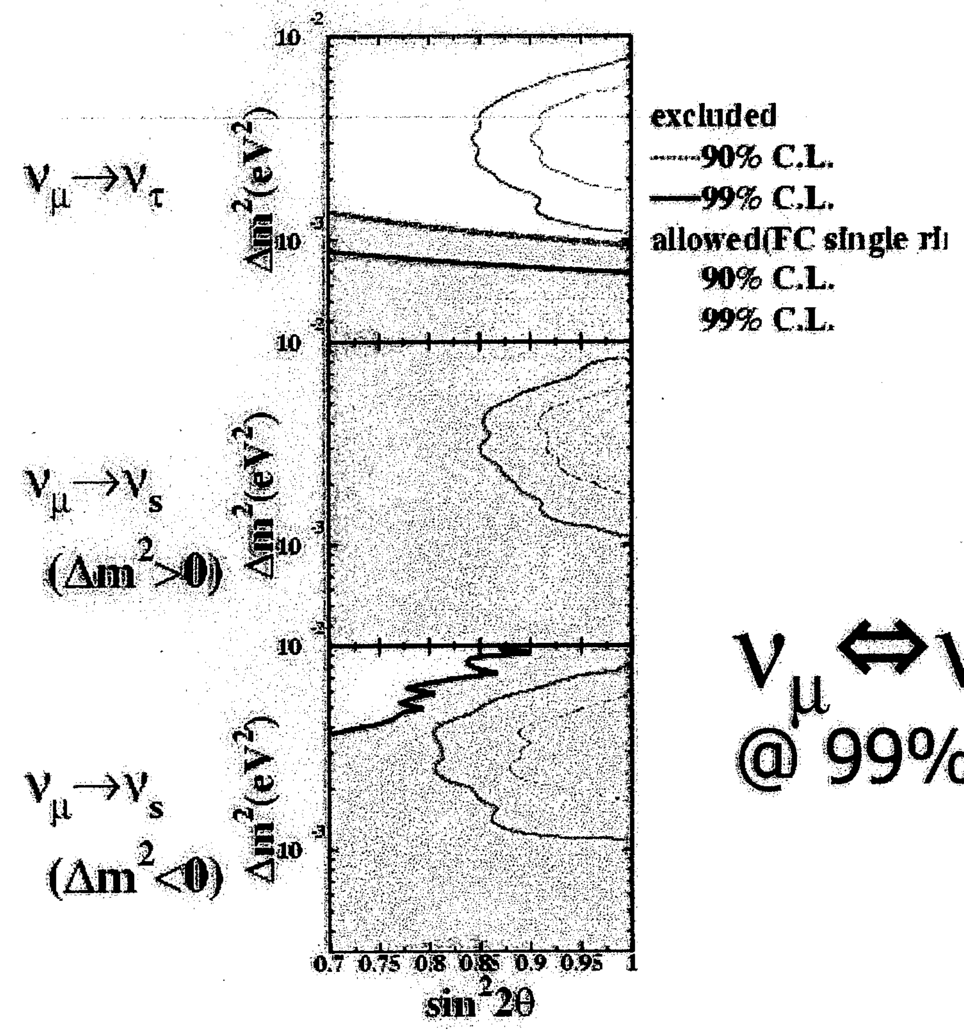
cosθ

10^{-3} 10^{-2}

UP/DOWN ratio

$\nu_\mu \Leftrightarrow \nu_\tau$ or $\nu_\mu \Leftrightarrow \nu_s$ result

excluded region from combined analysis(multi+PC+upμ)



$\nu_\mu \Leftrightarrow \nu_s$ excluded @ 99% C.L.

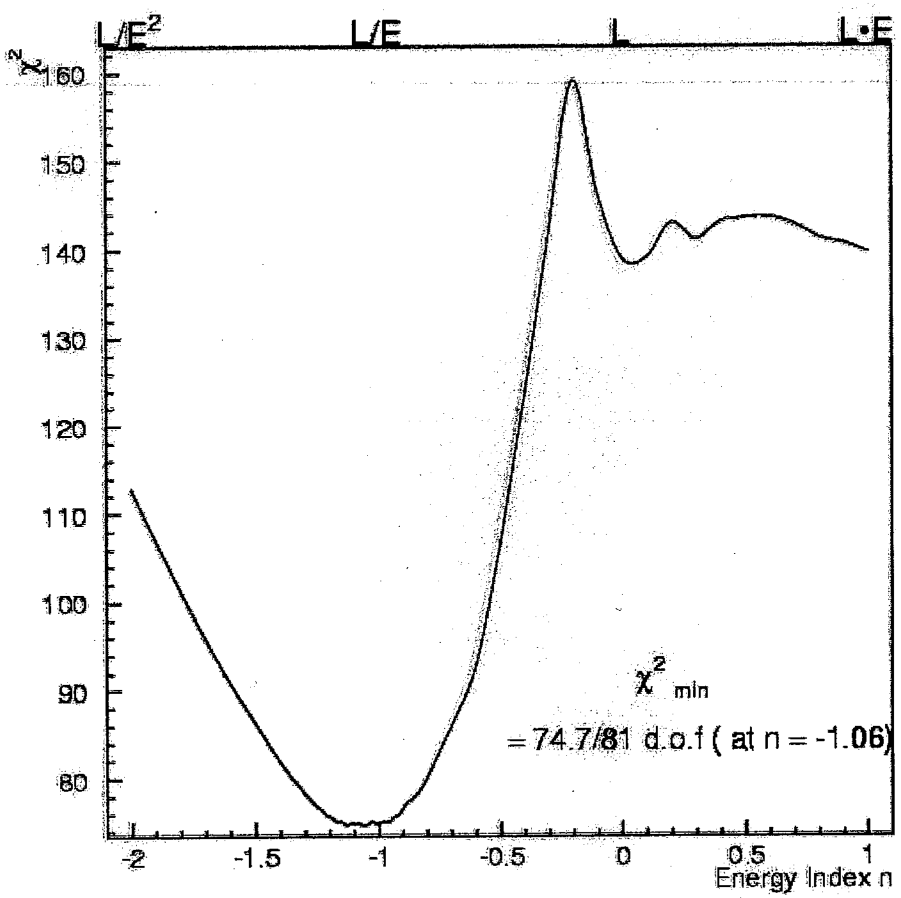
Exotic neutrino oscillation analysis

- Test several fundamental principle with atmospheric neutrino data

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2\theta \sin^2(\beta L E^n)$$

E^{-1}	standard
E	violations of equivalence principle, Lorentz invariance
E^0	violations of CPT symmetry

Oscillation analysis with LE^n



- Test $\nu_\mu \Leftrightarrow \nu_\tau$ with
  $P(\nu_\mu \Leftrightarrow \nu_\tau) = \sin^2 2\theta \sin^2(\beta L E^n)$
- Result
  $\chi^2_{min} = 74.7/81$ d.o.f.
  $n = -1.06 \pm 0.14$

Search for tau neutrino

Assumption

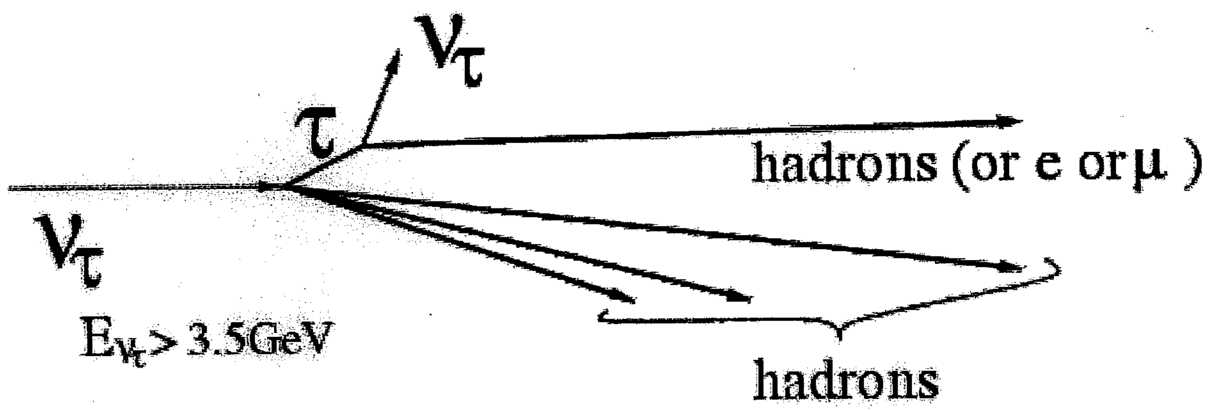
$\nu_\mu - \nu_\tau$ oscillation

at $\Delta m^2 = 3\times10^{-3}\,eV^2$, $\sin^2 2\theta = 1$

~20 events/year

S/N ~ 0.7%

$CC\nu_\tau$ $CC\nu_e$, $CC\nu_\mu$, NC



Many hadrons are produced!

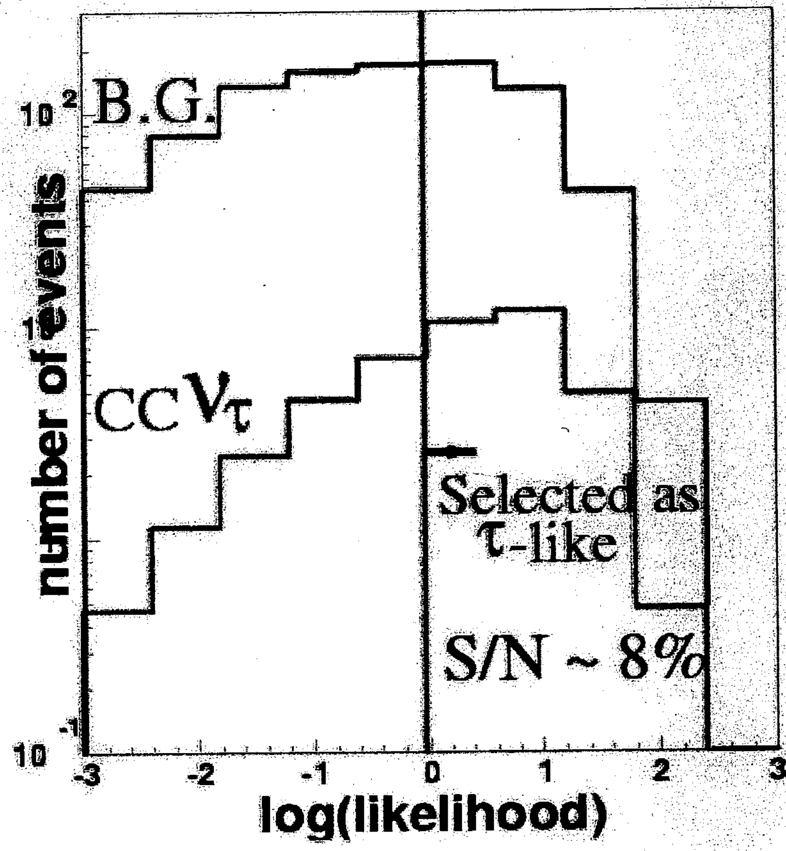
CC tau neutrino analysis

basic cuts;

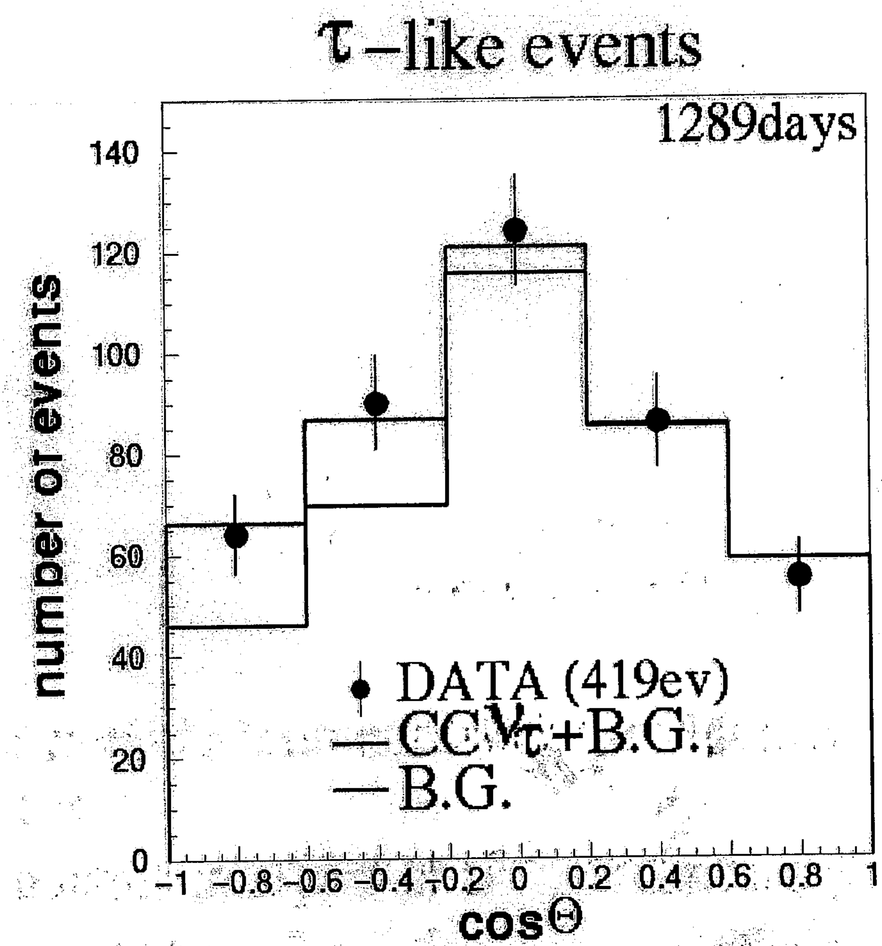
FC,Evis>1.33GeV,brightest ring:e-like

likelihood analysis with;

- Evis
- # of decay-e
- # of rings
- max(E of a ring)/Etot
- max distance from 1ry to decay-e
- max Pμ
- Pt
- PID likelihood of brightest ring



CC ν_τ analysis result



- ν_τ events will appear upward ($\cos\theta<0$)
- $N^{\tau}_{obs}=43\pm17$ events

Summary

- Super-K atmospheric neutrino data well explains $\nu_\mu \Leftrightarrow \nu_\tau$ neutrino oscillation
  $\Delta m^2 \sim 2.5 \times 10^{-3} eV^2$ $\sin^2\theta_{23} \sim 1.0$
- subdominant $\nu_\mu \Leftrightarrow \nu_e$ channel ($\sin\theta_{13}$) is small
- oscillation to sterile neutrino disfavored at 99% C.L.
- possible detection of ν_τ events with tau enriched events