Super-Kamiokande

Y.Totsuka
Kamioka

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Super-Kamiokande collaboration

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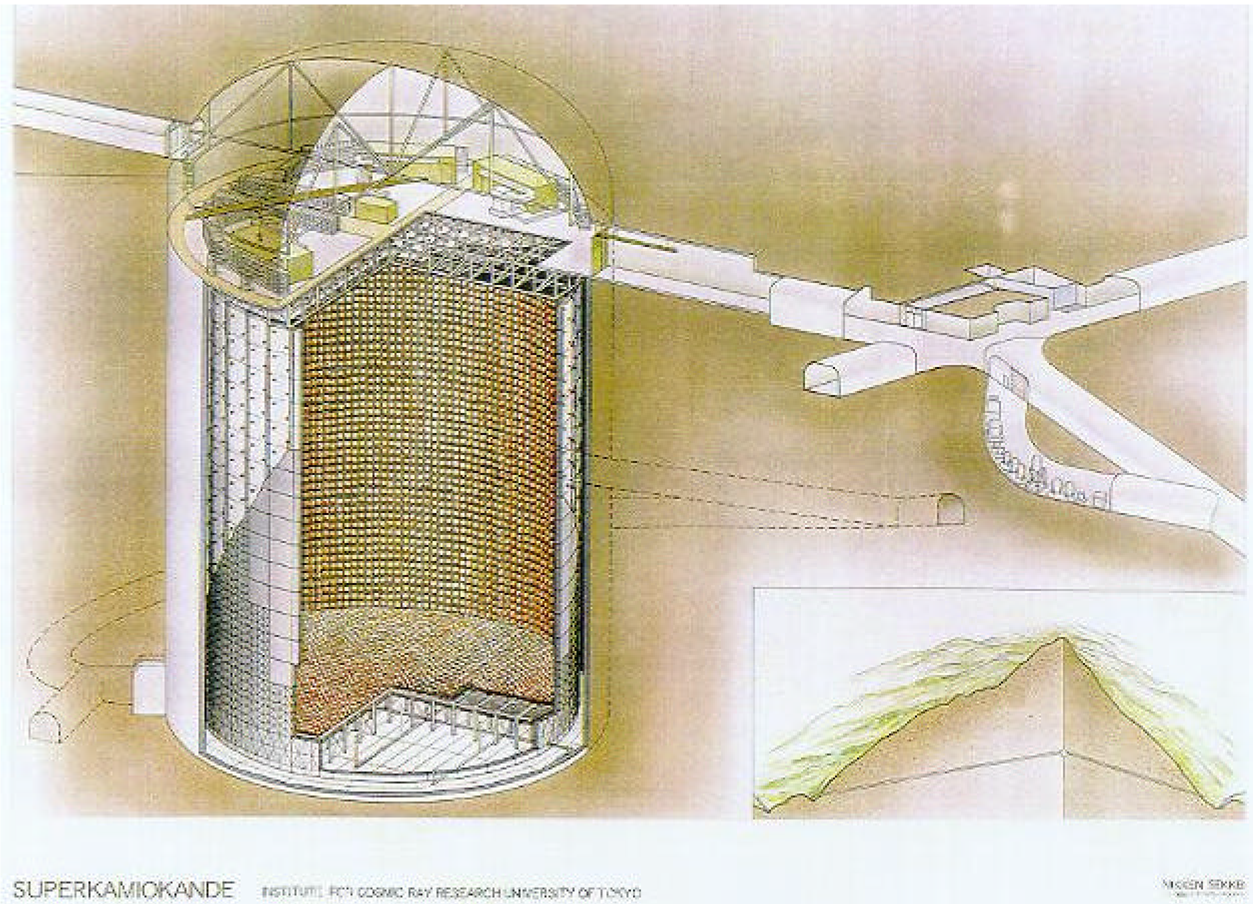
Super-Kamiokande detector



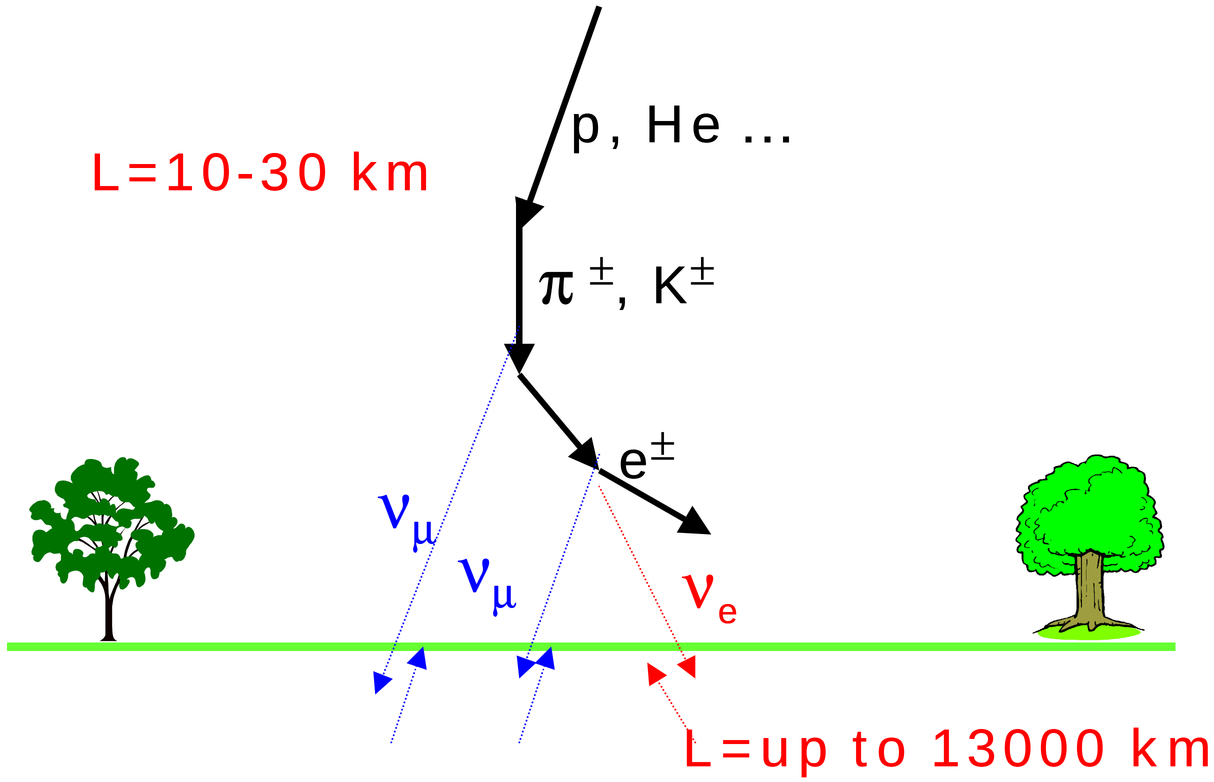
50,000 ton water Cherenkov detector
(22.5 kton fiducial volume)

1000m underground (2700 m.w.e.)

11,146 20-inch PMTs for inner detector

1,885 8-inch PMTs for outer detector

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

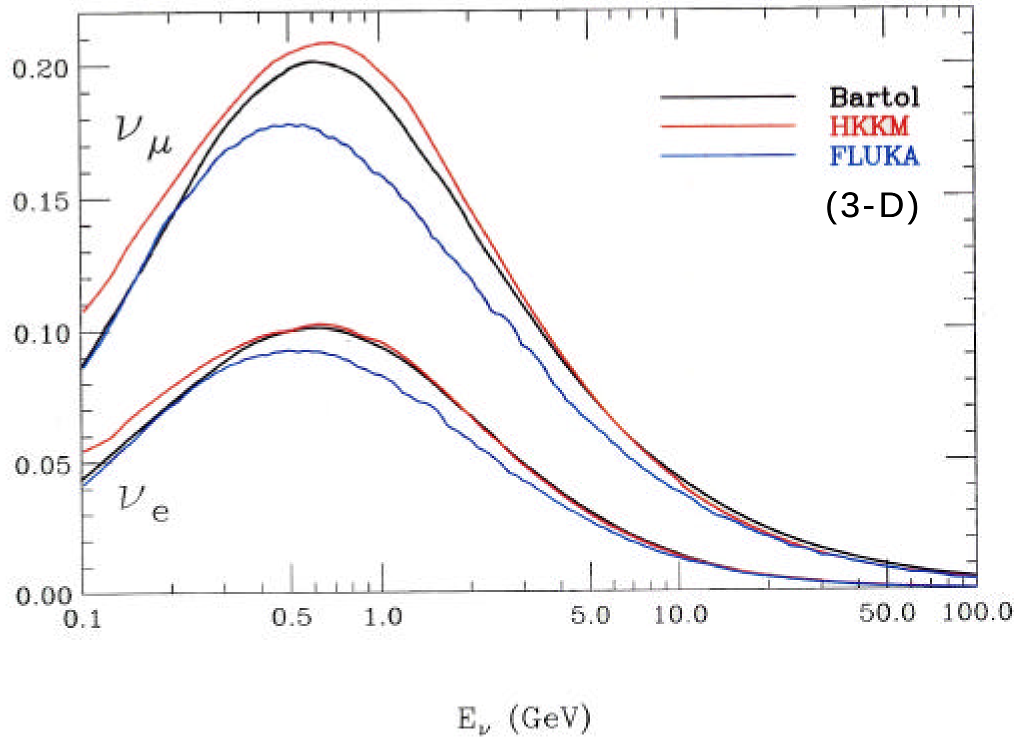
Error in absolute flux ~20%, but ν_μ/ν_e ratio ~5%

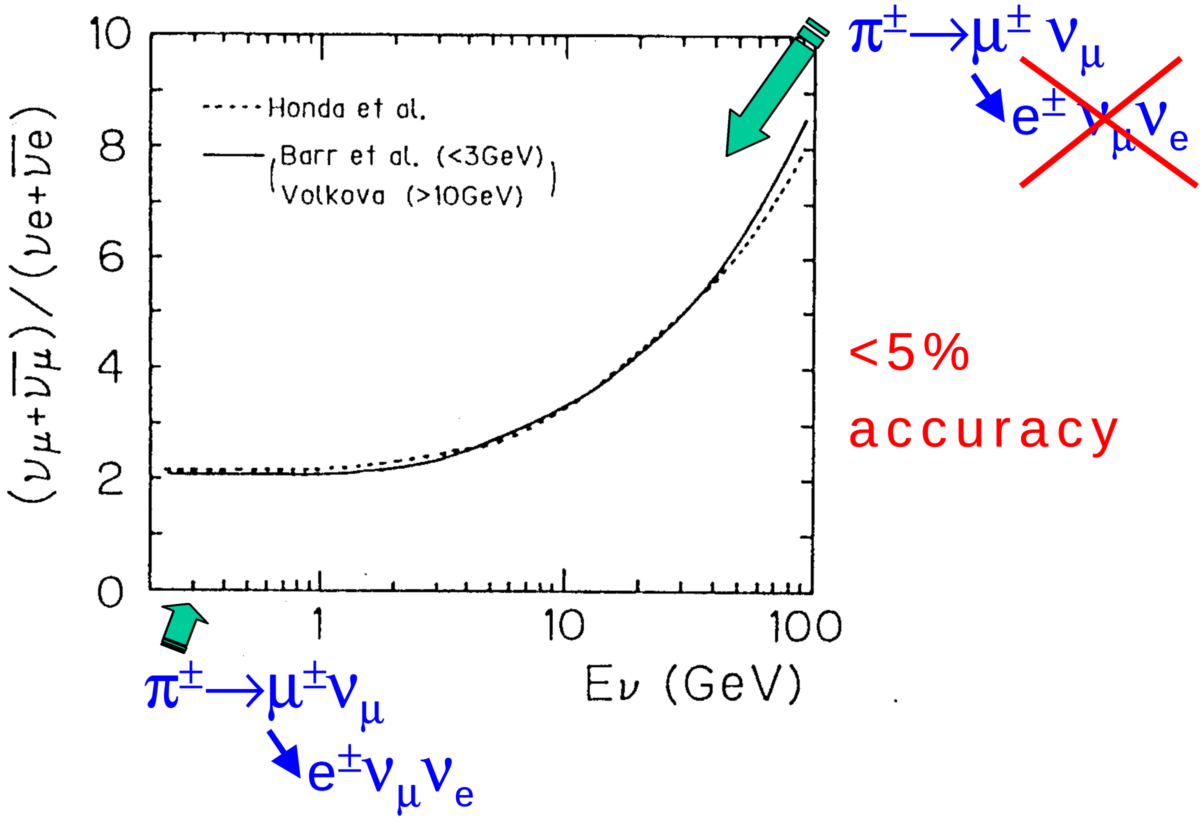
Neutrino oscillations :

$$\Rightarrow \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{data} \Big/ \left(\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}\right)_{MC} \neq 1$$

Atmospheric neutrino spectrum

MODEL dependence of ENERGY spectrum (P.Lipari)





Primary cosmic ray flux

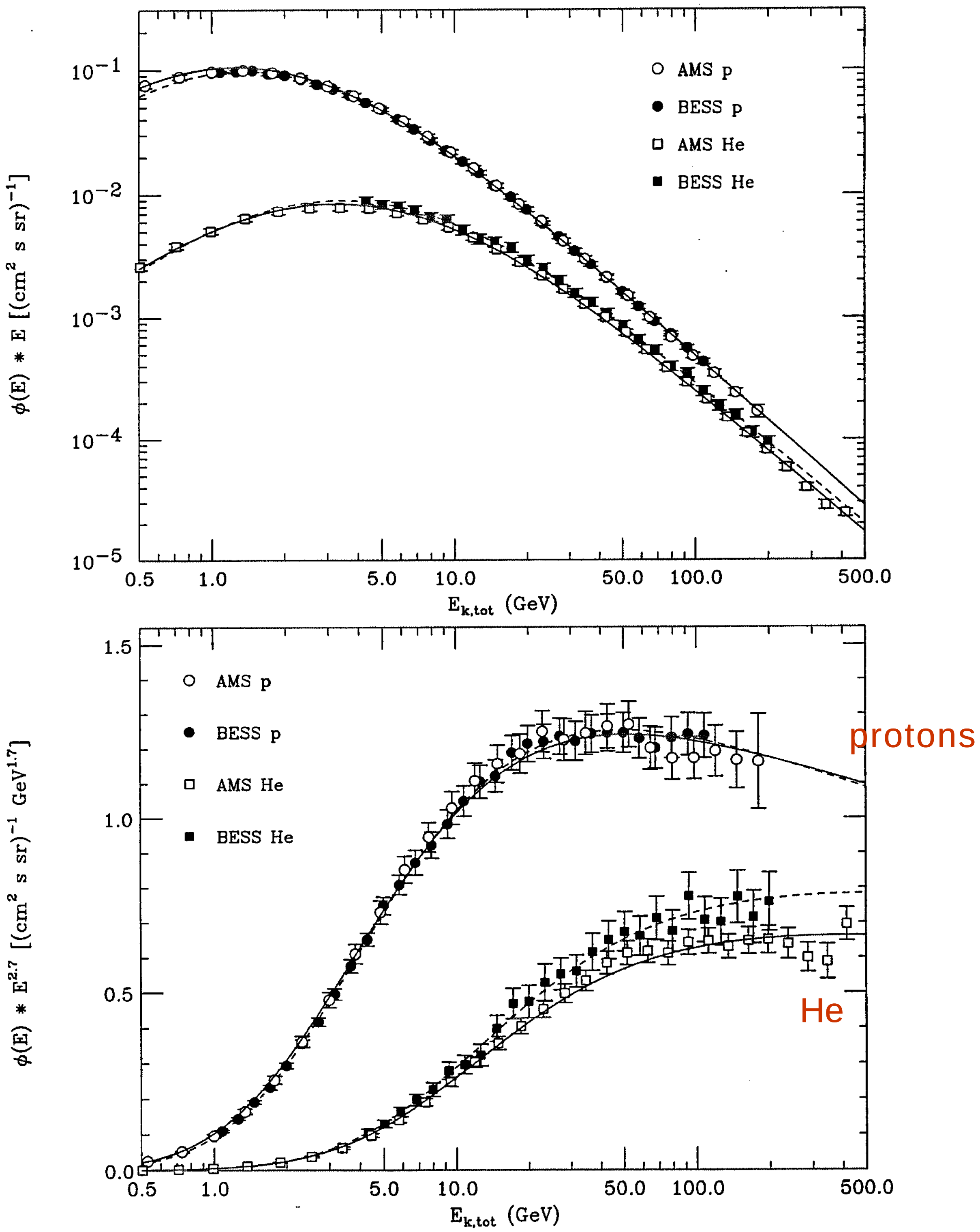
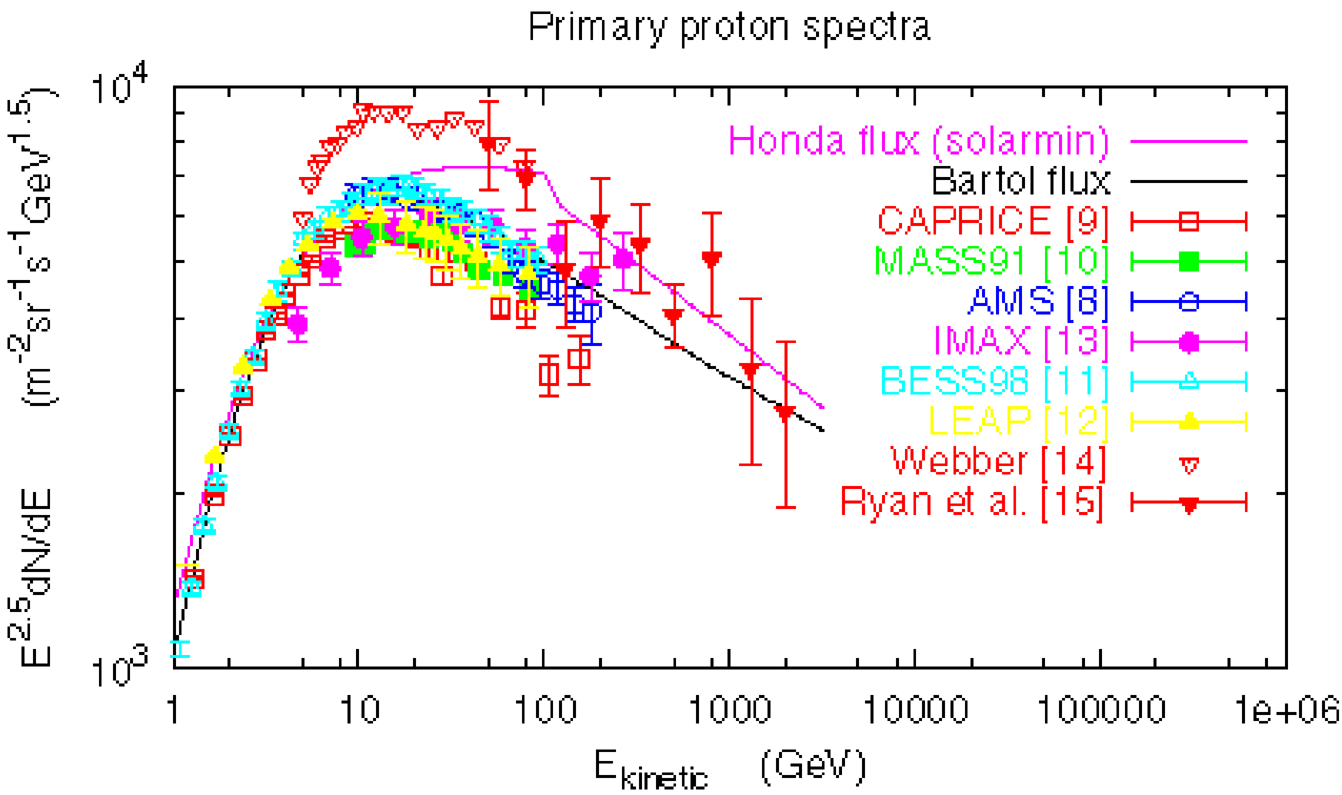


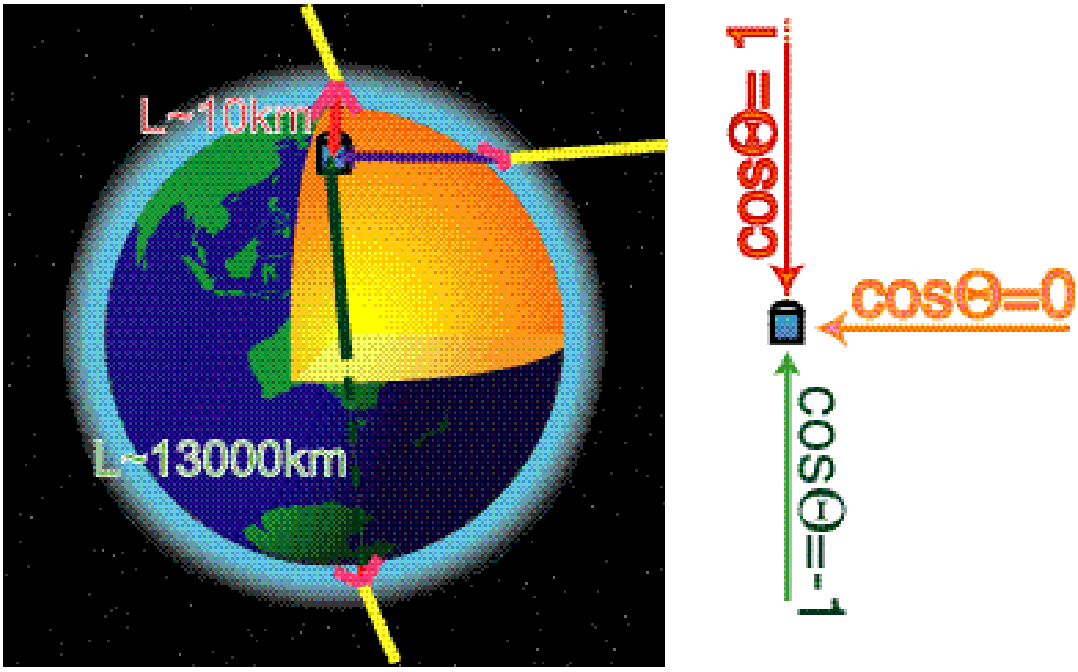
Figure 2: Fits to the AMS and BESS data (Energy per particle)

From P.Lipari

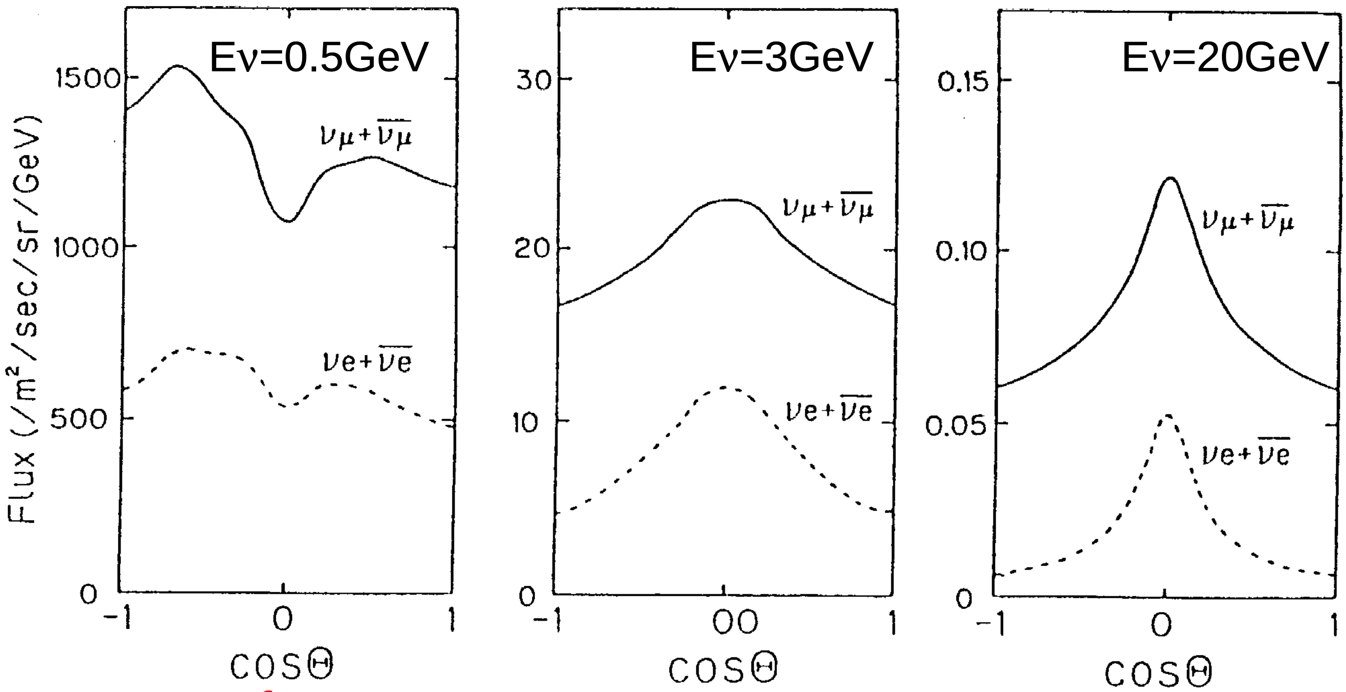
Bartol and Honda fluxes



Zenith angle distribution(1D)



Calculated zenith angle distribution

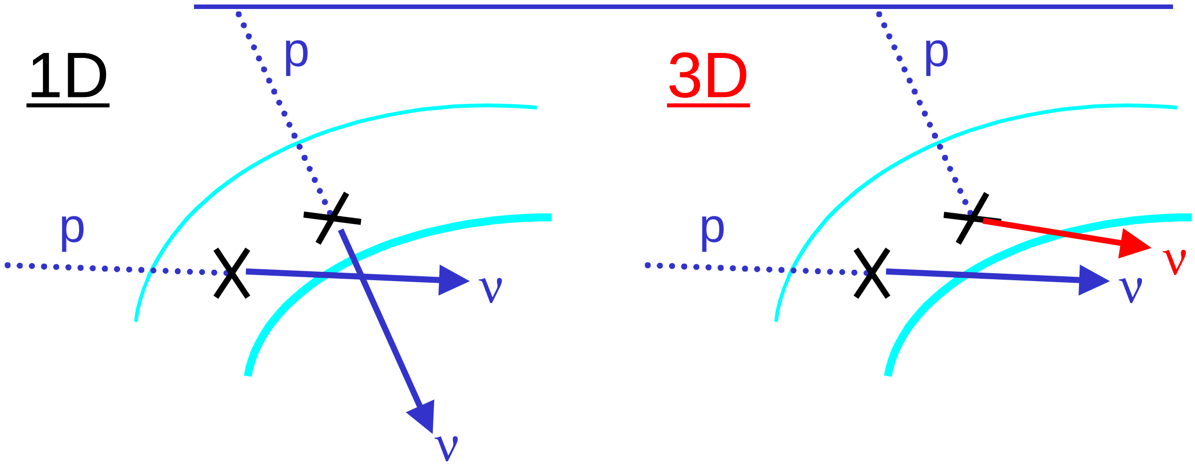


For E_ν > a few GeV,

Upward / downward = 1 (within a few %)

Up/Down asymmetry for neutrino oscillations

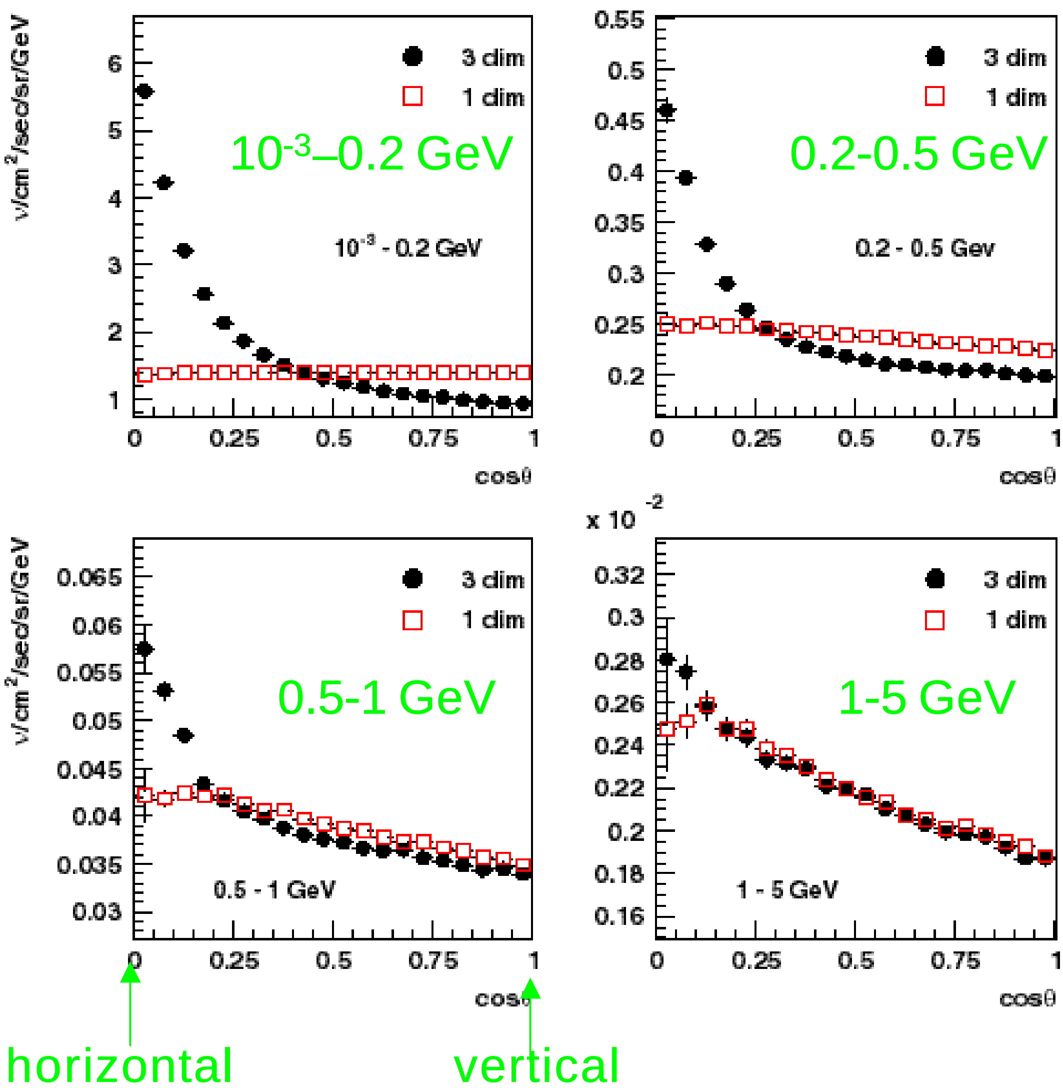
3D neutrino flux calculation



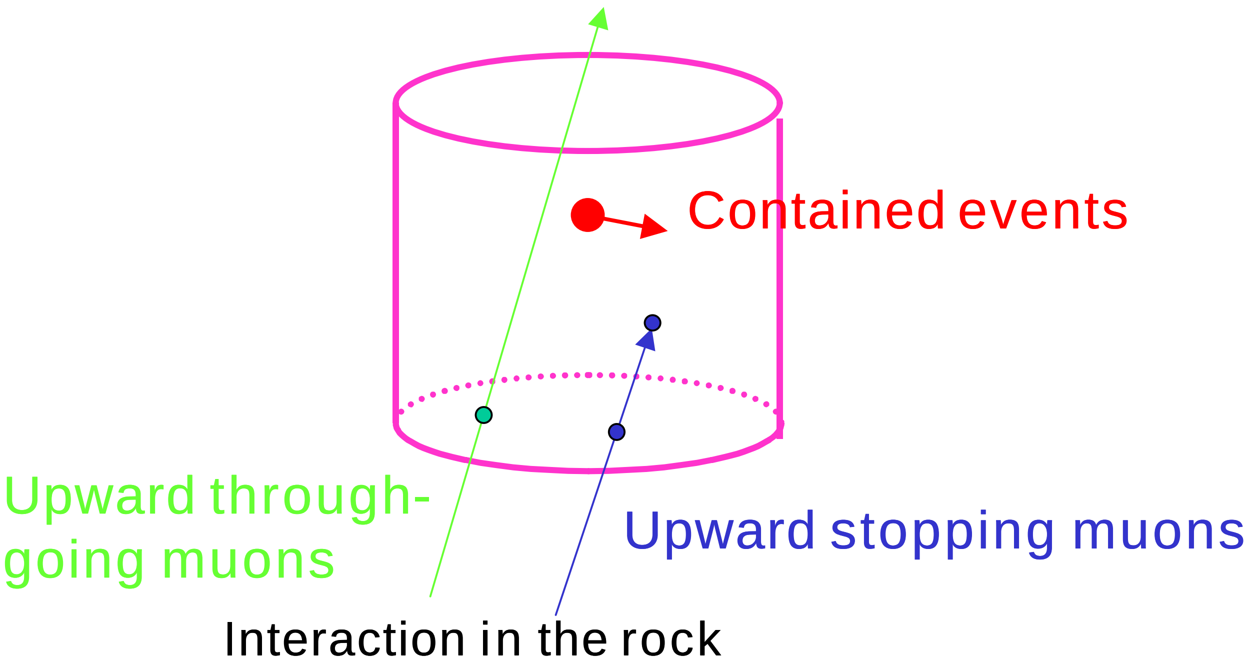
3D calculation by G.Battistoni et al.

(hep-ph/9907408)

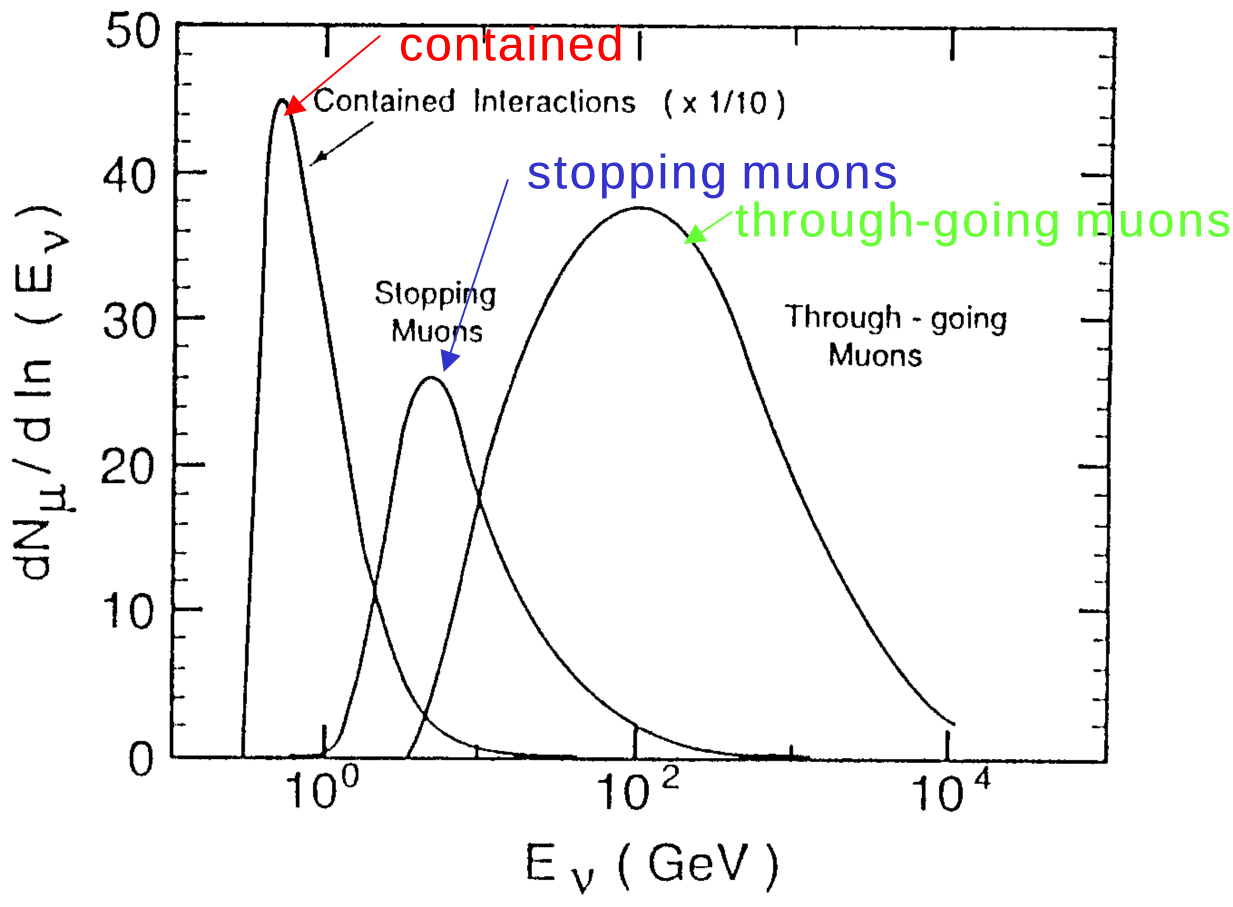
ν_μ



How to detect atmospheric neutrinos

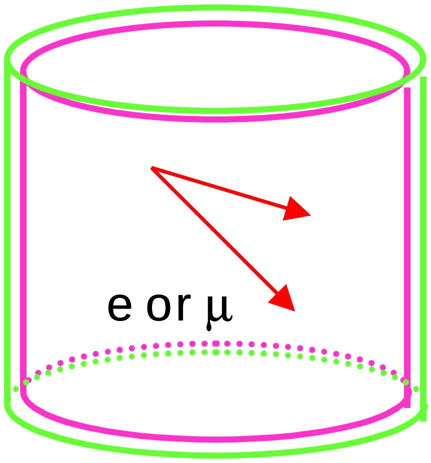


Initial neutrino energy spectrum



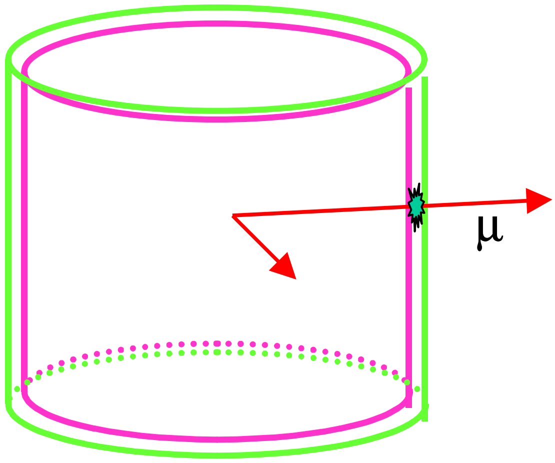
Contained event analysis

Fully Contained (FC)



No hit in Outer Detector

Partially Contained (PC)



One cluster in Outer Detector

Reduction

↓

Automatic ring fitter
Particle ID
Energy reconstruction

↓

Fiducial volume (>2m from wall, 22 ktons)
E_{vis} > 30 MeV (FC), > 3000 p.e. (~350 MeV) (PC)

↓

Final sample:
FC: 8.2 ev./day, PC: 0.58 ev./day

E_{vis} < 1.33 GeV : Sub-GeV
E_{vis} > 1.33 GeV : Multi-GeV

Fully contained event summary

(1289.4 d (79.3 kt . y))

Sub-GeV (Fully Contained)

$E_{vis} < 1.33$ GeV, $P_e > 100$ MeV, $P_\mu > 200$ MeV

		Data	MC(Honda flux)
1ring	e-like	2864	2667.6
	μ-like	2788	4072.8
Multi ring		2159	2585.1
Total		7811	9325.5

$$\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}} = 0.638 \pm 0.017 \pm 0.050$$

Multi-GeV

Fully Contained ($E_{vis} > 1.33$ GeV)

		Data	MC(Honda flux)
1ring	e-like	626	612.8
	μ-like	558	838.3
Multi ring		1318	1648.1
Total		2502	3099.1

Partially Contained (assigned as μ-like)

	Data	MC
Total	754	1065.0

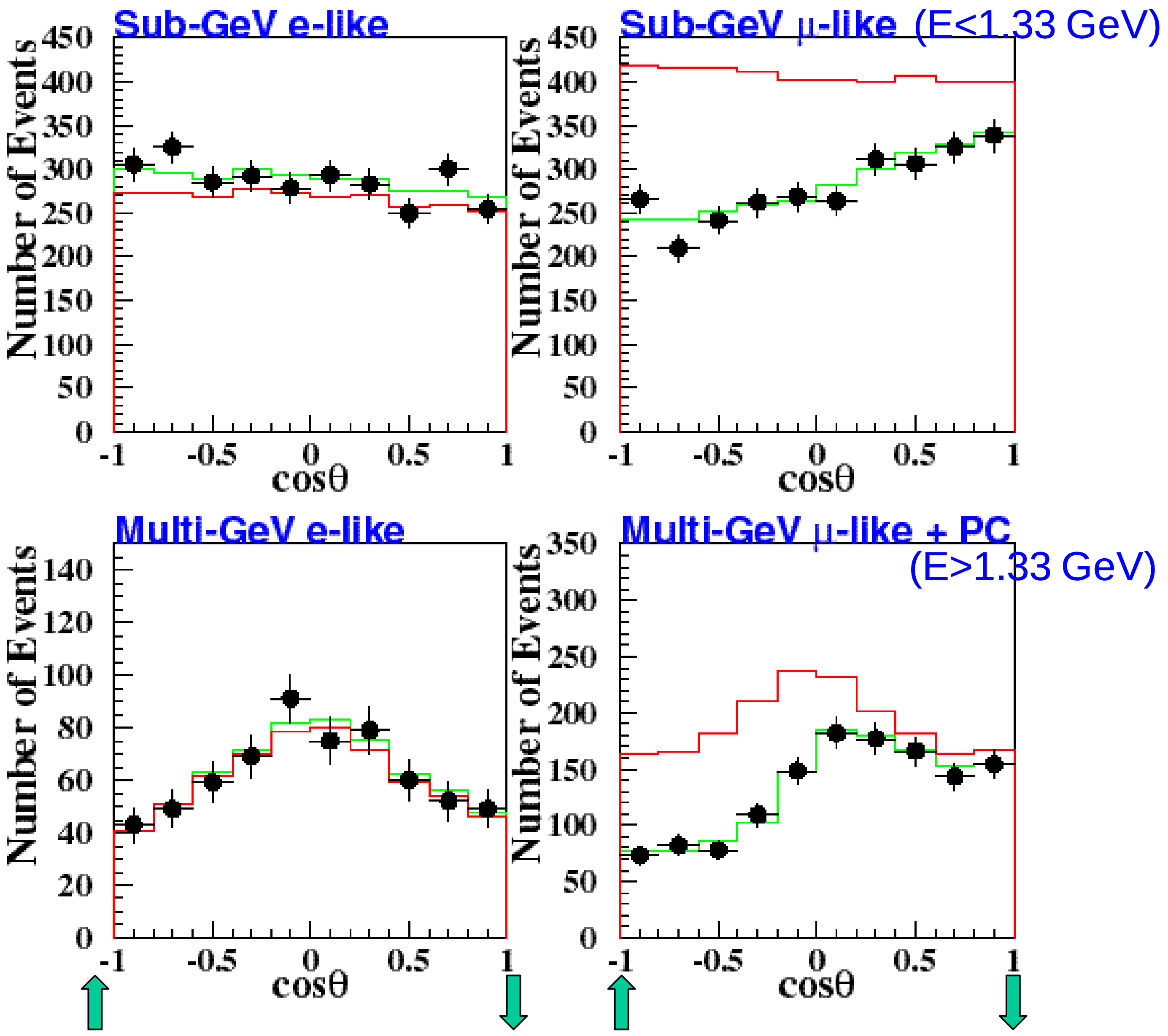
$$\frac{(\mu/e)_{Data}}{(\mu/e)_{MC}} = 0.675 \, {}^{+0.034}_{-0.032} \pm 0.080$$

Zenith angle distribution

1289 days (79.3 kt . yrs)

No oscillation

Best fit (Δm^2=2.4x$10^{-3}$$eV^2$, $\sin^2 2\theta$=1.00)



χ^2(best fit) = 132.4/137 d.o.f.

χ^2(no osc.) = 299.3/139 d.o.f.

$\Delta\chi^2$=167

Multi-ring event analysis

1289 days (79.3 kt . yrs)

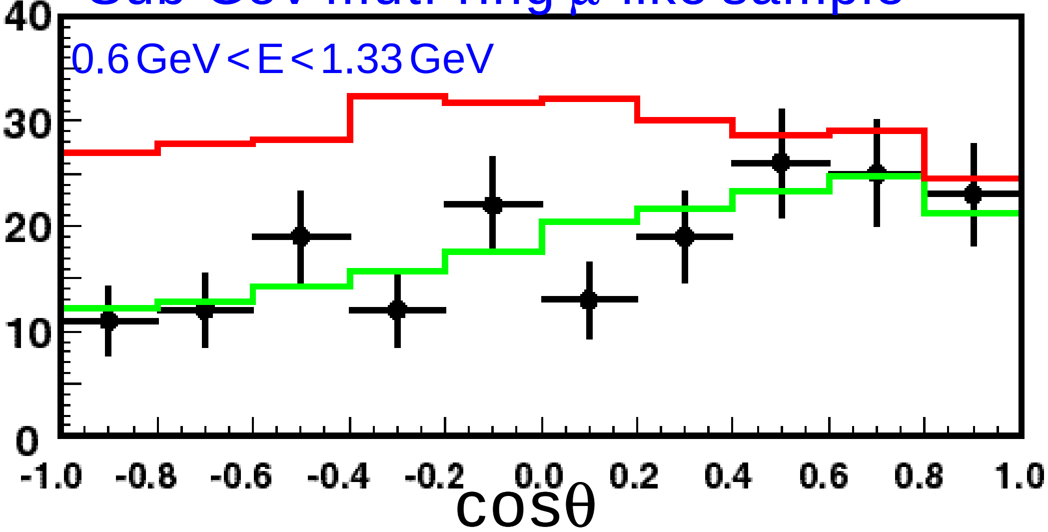
Zenith angle distributions

preliminary

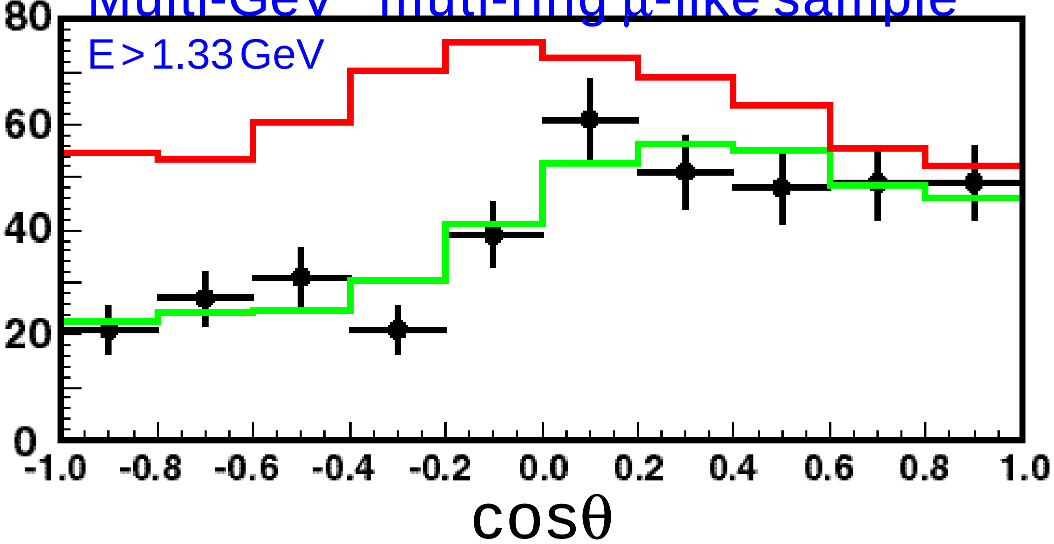
No oscillation

Best fit (Δm^2=2.0x10^{-3}eV^2, $\sin^2 2\theta$=1.00)

Sub-GeV muti-ring μ-like sample



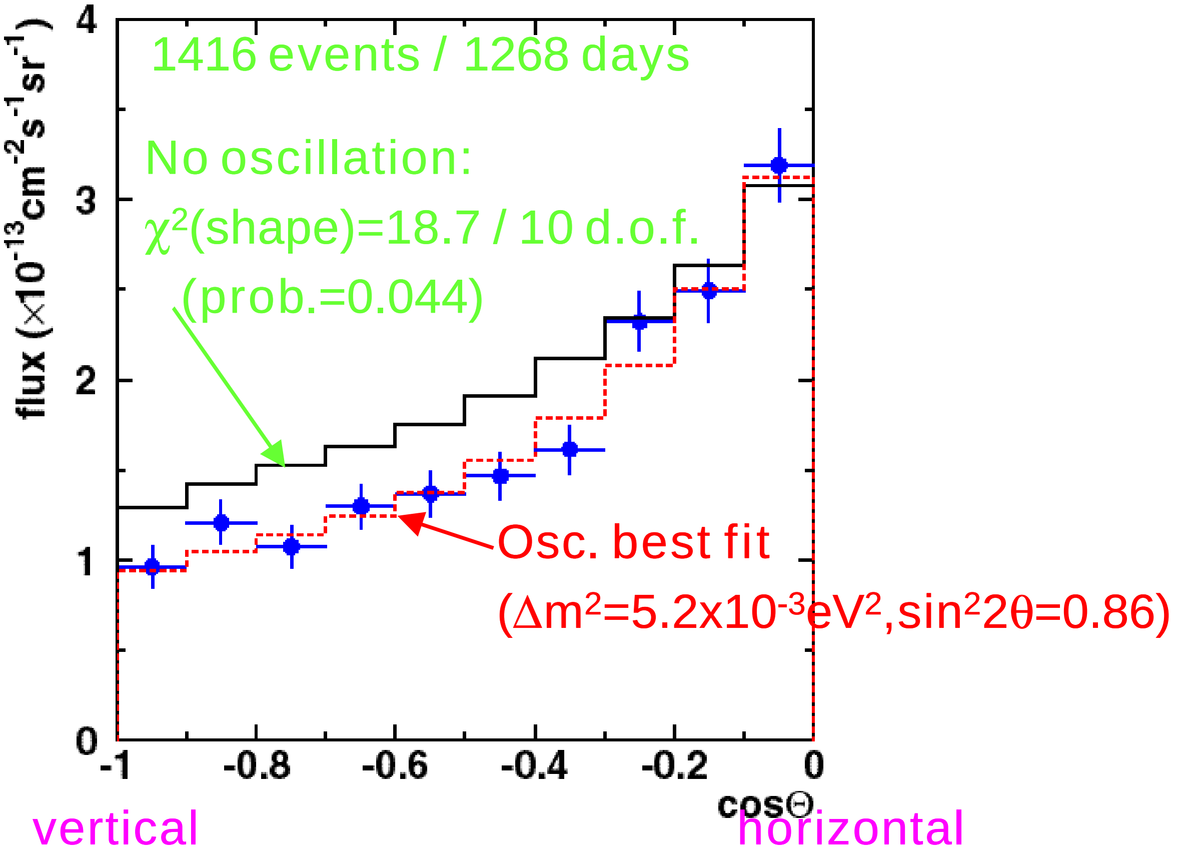
Multi-GeV muti-ring μ-like sample



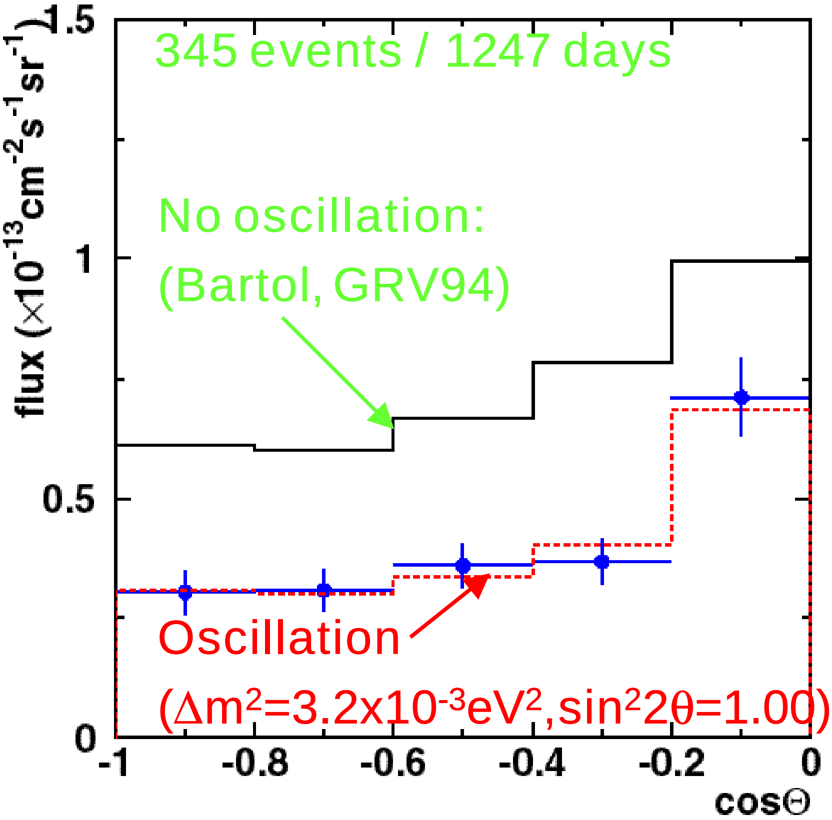
The zenith angle distortion is consistent with single-ring analysis.

Zenith angle distributions of upward-going muons

Upward through-going muons



Upward stopping muons



$$\frac{\left(\frac{\uparrow \text{stopping } \mu}{\uparrow \text{through } \mu}\right)_{Data}}{\left(\frac{\uparrow \text{stopping } \mu}{\uparrow \text{through } \mu}\right)_{MC}} = \frac{0.241 \pm 0.016 \;{}^{+0.013}_{-0.011}}{0.368 \;{}^{+0.049}_{-0.044}}$$

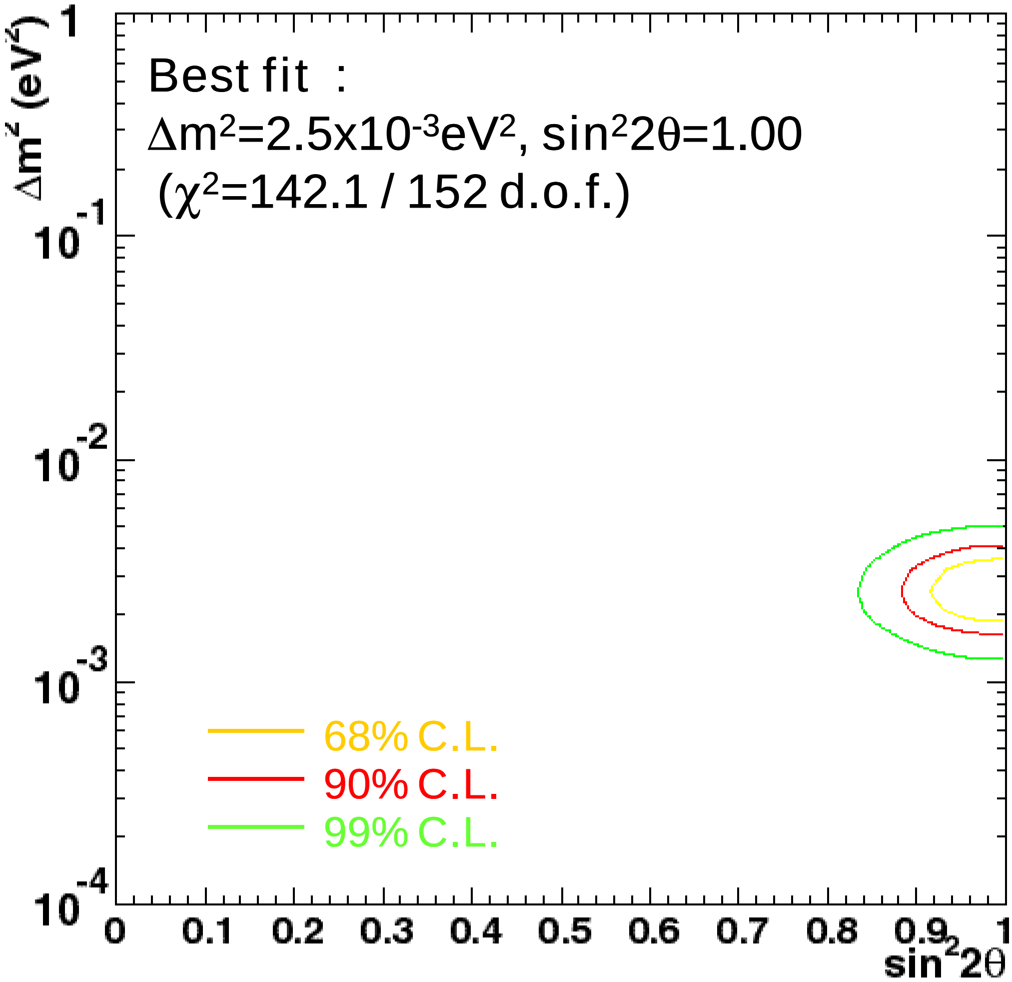
$$= 0.65 \pm 0.04 \pm 0.09$$

$$<< 1$$

Allowed region
(FC + PC + UP-thru + UP-stop)

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

79.3 kt . yrs

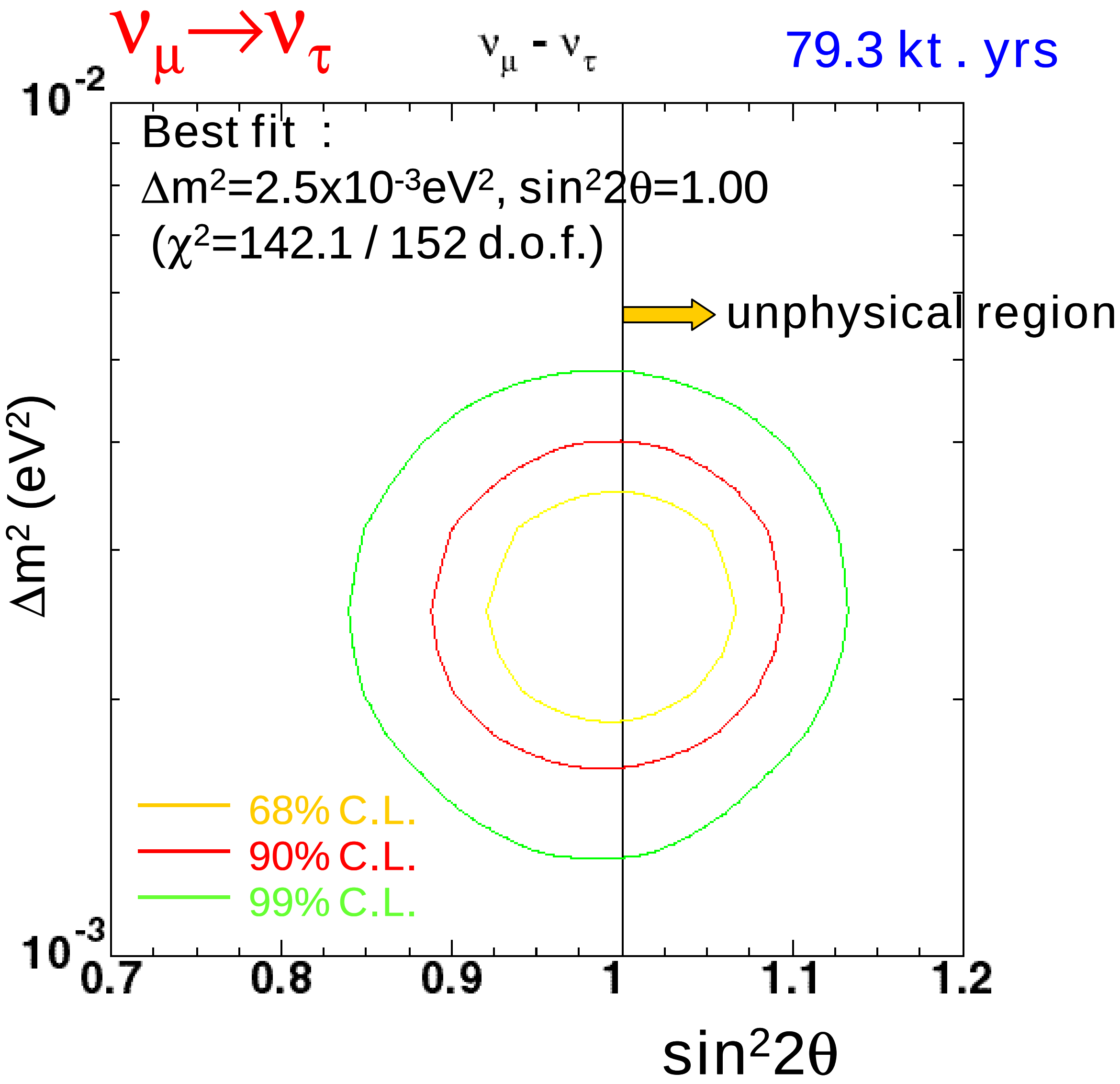


SK combined result

$\Delta m^2 = (1.7\sim4)\text{x}10^{-3}\text{eV}^2$

$\sin^2 2\theta > 0.89$ (90% C.L.)

Allowed region - II
(FC + PC + UP-thru + UP-stop)



SK combined result

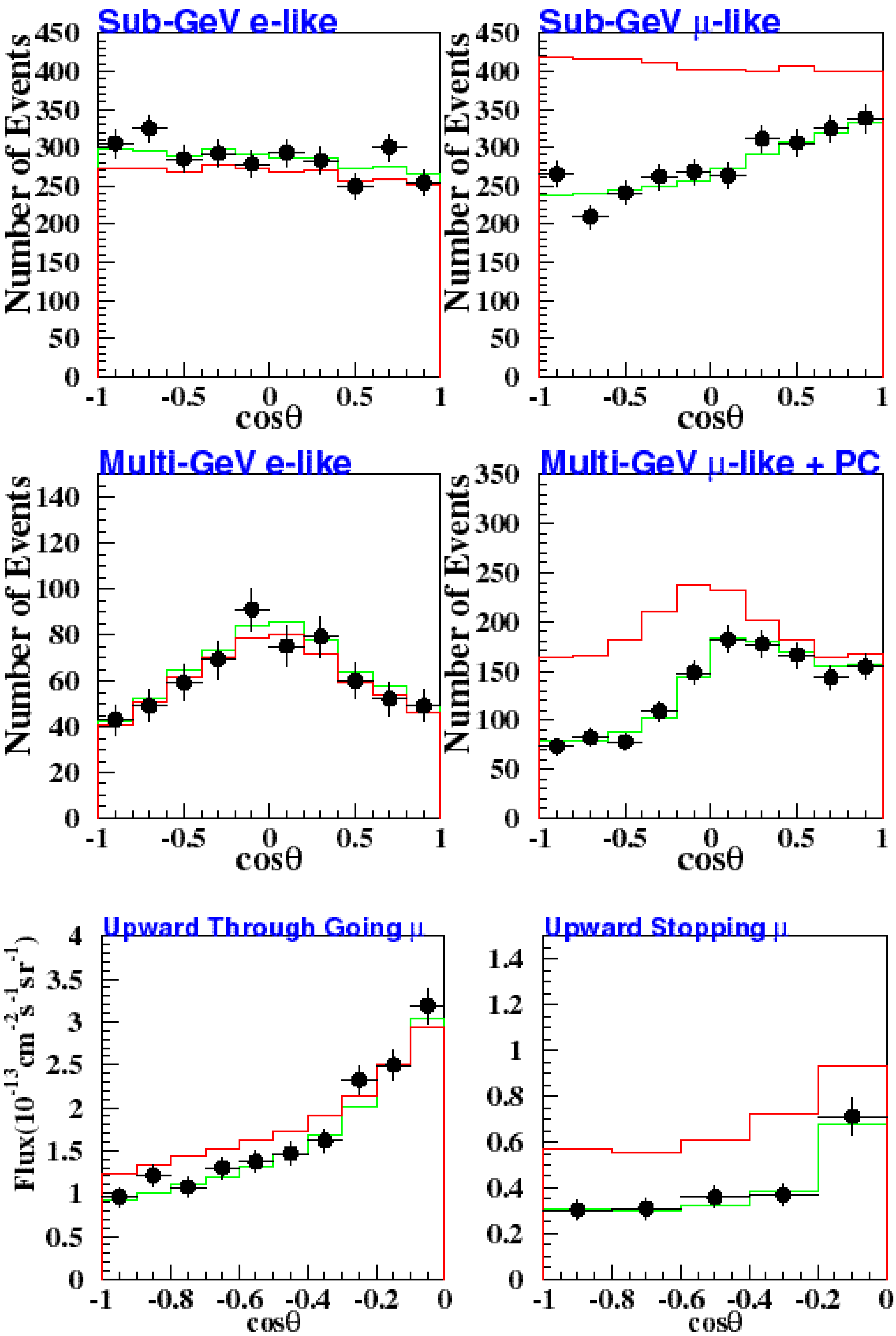
$\Delta m^2 = (1.7\sim4)\times10^{-3}$eV^2

$\sin^2 2\theta > 0.89$ (90% C.L.)

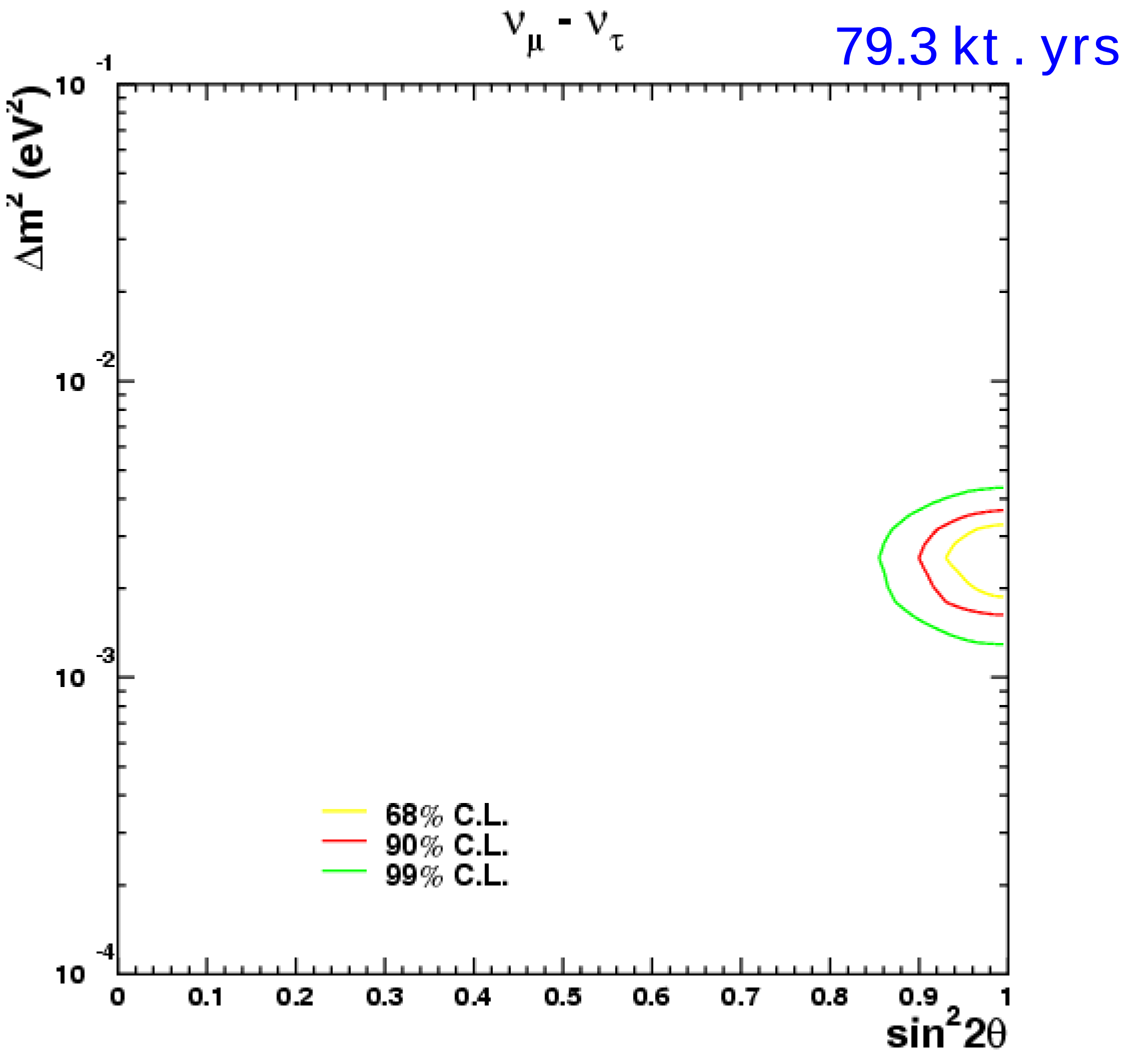
Zenith angle distributions for the best fit

No oscillation

Best fit ($\Delta m^2=2.5\times10^{-3}eV^2$, $\sin^2 2\theta=1.00$)



Allowed region (grand global fit)
(FC + PC + UP-thru + UP-stop + multi-rings)



Within physical region;

x^2min = 157.5/170 dof

at $\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.5\times10^{-3}$ eV^2

With unphysical region;

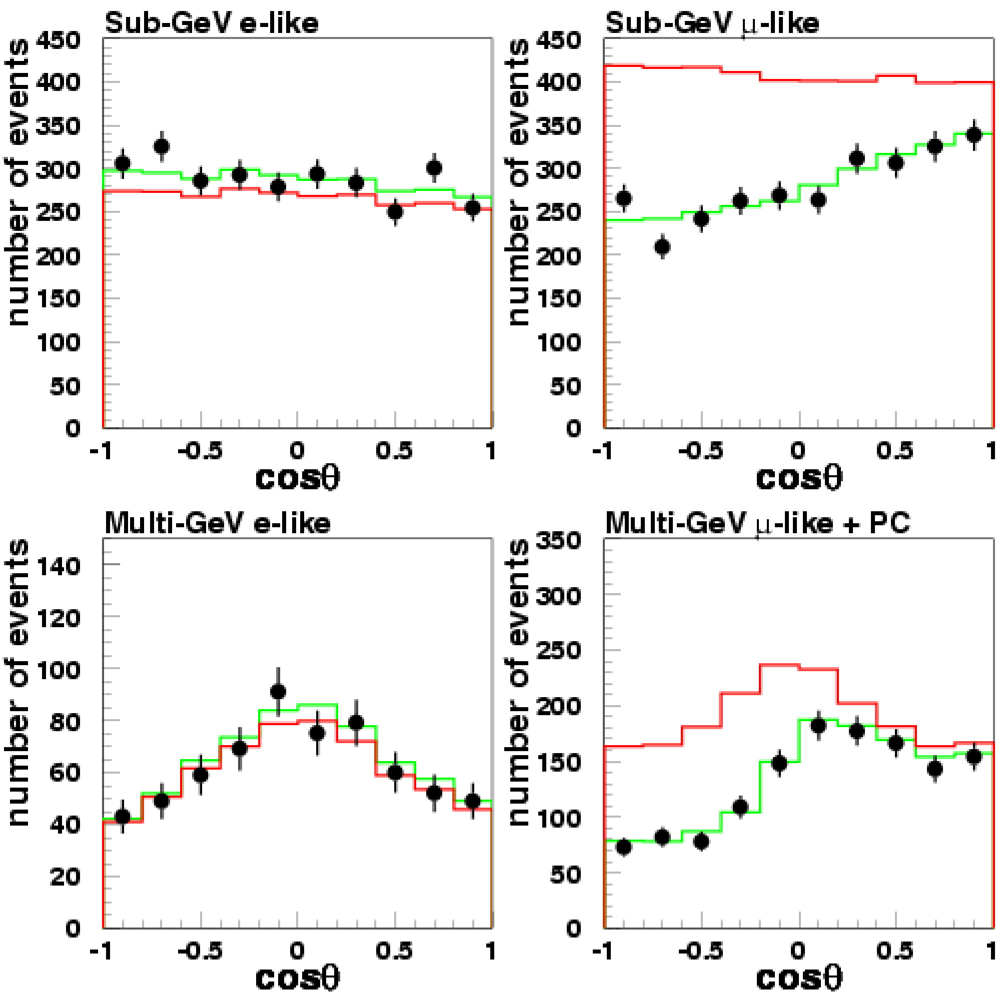
x^2min = 157.4/170 dof

at $\sin^2 2\theta = 1.01$, $\Delta m^2 = 2.5\times10^{-3}$ eV^2

Zenith angle distributions for the best fit (grand global fit)

No oscillation

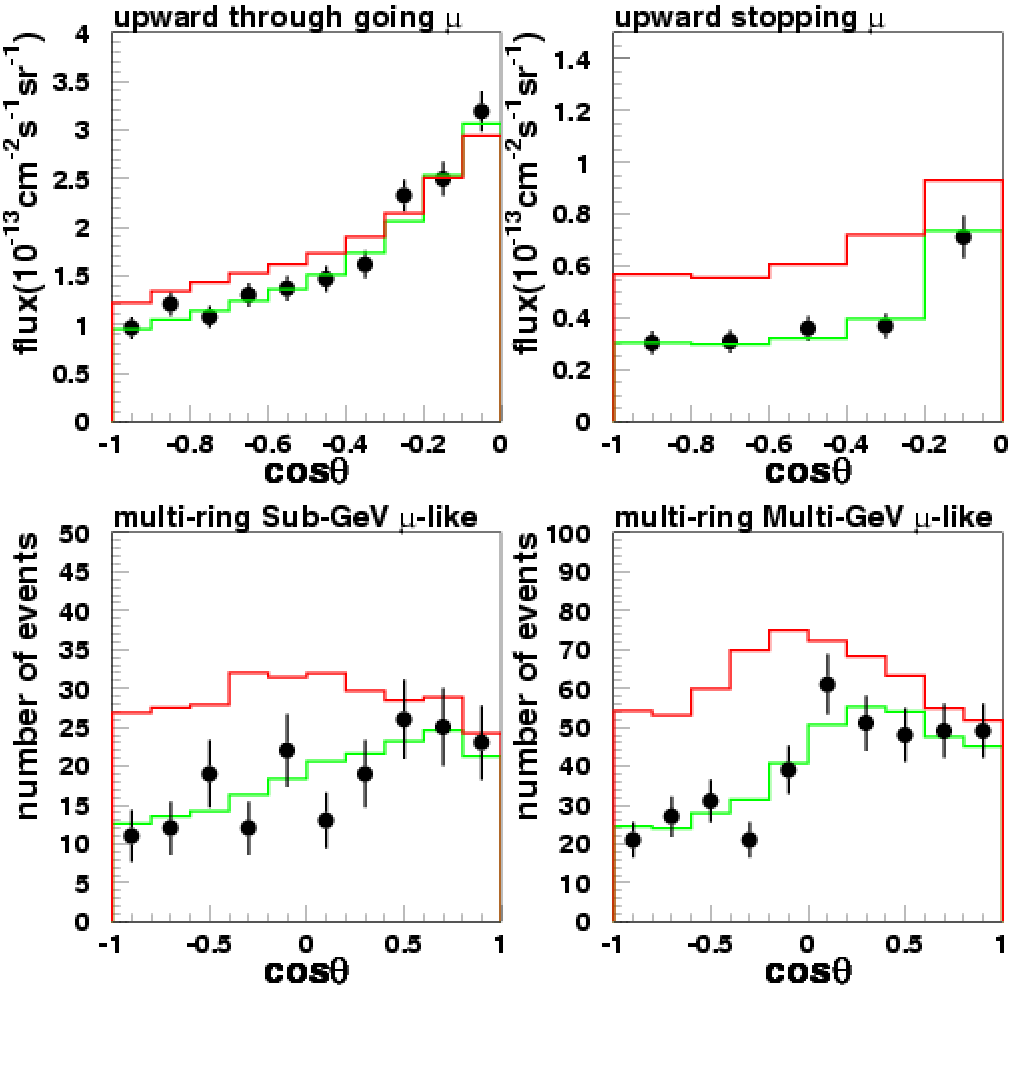
Best fit ($\Delta m^2 = 2.5\times10^{-3} eV^2$, $\sin^2 2\theta = 1.00$)



Zenith angle distributions for the best fit (cont) (grand global fit)

No oscillation

Best fit ($\Delta m^2=2.5\times10^{-3}eV^2$, $\sin^2 2\theta=1.00$)



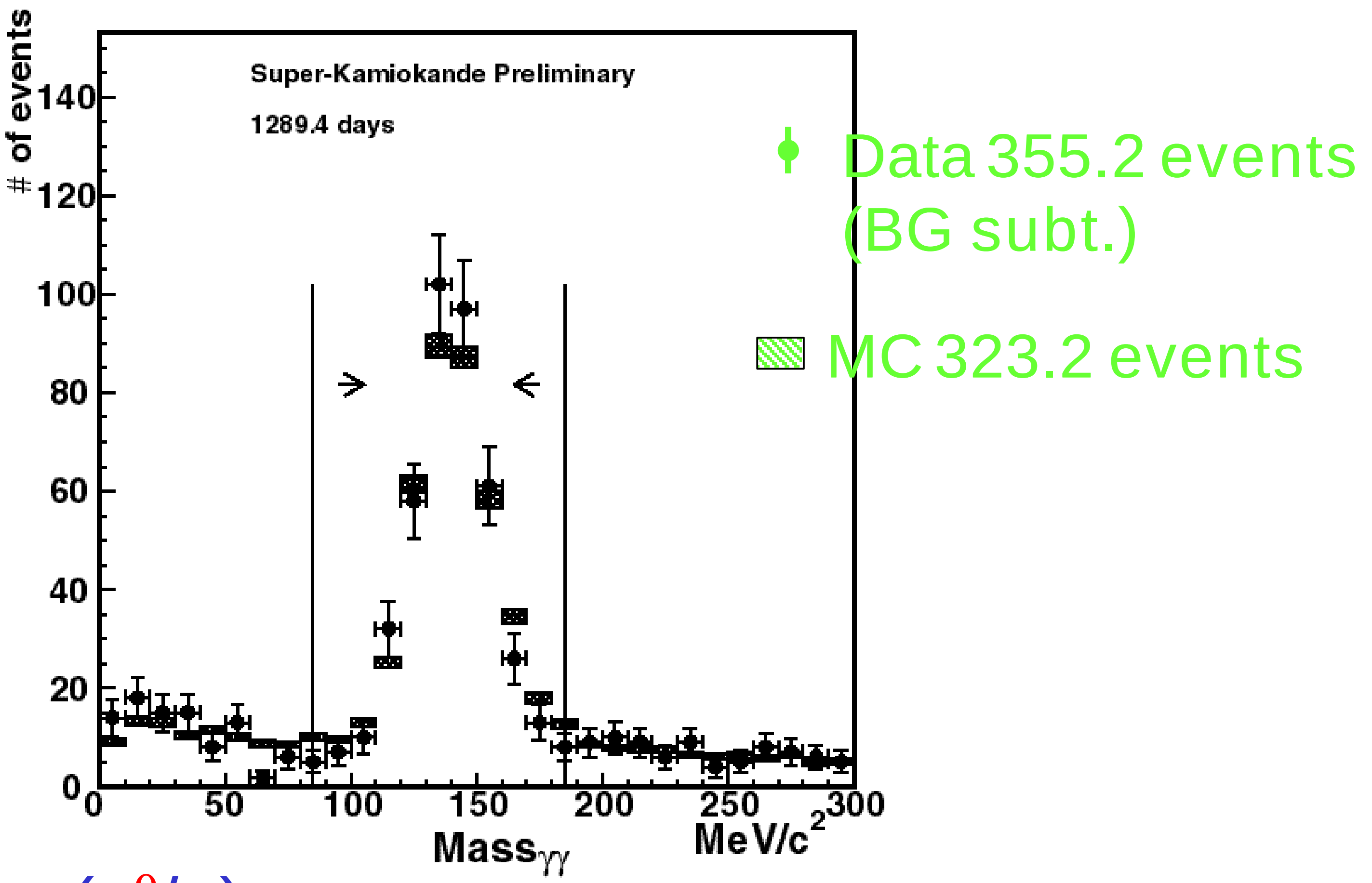
Systematics in the 1D fit

Combined Systematic Errors

		σ_i	best fit
α	Absolute Normalization Uncertainty	Free	3.4 %
δ	Eν Spectrum Index	0.05	-0.01
β_L	SubGeV μ/e Ratio	8 %	-5.9 %
β_H	MultiGeV μ/e Ratio	12 %	-12 %
ρ	FC/PC Relative Normalization	8 %	1.1 %
η_L	SubGeV Up/Down Asymmetry	2.4 %	-1.9 %
η_H	MultiGeV Up/Down Asymmetry	2.7 %	-0.6 %
β_1	FC+PC/Through ↑μ Relative Normalization	7 %	8.7 %
β_2	Through ↑μ/Stop ↑μ Relative Normalization	7 %	-0.7 %
	FC+PC Horizontal/Vertical Uncertainty	4 %	0.2 %
	↑μ Horizontal/Vertical Uncertainty	3 %	0.2 %
	L/E Uncertainty	15 %	-2.5 %
	Mulit-ring/1 ring (Sub-GeV) Relative Normalization	Free	-14.1 %
	Mulit-ring/1 ring (Multi-GeV) Relative Normalization	Free	-15.7 %

$\nu_\mu \rightarrow \nu_{sterile}$ (π^0 method)

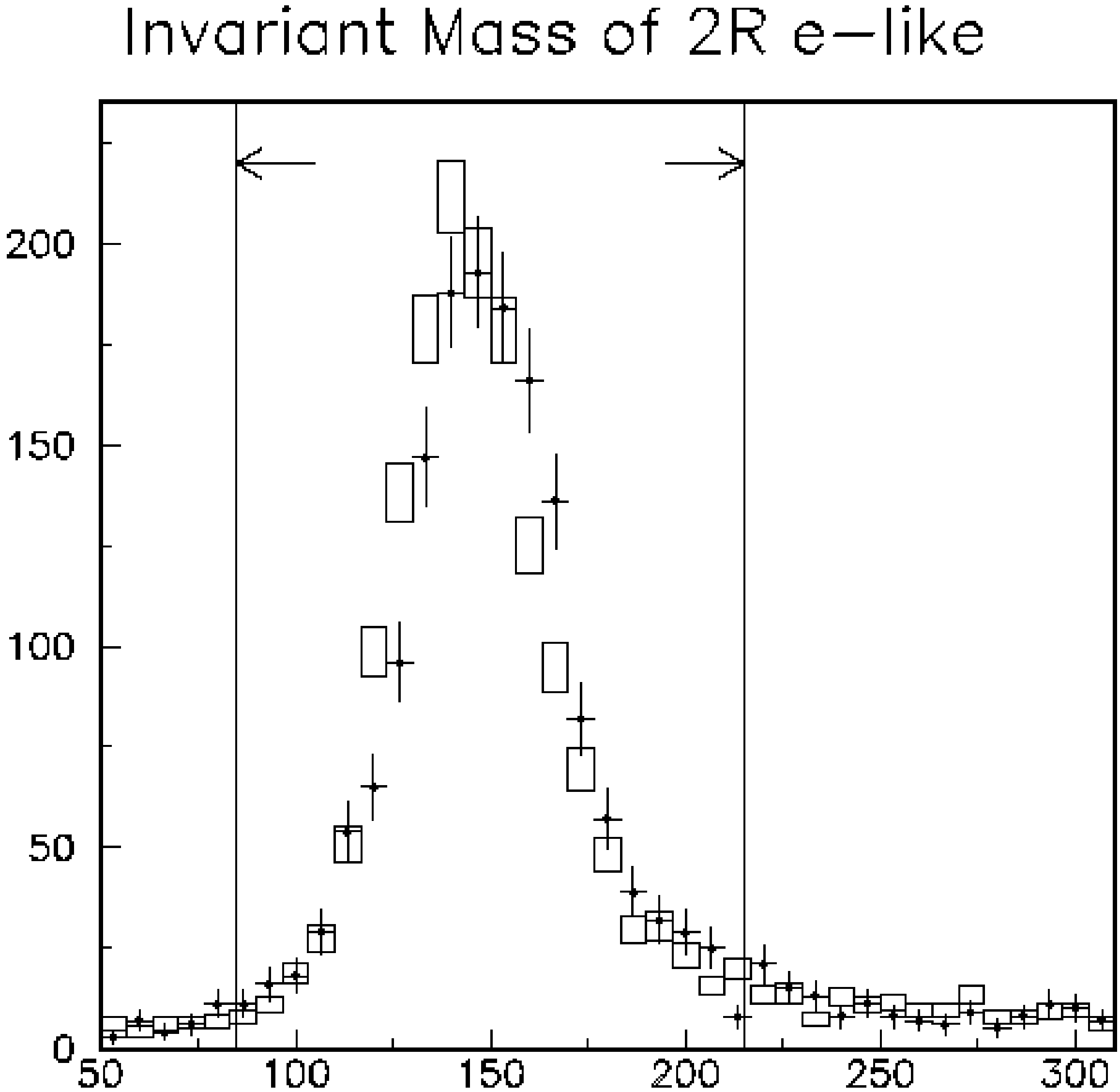
$$\frac{(\pi^0/\mu)_{Data}}{(\pi^0/\mu)_{MC}} \begin{cases} > 1 & \text{for } \nu_\mu \rightarrow \nu_\tau \\ \approx 1 & \text{for } \nu_\mu \rightarrow \nu_s \end{cases}$$



$$\frac{(\pi^0/\mu)_{Data}}{(\pi^0/\mu)_{MC}} = 1.49 \pm 0.08(\text{stat.}) \pm 0.11(\text{sys.})$$

Experimental only

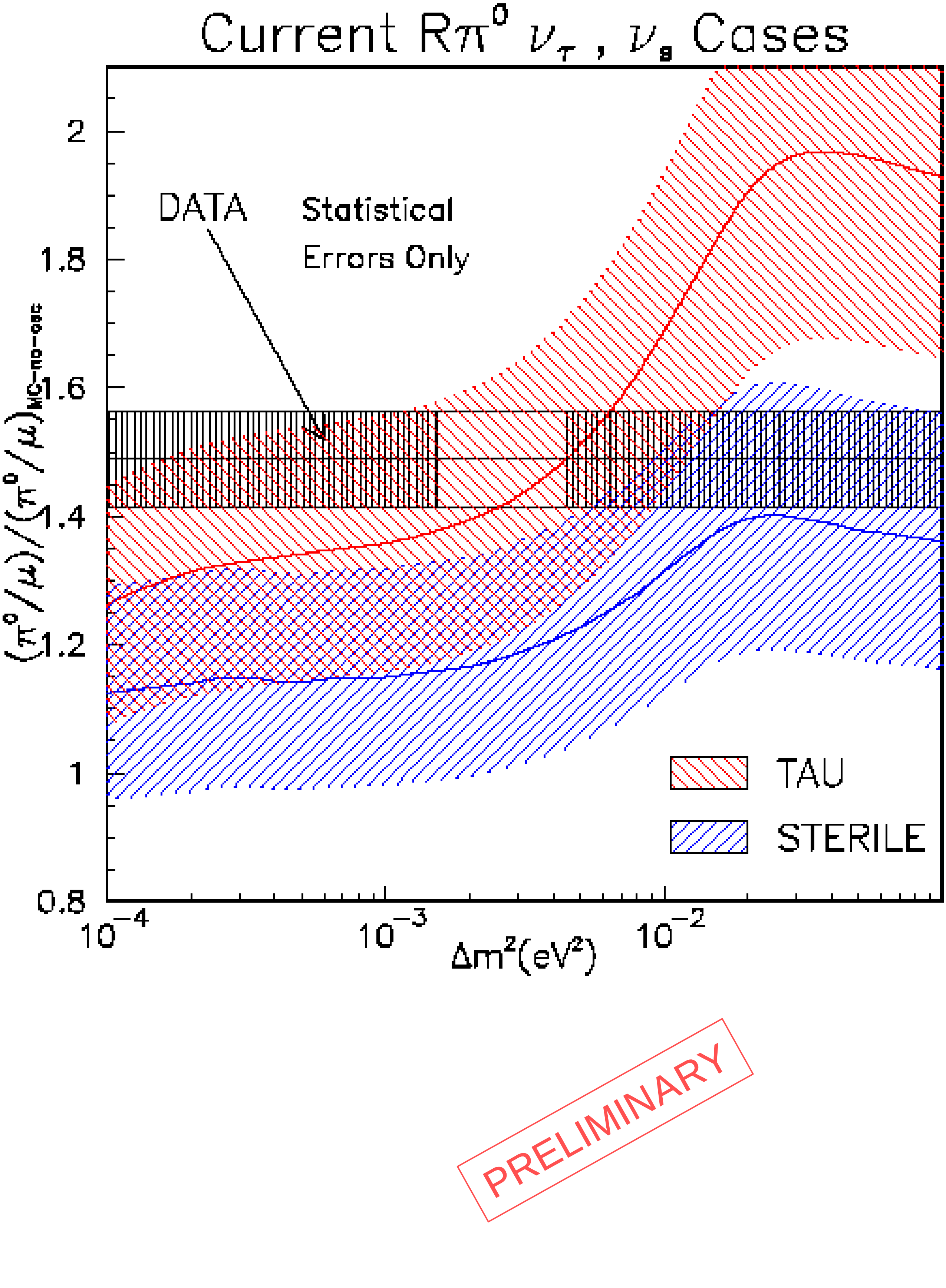
π^0 info from K2K-1kt



$$\frac{\left(\frac{\pi^0}{\text{FC-}\mu}\right)_{\text{data}}}{\left(\frac{\pi^0}{\text{FC-}\mu}\right)_{\text{MC}}} = 0.99 \pm 0.03 \pm 0.1$$

PRELIMINARY

$(\pi^0/\mu)_{data}$ vs $(\pi^0/\mu)_{MC\text{-}no\text{-}osc}$



$\nu_\mu \to \nu_{sterile}$ (matter in earth)

Using matter effect and enriched NC sample

$\nu_\mu \to \nu_\tau$: No matter effect

$\nu_\mu \to \nu_s$: With matter effect

Neutrino oscillation in matter:

$$\begin{pmatrix} \nu_\mu \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\zeta - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\zeta = -\sqrt{2}\, G_F n_n E_\nu / \Delta m^2$$

For $\sin^2 2\theta = \sim 1$ $\quad \sin^2 2\theta_m \sim \dfrac{1}{\zeta^2 + 1}$

And for $E_\nu = 30 \sim 100$ GeV → $\zeta >> 1$ and

$\sin^2 2\theta_m << 1$

Suppression !

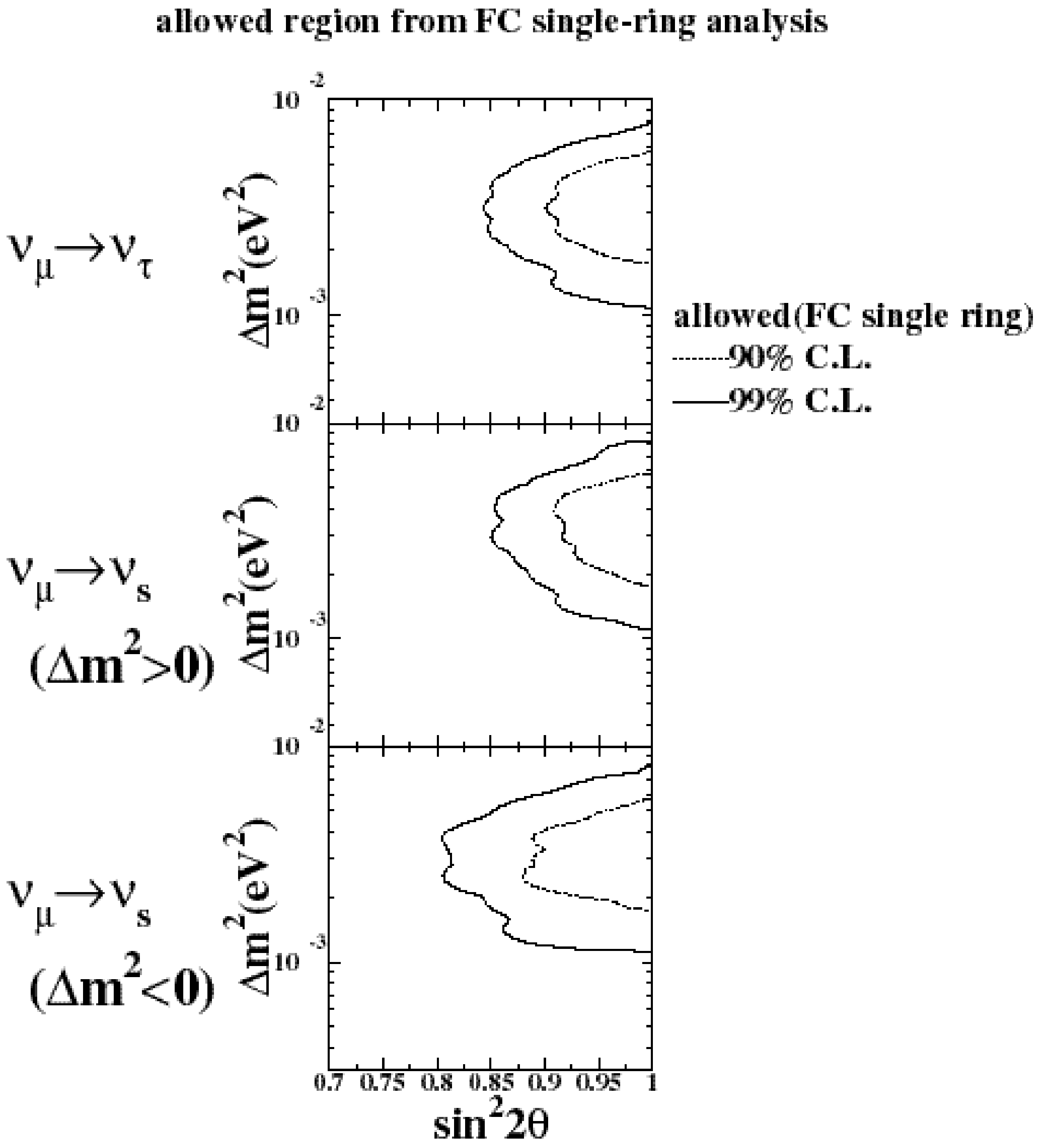
Strategy:

Obtain allowed region using lower energy events (Fully contained sample)

Then,

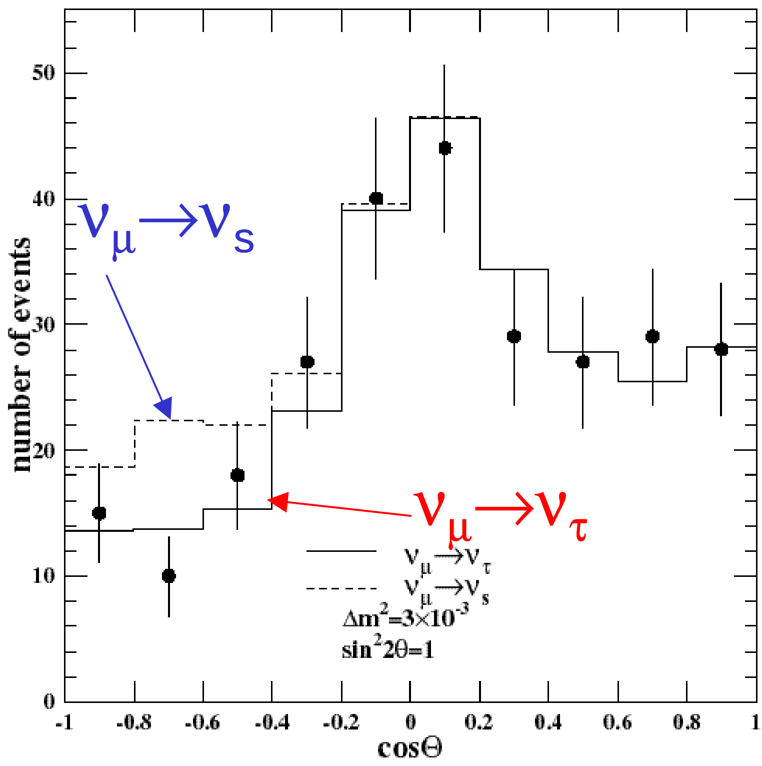
Test zenith angle of NC enriched events, high energy PC and through-going muon events.

Allowed region using only FC events



Zenith angle of high energy PC events

zenith angle distribution of high E (E_{vis}>5GeV) PC events (1144days)



> 45000 p.e.

(E> ~ 5 GeV)

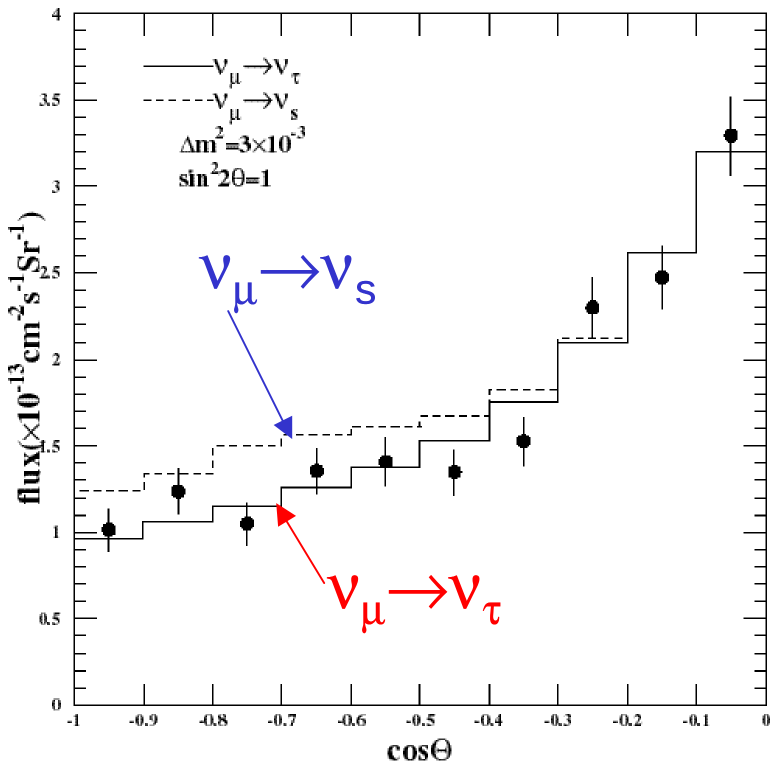
<E>=~25 GeV

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

$\sin^2 2\theta = 1$

Zenith angle of upward-going muon

zenith angle distribution of upward through going μ events (1138days)



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

$\sin^2 2\theta = 1$

Zenith angle of NC enriched events

Criteria

> 400 MeV visible energy

Multi-ring event

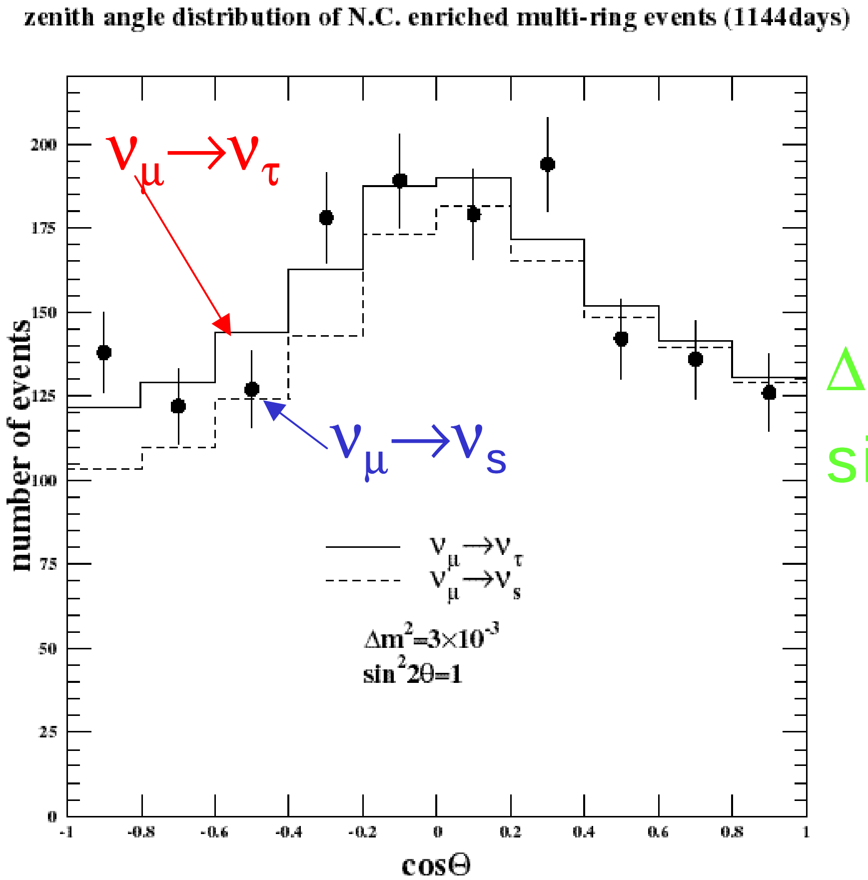
e-like ring is the most energetic ring

Contents

NC : 29 %

ν_e CC : 46 %

ν_μ CC : 25 %

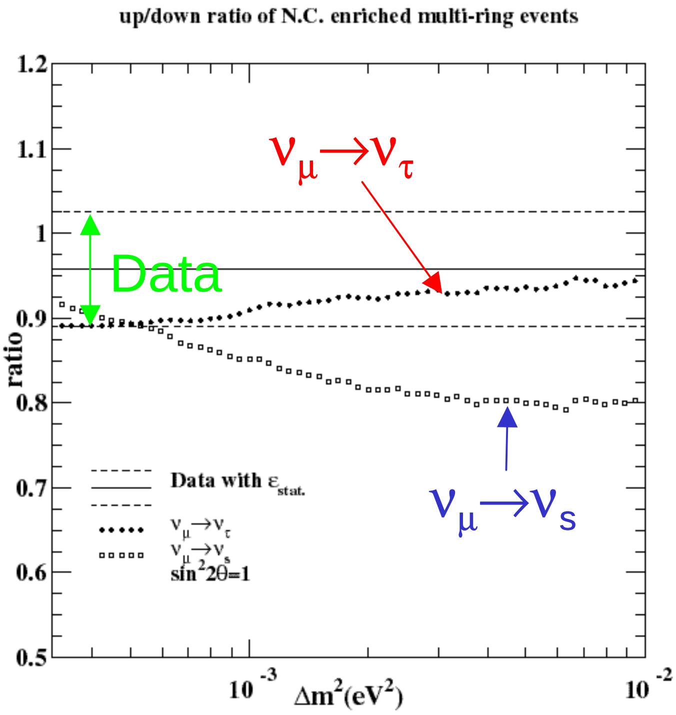


$\Delta m^2 = 3 \times 10^{-3} eV^2$

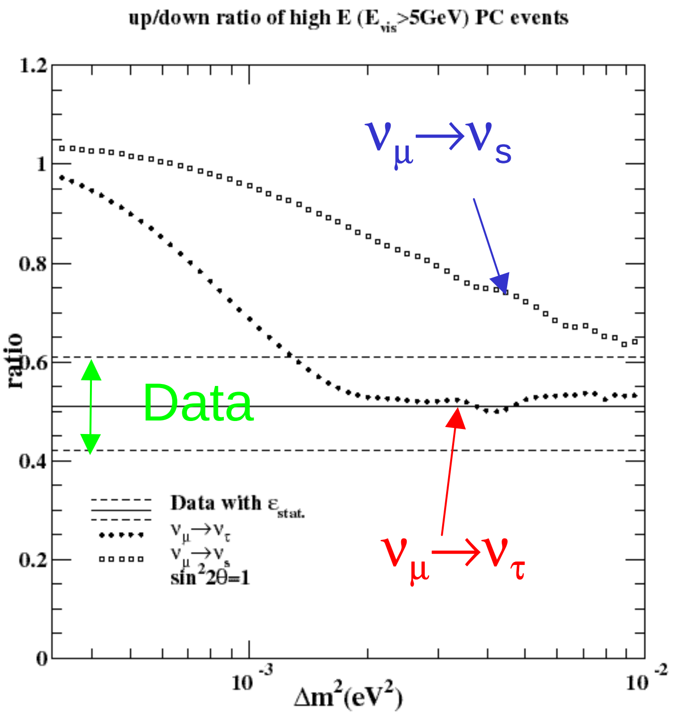
$\sin^2 2\theta = 1$

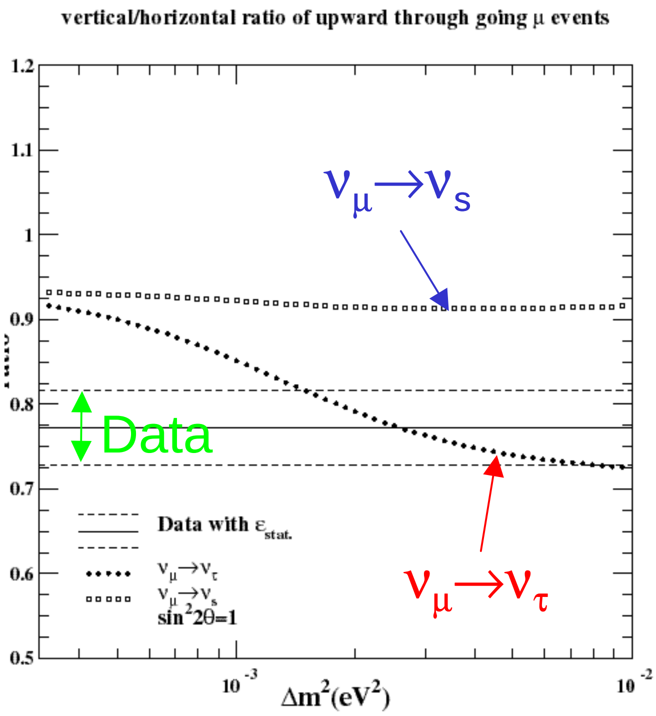
Ratios vs. Δm^2

$\sin^2 2\theta = 1$



Up/Down ($\cos\Theta$ $\lessgtr$ $^{<-0.4}_{>0.4}$)
ratio of NC enriched
multi-ring





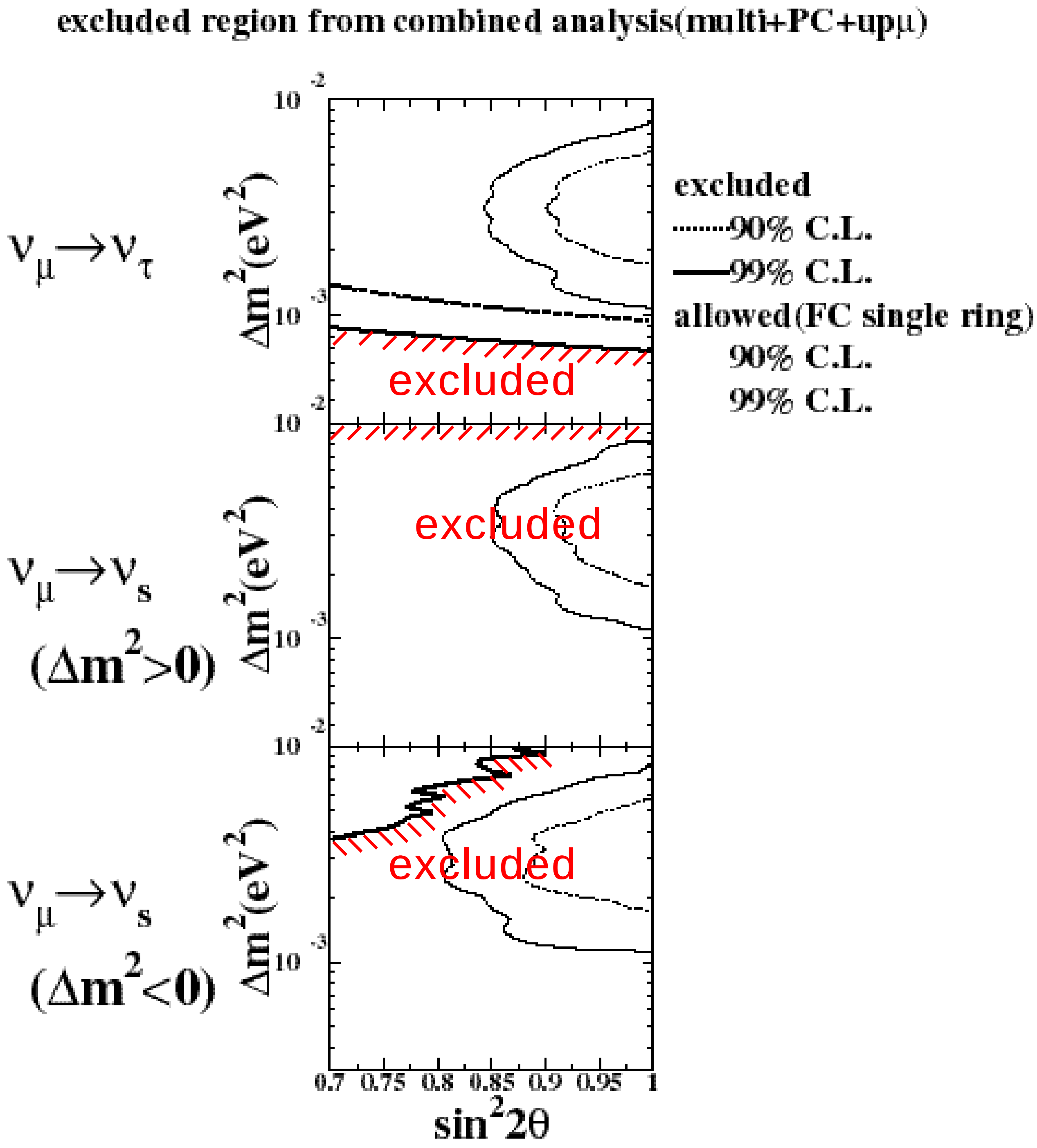
10^{-3} 10^{-2} eV^2 10^{-3} 10^{-2} eV

Up/Down ($\cos\Theta$ $^{<-0.4}_{>0.4}$)
ratio of High Energy PC

Vertical/Horizontal ratio
($\cos\Theta \gtrless -0.4$) of up muons

Allowed vs. excluded regions

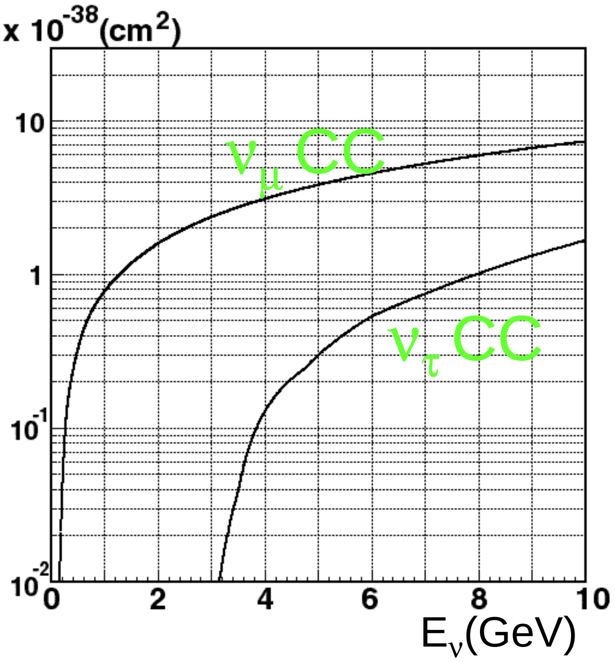
combine NC enriched, high E PC and up muons



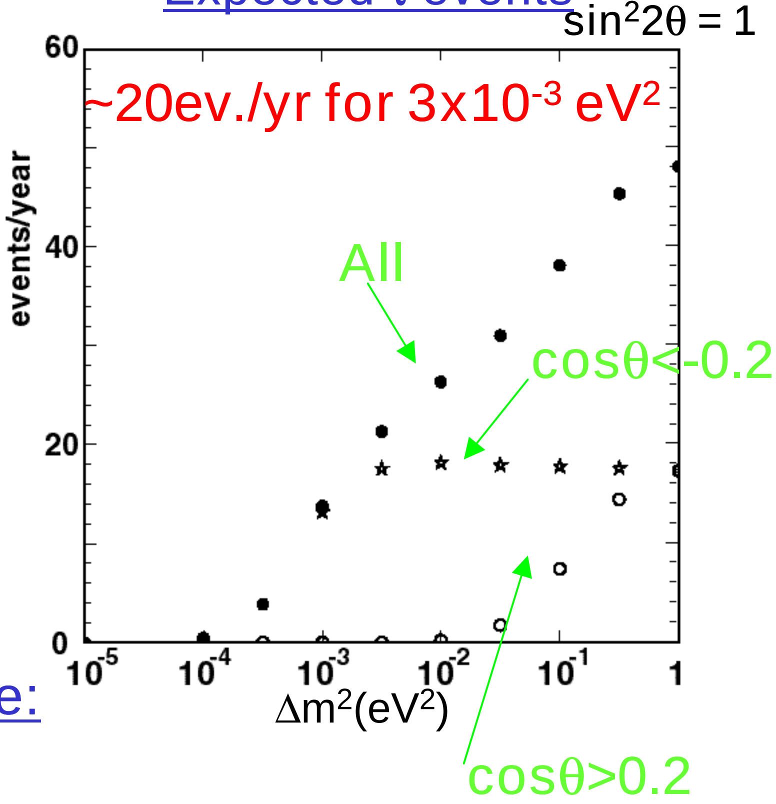
$\nu_\mu \rightarrow \nu_s$ is excluded with 99 % C.L.

Search for τ leptons

Neutrino CC cross sections



Expected τ events



Signature of τ appearance:

$\nu_\tau + N \rightarrow \tau + N' + \pi + \pi$ .....

↳ $\mu\nu\nu$, $e\nu\nu$, ν+hadrons(π,π,....)

- Higher multiplicity of Cherenkov rings
- More $\mu \rightarrow e$ decay signals
- More spherical event pattern

Search for τ appearance (3 methods) :

(1) Energy flow and event shape analysis

(2) Likelihood method using # of rings, $\mu \rightarrow e$, max p.e. ring and etc.

(3) Neural network method

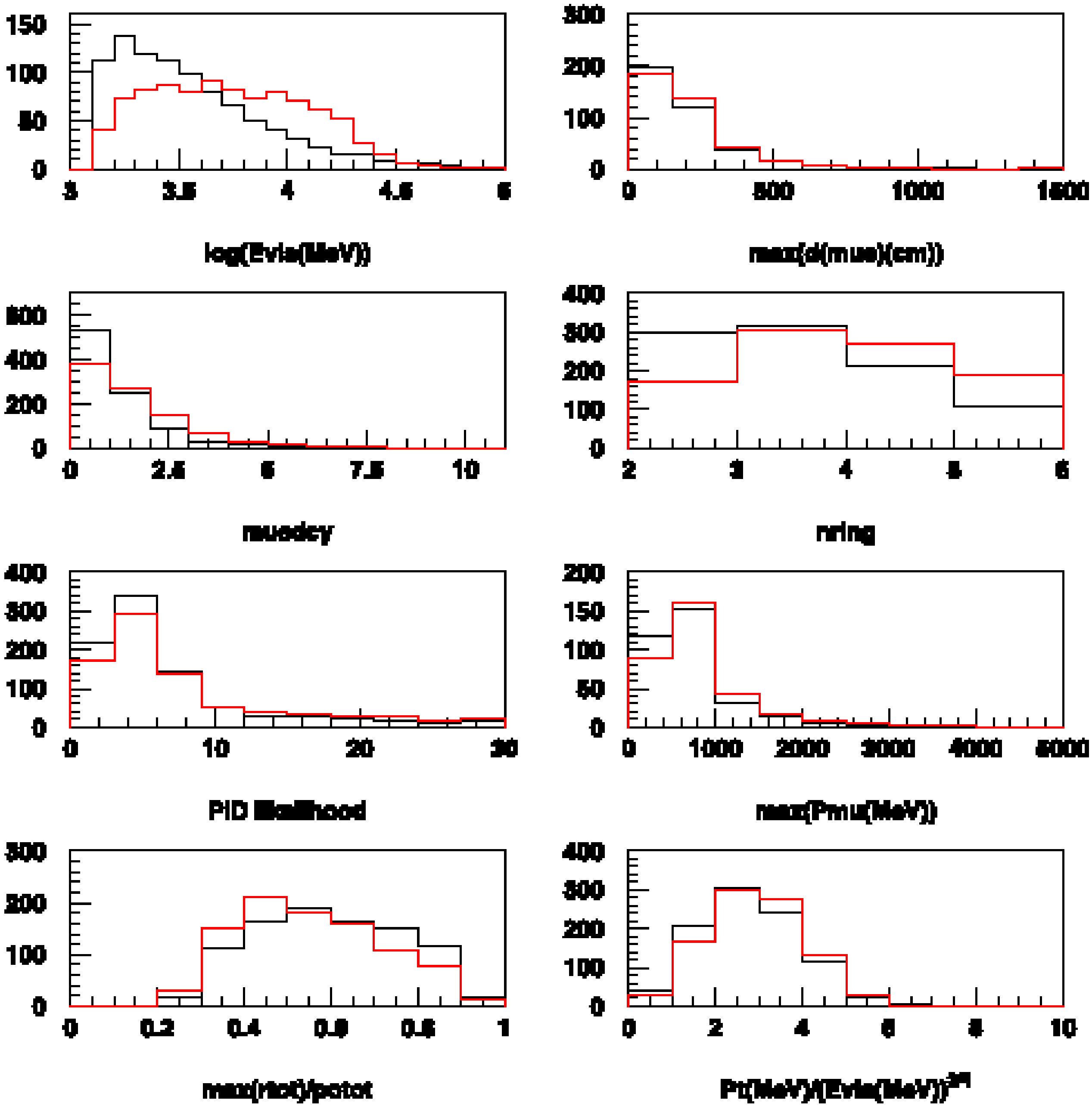
Each method is optimized using only downward going events and then looks at upward going events.

(I.e. blind method to disable systematic bias.)

Multi-ring samples

— : atm $\nu_\mu + \nu_e$ w/o ν_τ

— : ν_τ CC



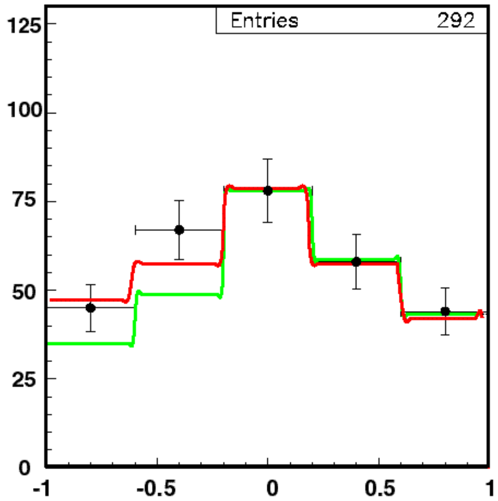
Zenith-angle distribution

MC without τ

MC with τ

$\Delta m^2=3\times10^{-3}eV^2$, $\sin^2 2\theta=1.00$

(expected # of τ : 74 events)

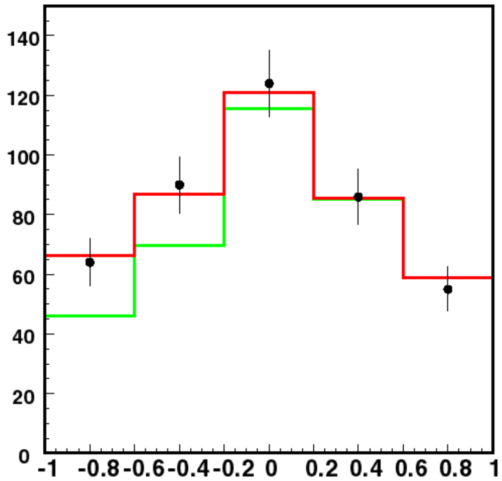


Energy flow method

Observed # of τ : 25.5 $^{+14}_{-13}$

Efficiency for τ: 32 %

of τ production: 79 $^{+44}_{-40}$

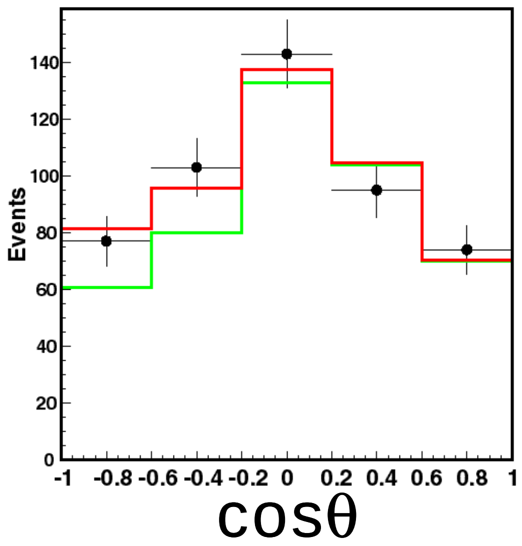


Likelihood method

Observed # of τ : 27 $^{+17}_{-16}$ $^{+9}_{-8}$

Efficiency for τ : 43.5 %

of τ production: 62 $^{+39}_{-27}$ $^{+21}_{-18}$



Neural network method

Observed # of τ : 42 $\pm$19 $^{+13}_{-13}$

Efficiency for τ : 45 %

of τ production: 92 $\pm$35.3 $^{+14}_{-0}$

All methods show ~2σ excess of τ-like events.

The result is consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations.

Probability of exotic oscillation models

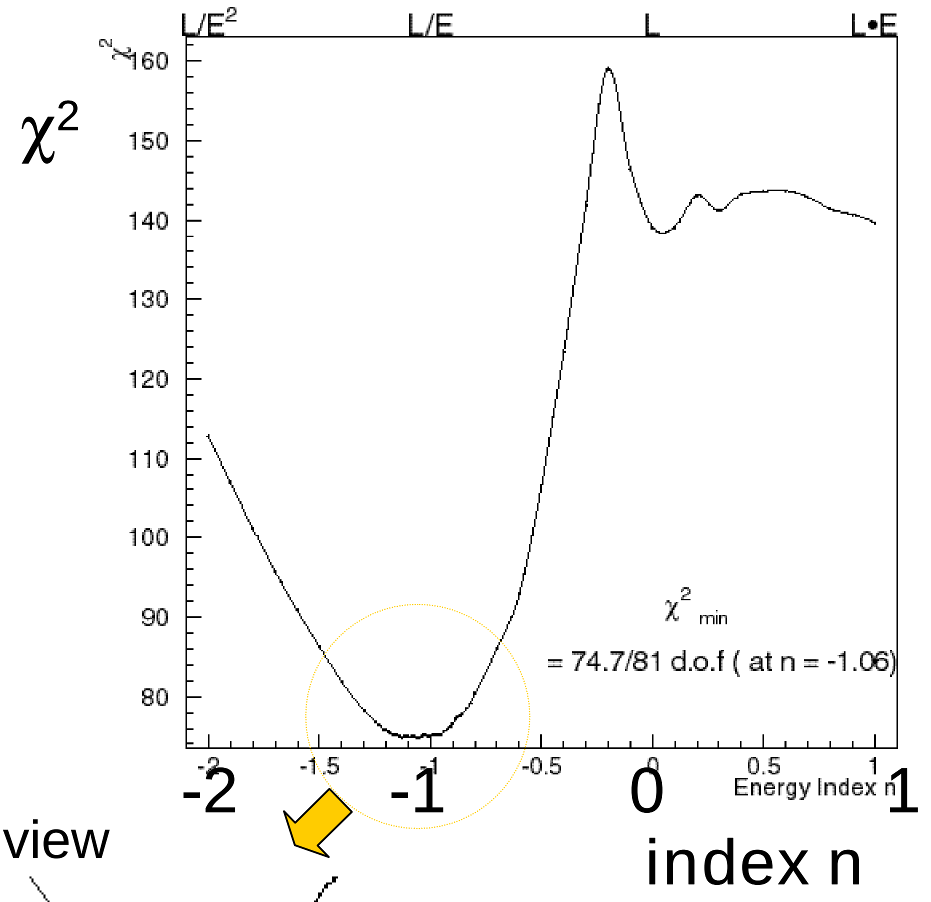
Test $\nu_\mu \rightarrow \nu_\tau$ oscillation with :

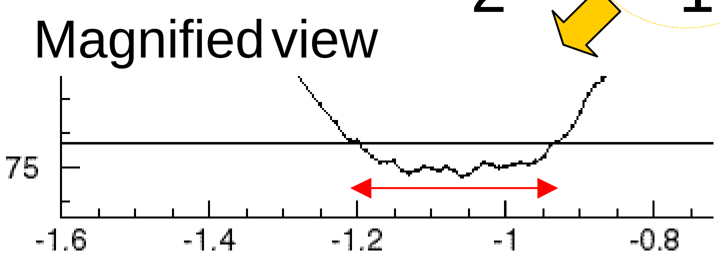
$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \, \sin^2(\beta L \times E^n)$

(θ, β, n : parameters)

n=-1 is the standard neutrino oscillation

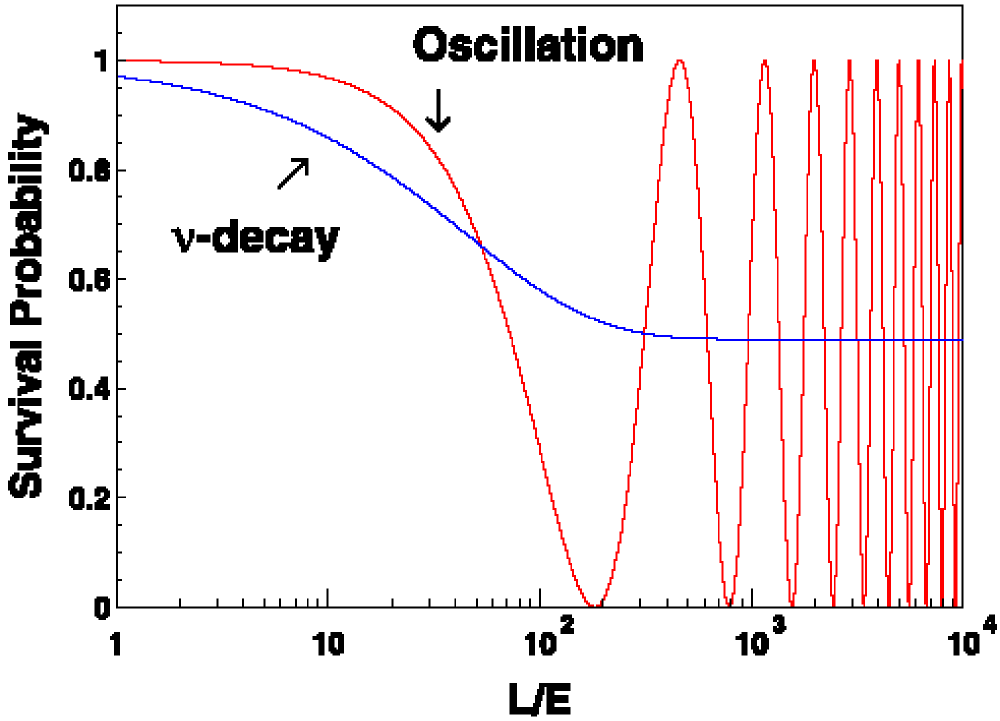
Use FC, PC, Up-through, and Up-stop data





$n = -1.06 \pm 0.14$

Neutrino decay



Let neutrinos oscillate and decay $\nu_3 \rightarrow X(\text{invis})$;

$$P(\nu_\mu \rightarrow \nu_\mu) = \sin^4\theta + \cos^4\theta \exp\left(-\frac{m_3}{\tau_3}\frac{L}{E}\right)$$

$$+ \quad \sin^2\theta \exp\left(-\frac{m_3}{2\tau_3}\frac{L}{E}\right)\cos\left(\frac{\Delta m^2 L}{2E}\right)$$

Consider two cases;

$\lambda dcy >> \lambda osc$, and $\lambda dcy << \lambda osc$,

where

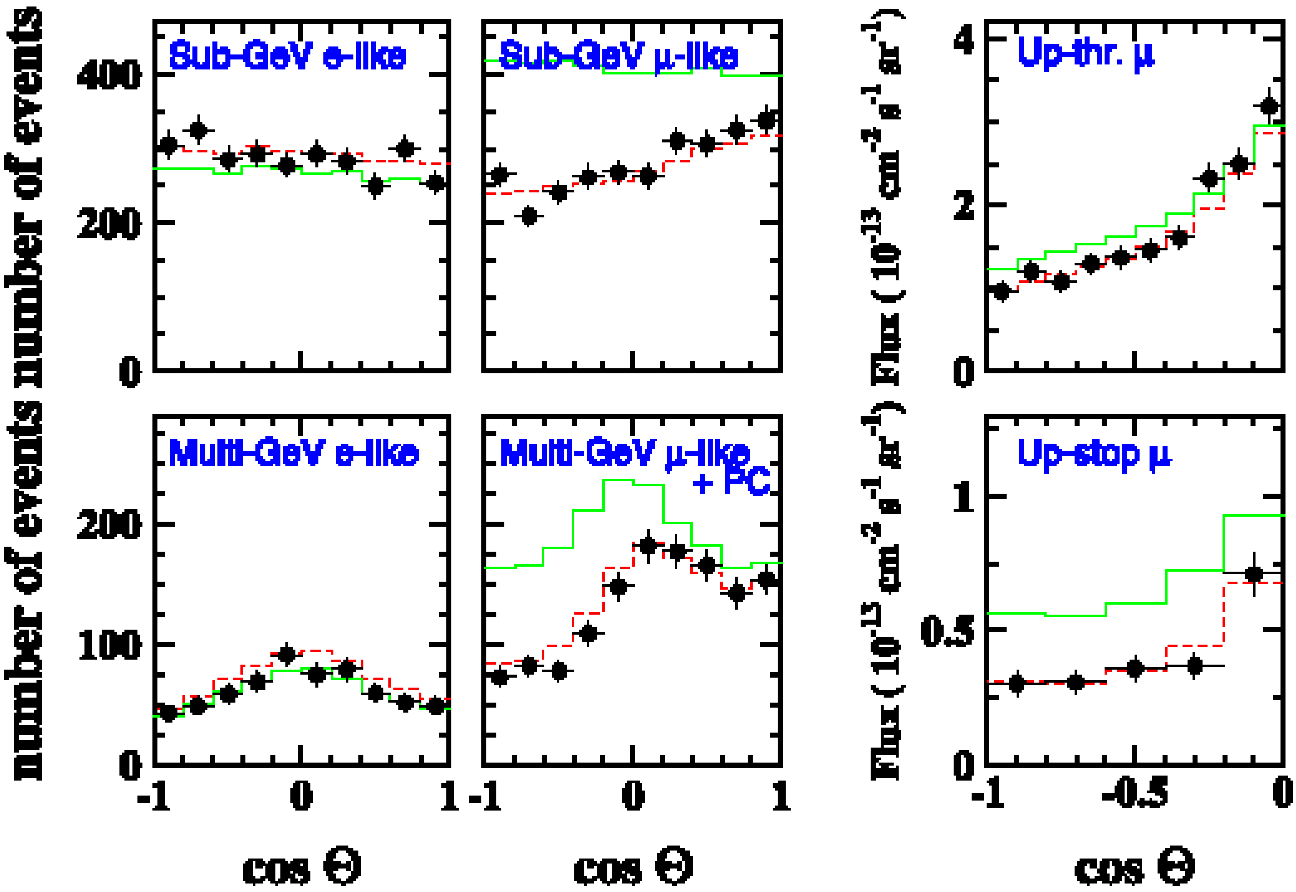
$$\lambda_{dcy} = \frac{\tau_3 E}{m_3} \quad , \lambda_{osc} = \frac{4\pi E}{\Delta m^2}$$

λdcy >>λosc

For $\Delta m^2 \rightarrow \infty$,

χ^2_{min} = 221.2/153 dof

Bad fit !



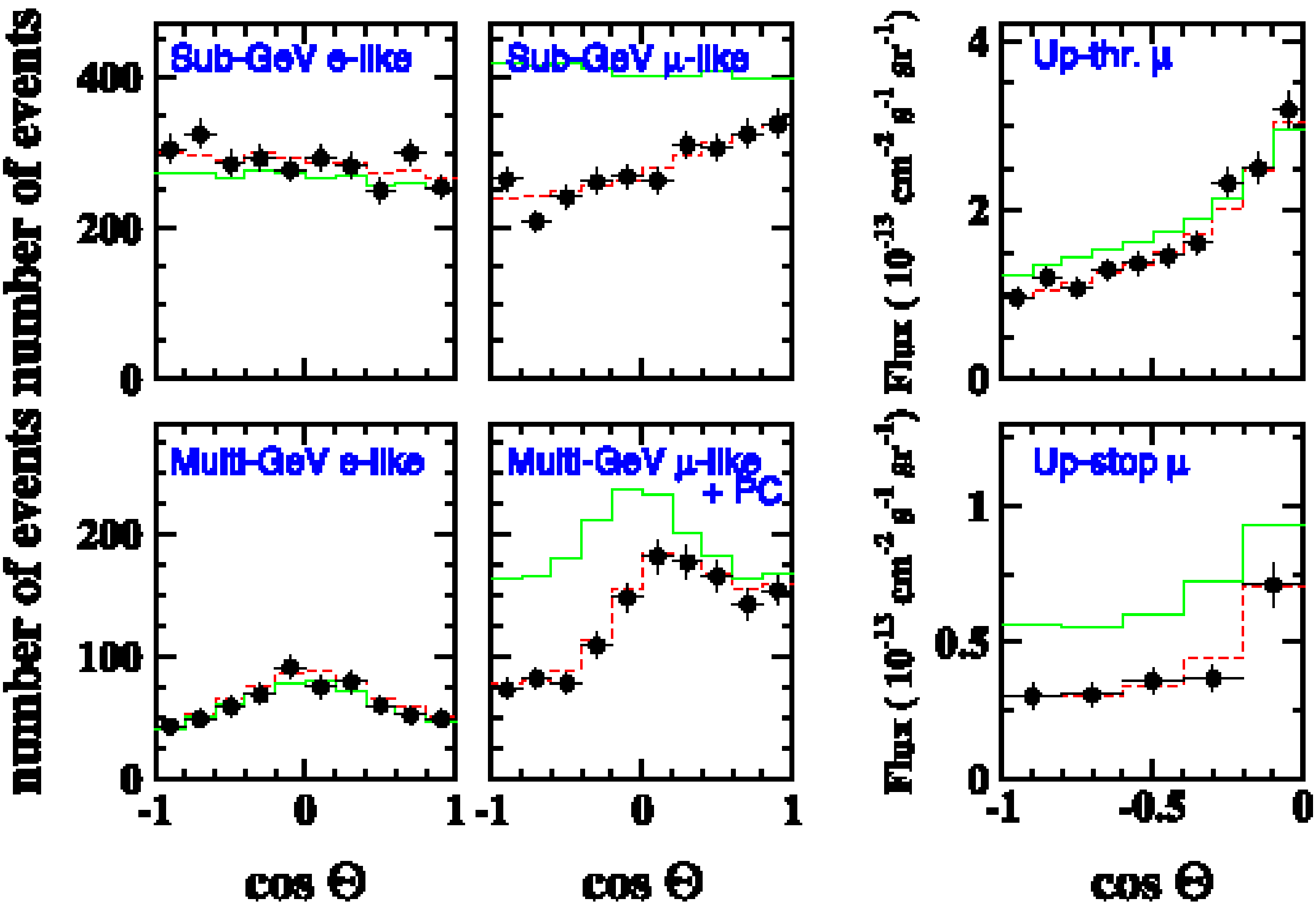
$\lambda dcy << \lambda osc$

For $\Delta m^2 \rightarrow 0$,

χ^2_{min} = 147.1/153 dof

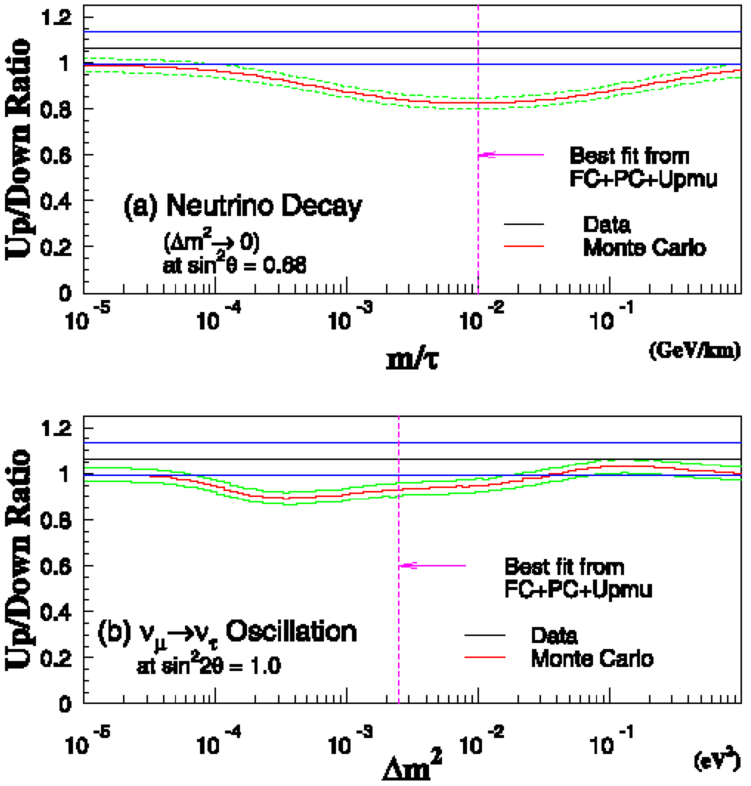
at $(\sin^2\theta, m_3/\tau_3)$ = (0.68, 0.01 (GeV/km))

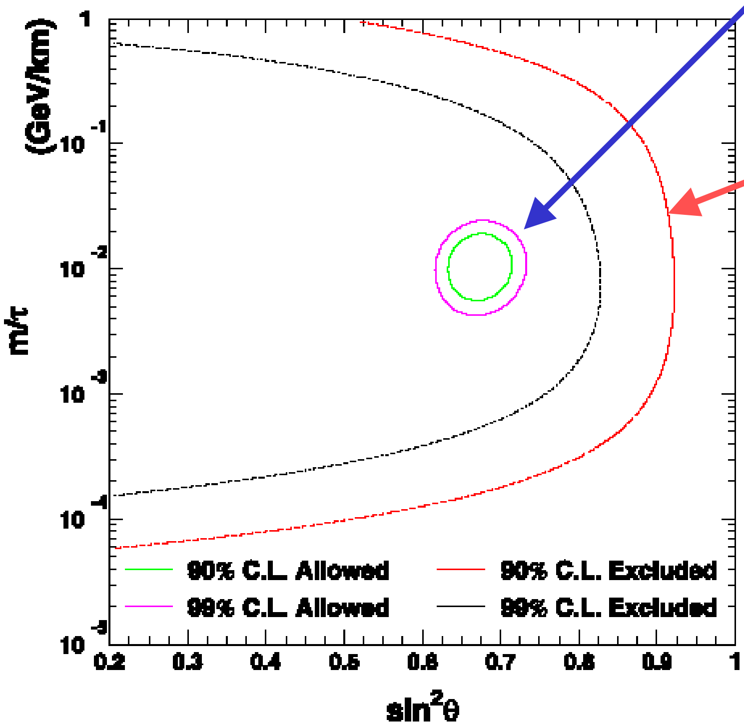
Good fit !



Up/down of NC enriched events (short λ_{dcy})

FC, Nring>1, Evis>400MeV, Brightest ring = e-like





Allowed from FC+PC+Upmu

Excluded from NC

The case of $\lambda_{dcy} << \lambda_{osc}$ is disfavored

Conclusions on atmospheric neutrinos

- Oscillation parameters for $\nu_\mu \rightarrow \nu_\tau$:
  $\Delta m^2 = 1.7 \sim 4 \times 10^{-3}$ eV^2, $\sin^2 2\theta > 0.89$ (90%CL)
- 3D flux does not change the conclusion but more precise 3D calculations are needed
- $\nu_\mu \rightarrow \nu_s$ is strongly disfavored
- π^0/μ ratio is consistent with $\nu_\mu \rightarrow \nu_\tau$
- Excess from τ leptons ~ 2σ
- Decay senario is disfavored with > 2σ
  for $\lambda_{dcy} >> \lambda_{osc}$ and $\lambda_{dcy} << \lambda_{osc}$