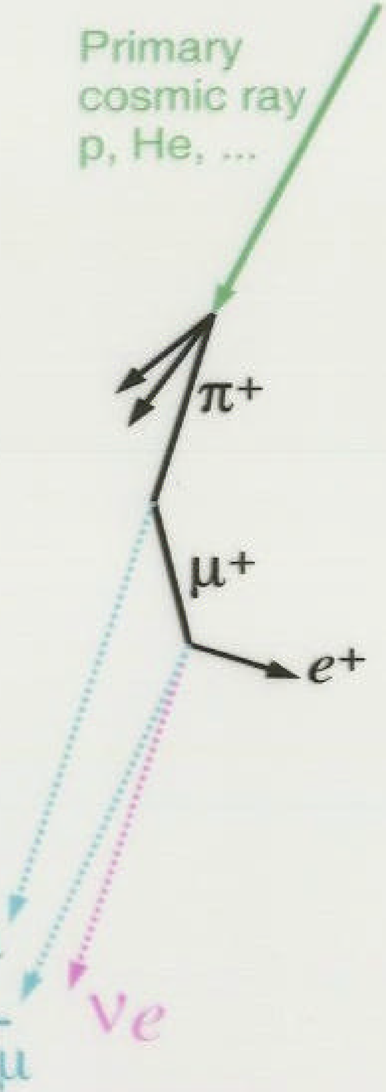
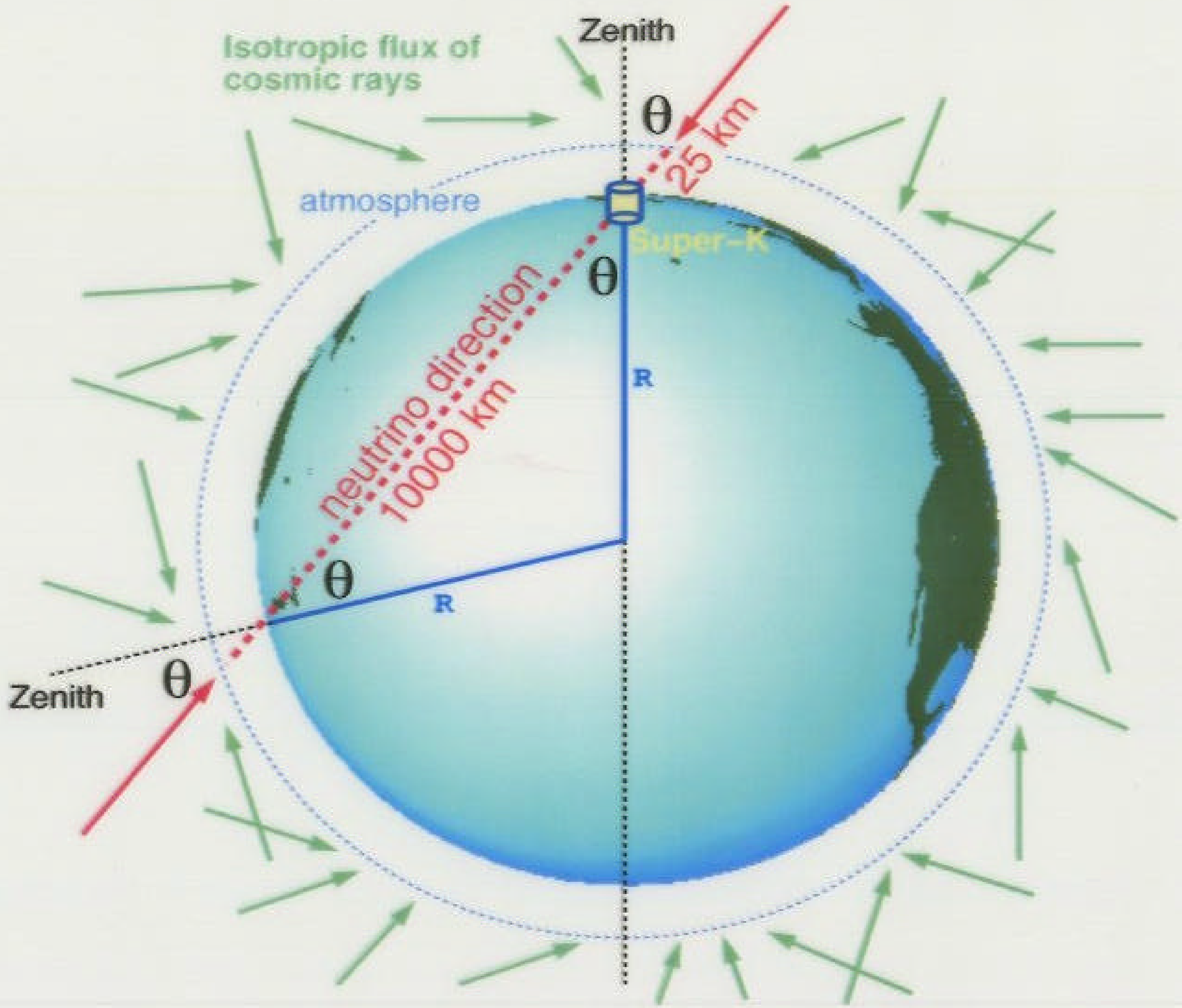
ATMOSPHERIC NEUTRINOS

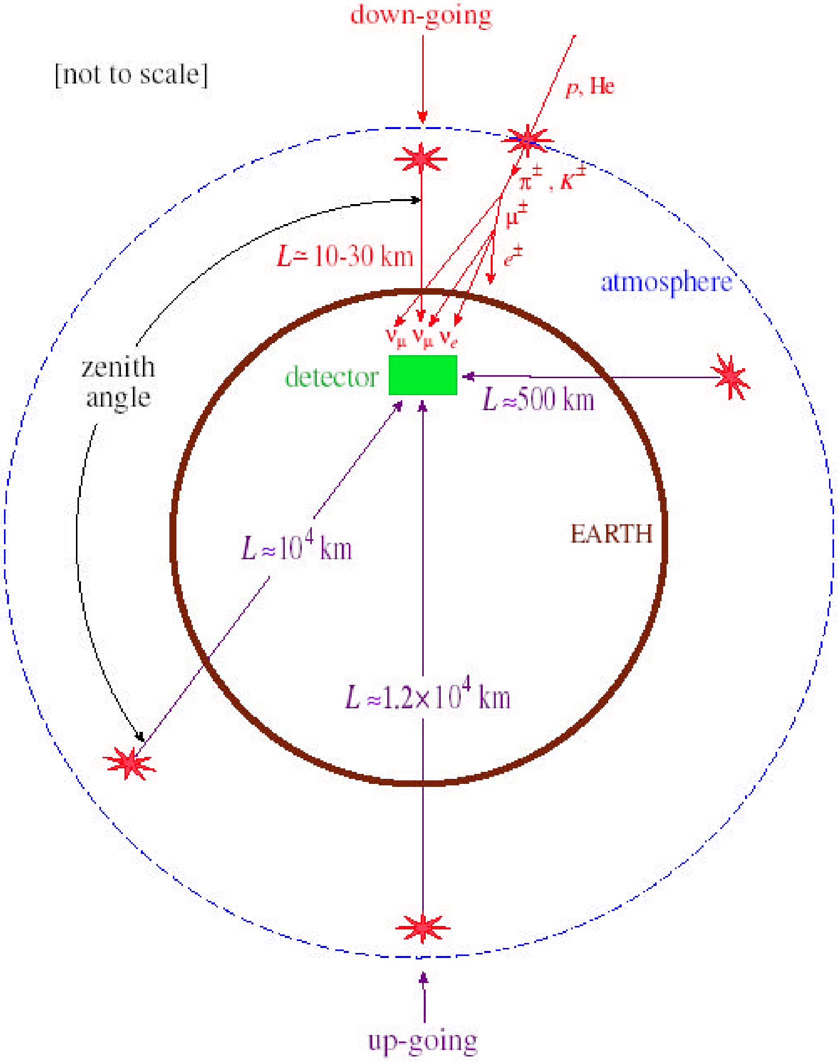


Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)

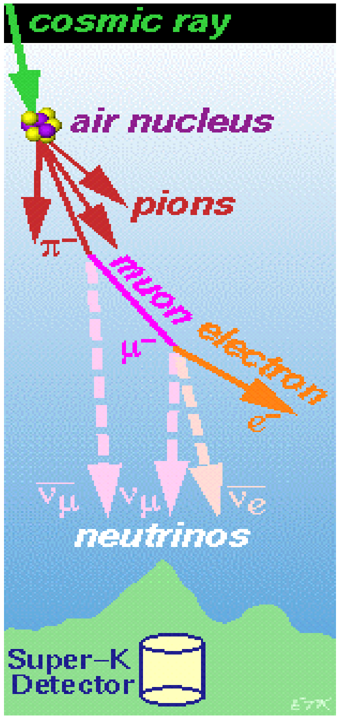


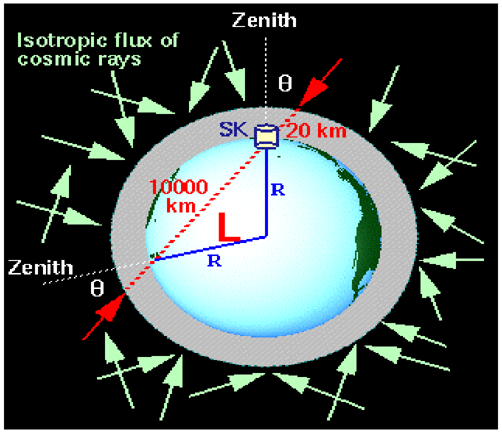
Up–Down Symmetric Flux
(for E_ν > few GeV)

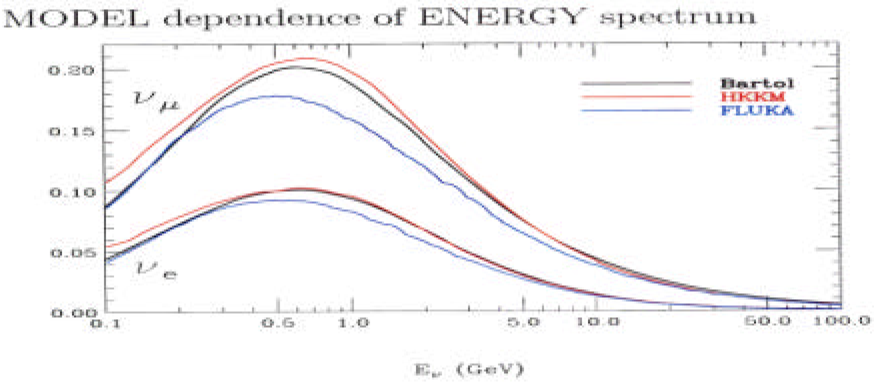
Schematic view of different zenith angles of atmospheric neutrinos and distances they travel before detection



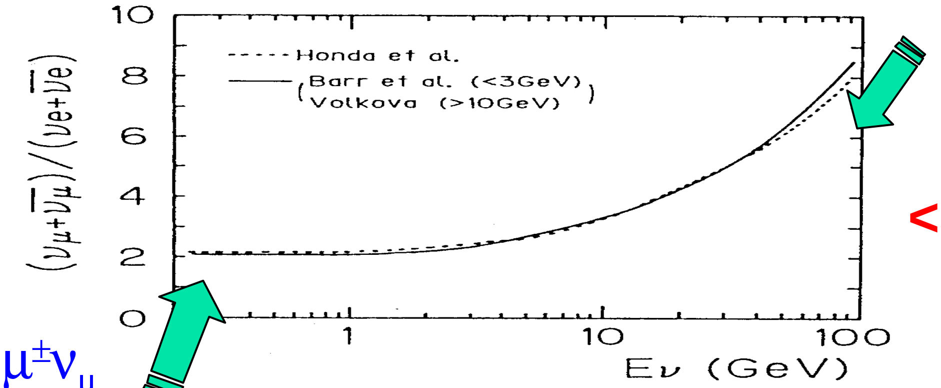
Atmospheric neutrinos







Energy dependence of n_m/n_e ratio



$\rightarrow\mu^{\pm}\,\nu_\mu$

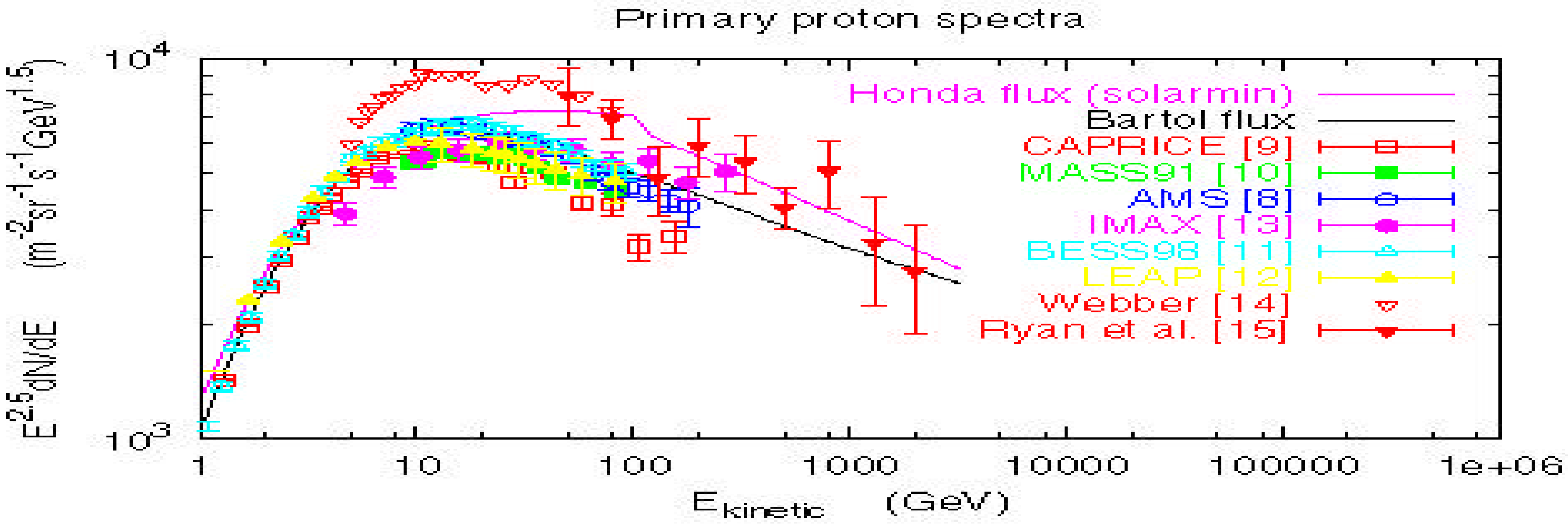
~~$e^{\pm}\nu_\mu\nu_e$~~

<5% accuracy

$\pi^{\pm}\rightarrow\mu^{\pm}\nu_\mu$

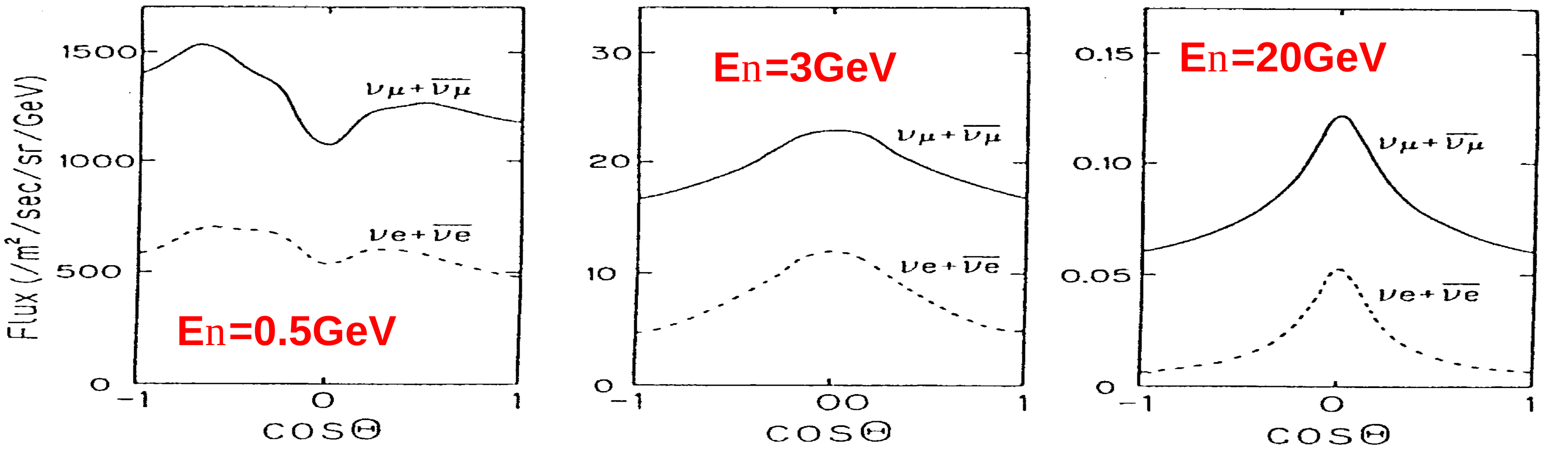
$e^{\pm}\nu_\mu\nu_e$

Bartol and Honda fluxes



Zenith angle distribution(1D)

Calculated zenith angle distribution



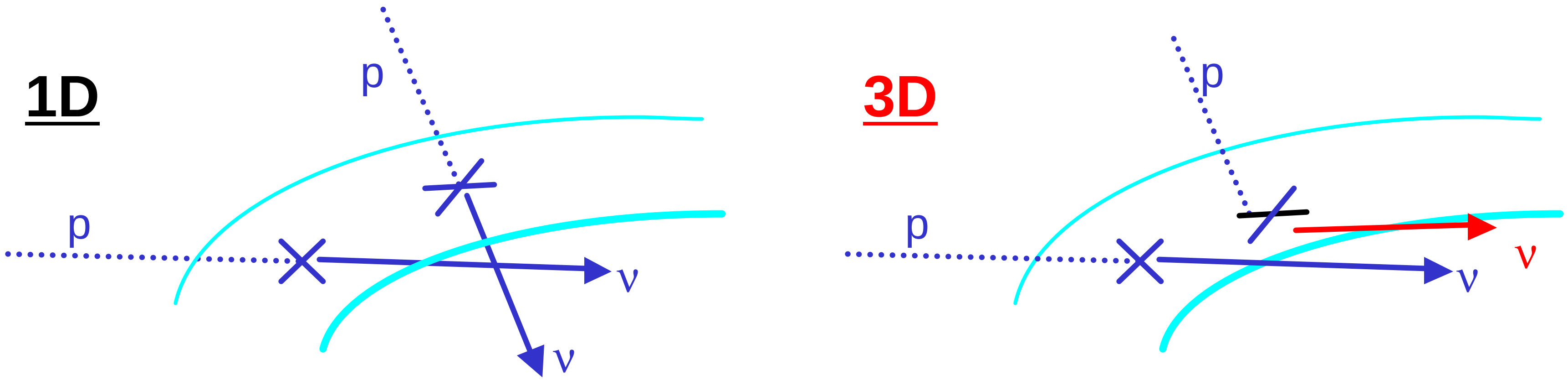
For E_ν > a few GeV,

Upward / downward = 1 (within a few %)

Up/Down asymmetry for neutrino oscillations!

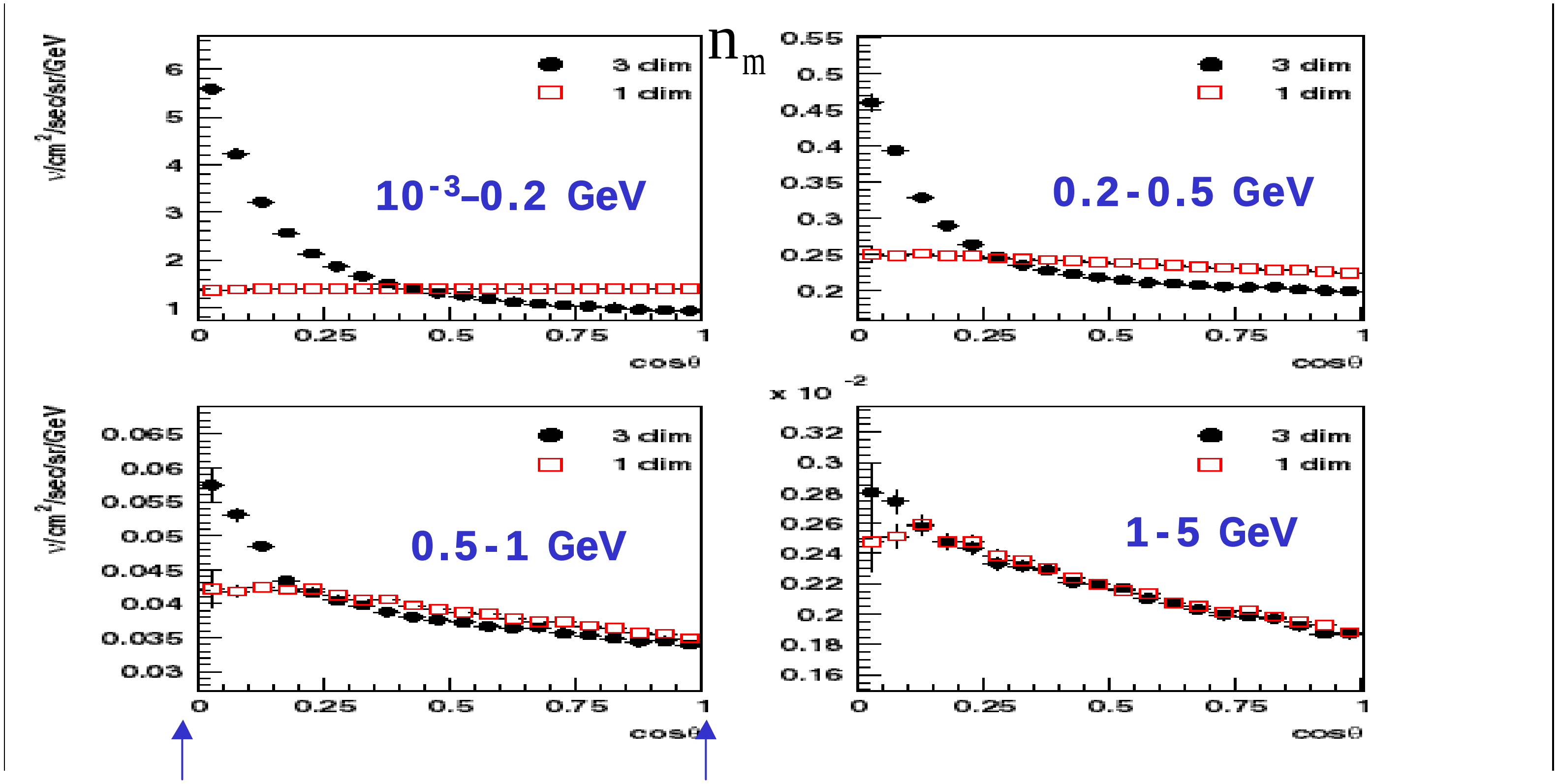
3D neutrino flux calculation

Till few years ago the flux calculation was based on the so called 1D model. Now 3D model is available, although still under development



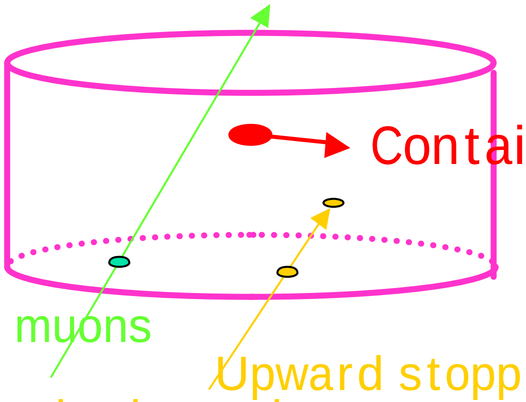
3D neutrino flux calculation

3D calculation by G.Battistoni et al. (hep-ph/9907408)



horizontal **vertical**

How to detect atmospheric neutrinos



Contained events

Upward through-going muons

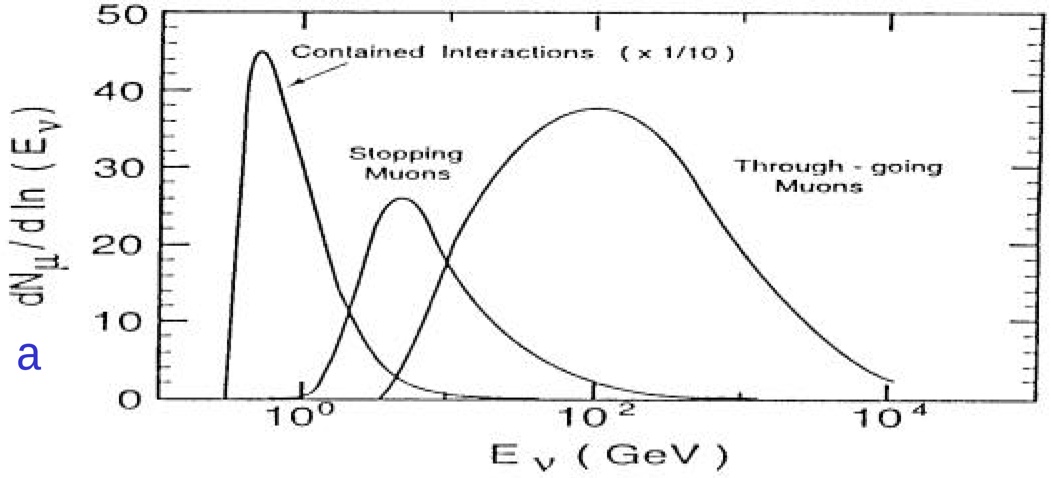
Upward stopping muons

Interaction in the rock

Initial neutrino spectrum

Energy range: 0.1 — 100 GeV

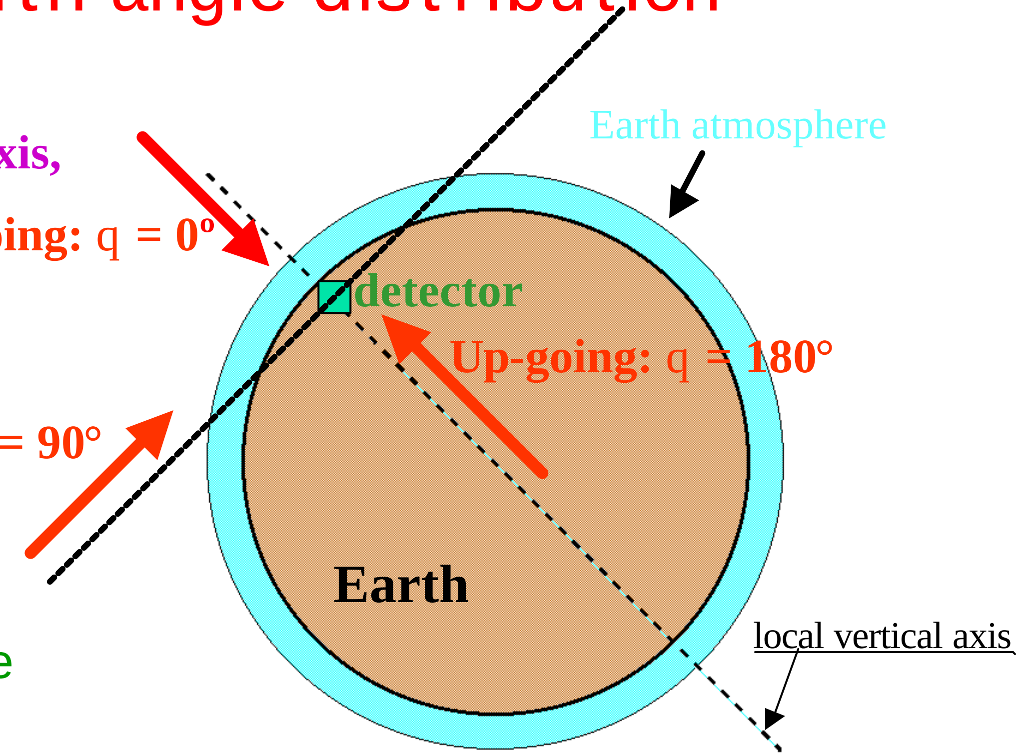
Very low event rate: ~100 /year for a detector mass of 1000 tons



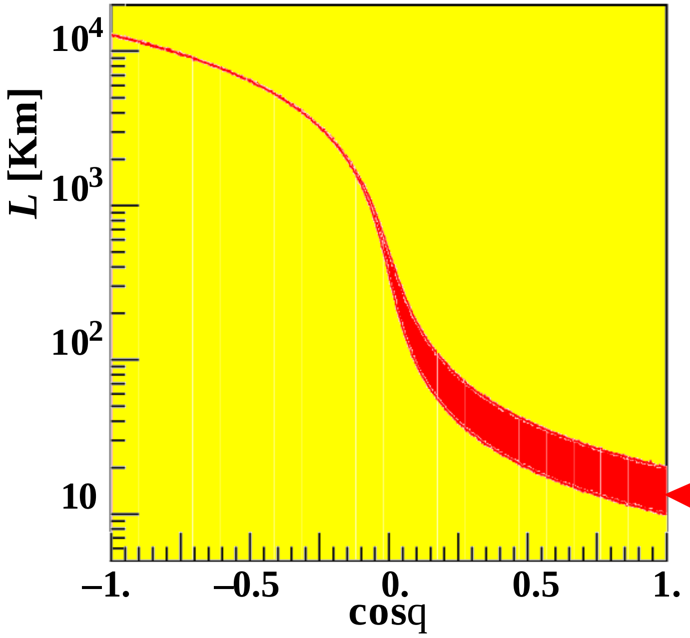
Measurement of zenith angle distribution

Definition of zenith angle q:

Polar axis along the local vertical axis, directed downwards



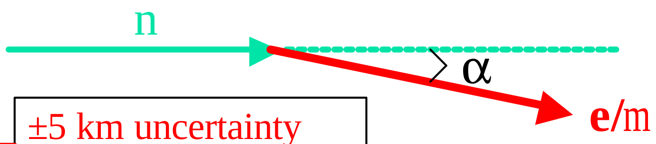
Baseline *L* (distance between neutrino production point and detector) depends on zenith angle



±5 km uncertainty
on ν production point

L **varies between ~10 and ~12800 km as q varies between 0º and 180º ⇒ search for oscillations with variable baseline**

Strong angular correlation between incident neutrino and outgoing electron/muon for *E* > 1 GeV:



a » 25° **for** ***E*** **= 1 GeV;**

a ® 0 **as** ***E*** **increases**

A bit of history

- ✓ In the '70 the most important problem in particle physics was the proton decay detection
- ✓ In this search the atmospheric neutrino interactions constituted the most tricky background: this is the reason why the study of atmospheric neutrinos started!
- ✓ The atmospheric neutrinos remained a "simple background" till when an anomalous results was obtained with Cerenkov detectors (Kamiokande, IMB) and lately confirmed with calorimeters (Soudan2)

$$\mathbf{R} = \frac{(\nu_\mu/\nu_e)_{\text{measured}}}{(\nu_\mu/\nu_e)_{\text{predicted}}} < \mathbf{1\ !!!}$$

Since then atmospheric neutrinos became the "high-way" towards new physics beyond the Standard Model

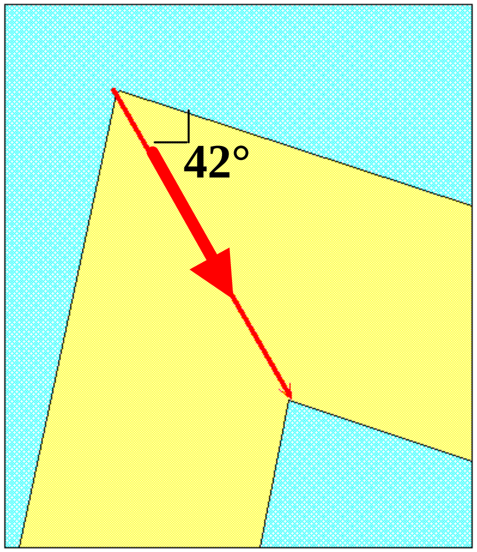
Detection of atmospheric neutrinos

ν_μ + Nucleon → $\underline{\mu}$ + hadrons: presence of a long, minimum ionizing track (the μ)

$\nu_e + n \rightarrow e^- + p$, $\nu_e + p \rightarrow e^+ + n$: presence of an electromagnetic shower

(ν_e interactions with multiple hadron production is difficult to separate from neutral current events
→ for atmospheric ν_e only quasi-elastic interactions can be studied)

Particle identification in a water Cerenkov counter



muon track:

dE/dx consistent with minimum ionization

sharp edges of Cerenkov light ring

electron shower:

high dE/dx

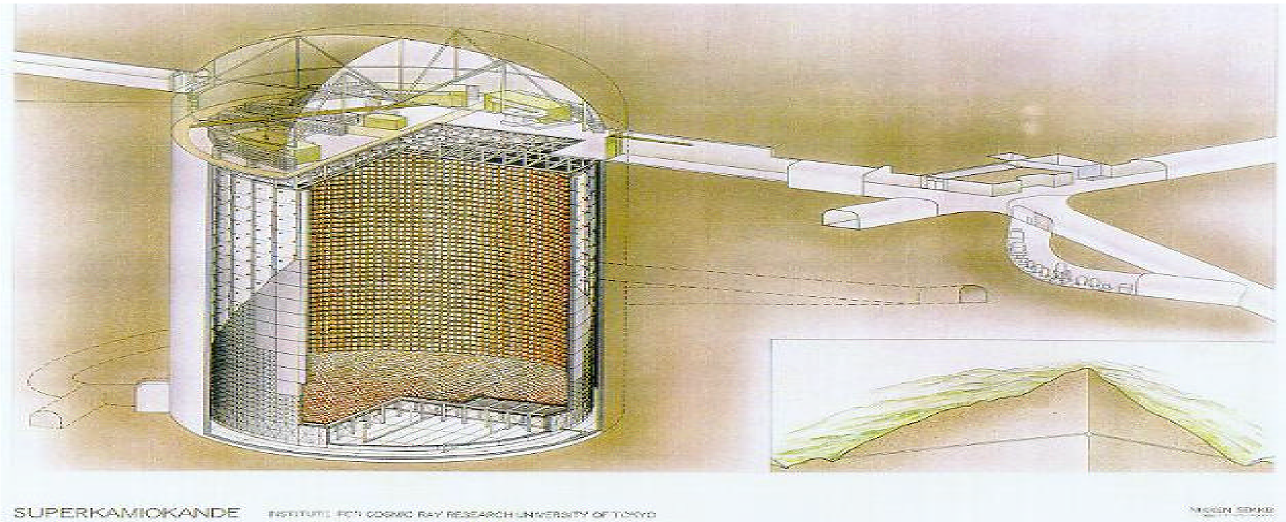
“fuzzy” edges of Cerenkov light ring
(from shower angular spread)

Measure electron/muon separation by exposing a 1000 ton water Cerenkov counter
(a small Super-K detector) to electron and muon beams from accelerators.
Probability of wrong identification ~2%

Super-Kamiokande

- ✓ Introduction
- ✓ Contained events and upward muons
- ✓ Updated results
  - Oscillation analysis with the full SK-I statistics
  - Multi-ring events
  - π^0/μ ratio
  - Search for τ leptons
  - $\nu_\mu \rightarrow \nu_s$
- ✓ Conclusion

Super-Kamiokande detector



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

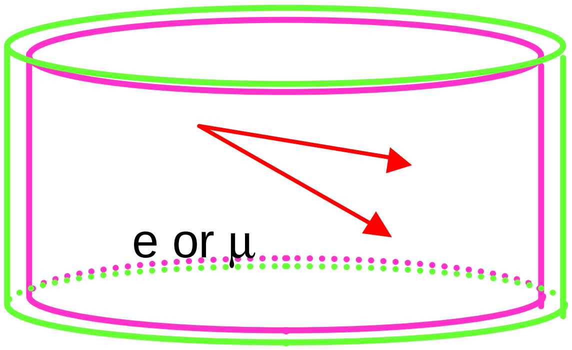
1000m underground (2700 m.w.e.)

11,146 20-inch PMTs for inner detector

1,885 8-inch PMTs for outer detector

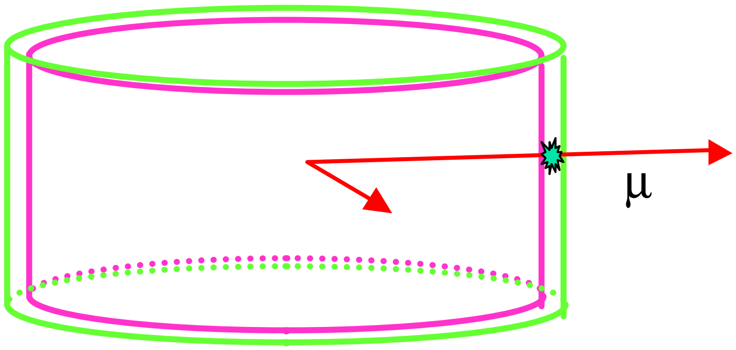
Contained event analysis

Fully Contained (FC)



No hit in Outer Detector

Partially Contained (PC)

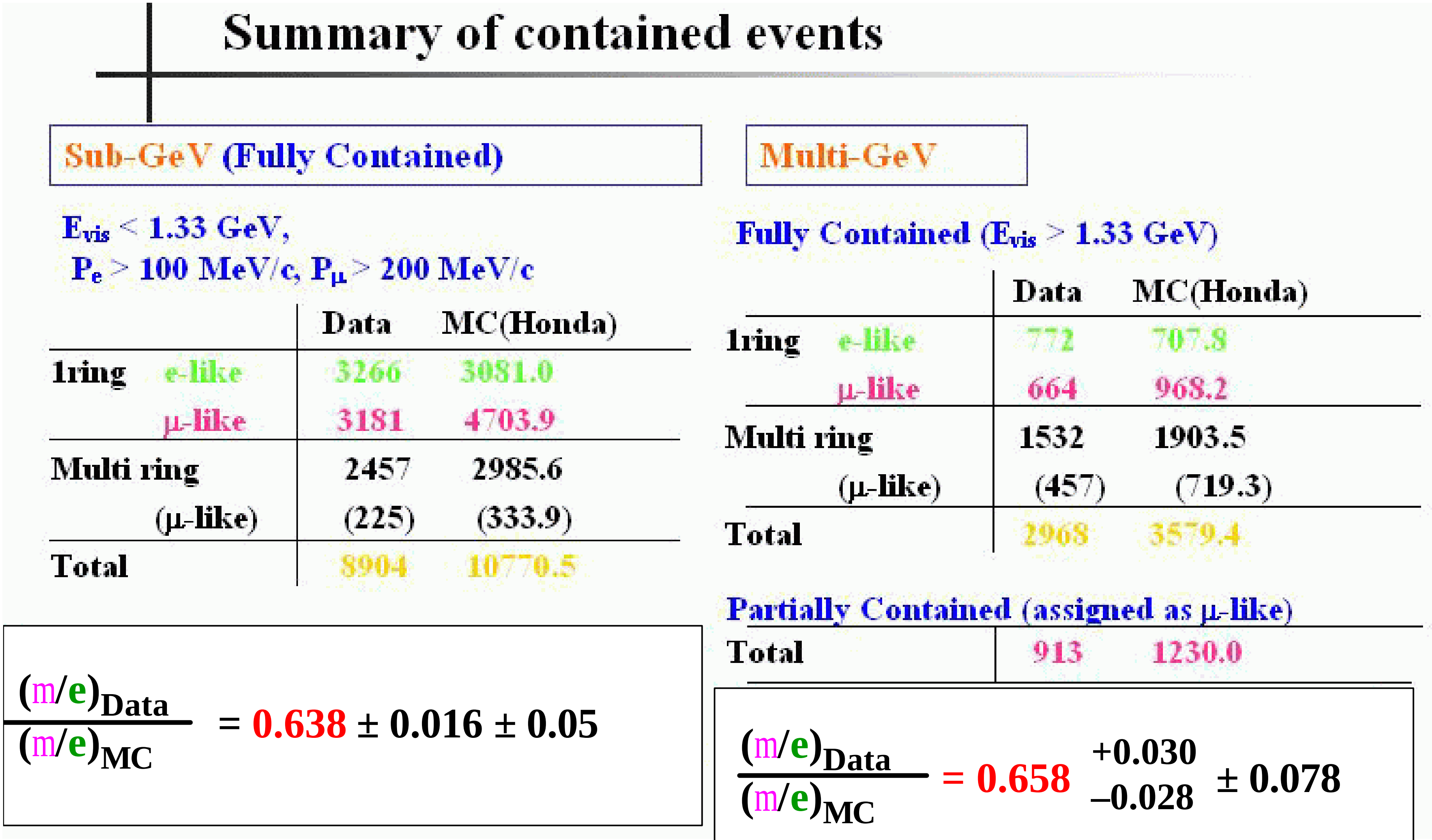


One cluster in Outer Detector

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



Summary of contained events

Sub-GeV (Fully Contained)

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

		Data	MC(Honda)
1ring	e-like	3266	3081.0
	μ-like	3181	4703.9
Multi ring		2457	2985.6
	(μ-like)	(225)	(333.9)
Total		8904	10770.5

Multi-GeV

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

		Data	MC(Honda)
1ring	e-like	772	707.8
	μ-like	664	968.2
Multi ring		1532	1903.5
	(μ-like)	(457)	(719.3)
Total		2968	3579.4

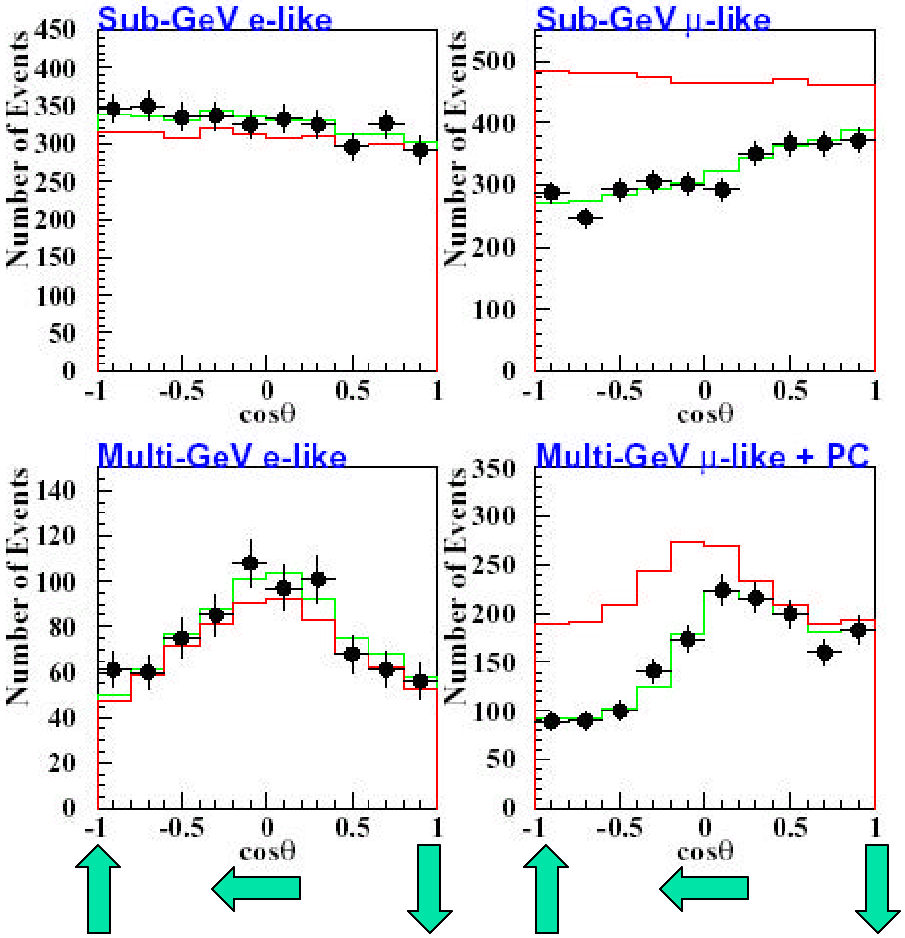
Partially Contained (assigned as μ-like)

	Data	MC(Honda)
Total	913	1230.0

$$\frac{(m/e)_{Data}}{(m/e)_{MC}} = 0.638 \pm 0.016 \pm 0.05$$

$$\frac{(m/e)_{Data}}{(m/e)_{MC}} = 0.658 \begin{array}{l}+0.030\\-0.028\end{array} \pm 0.078$$

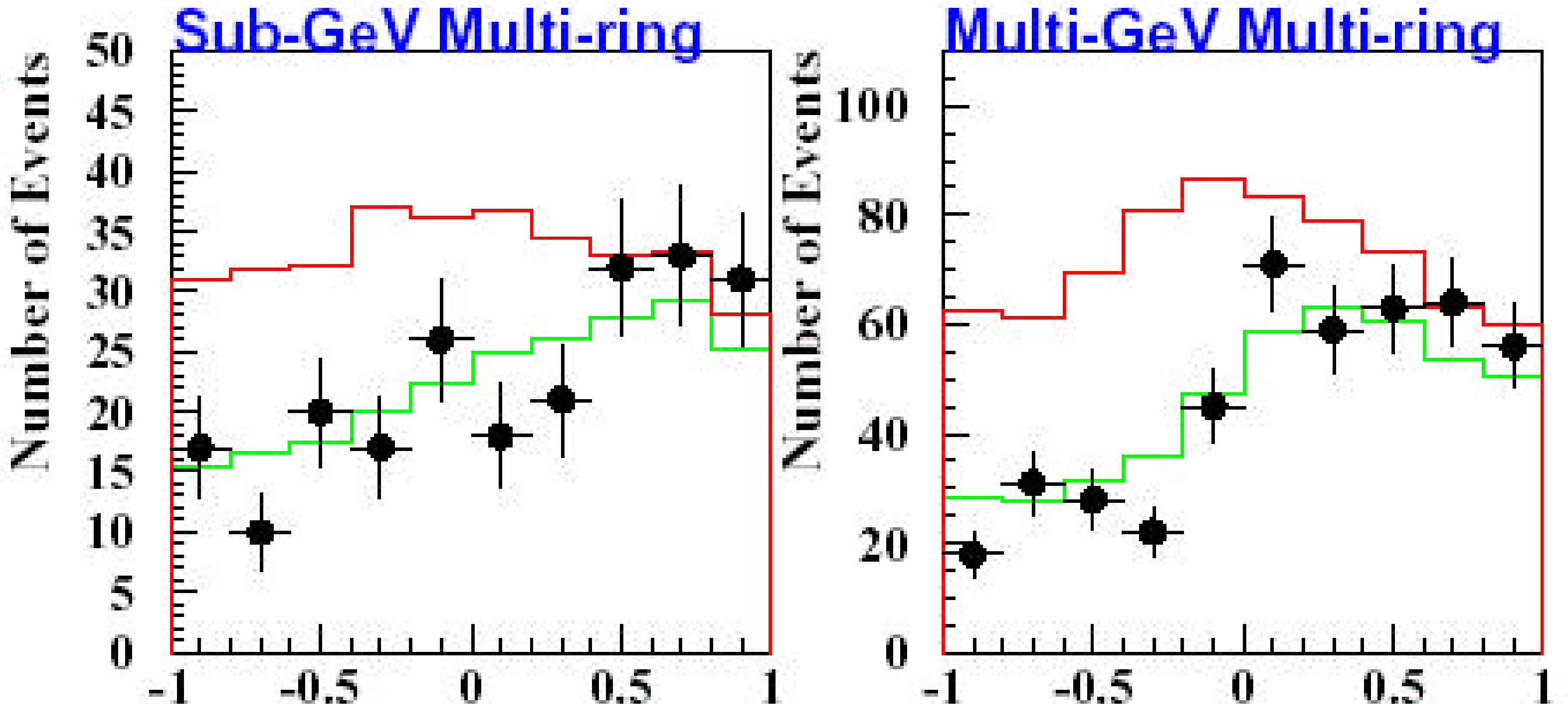
Zenith angle distribution



🟥 **No oscillation**
$(c^2 = 456.5 / 172$ dof)

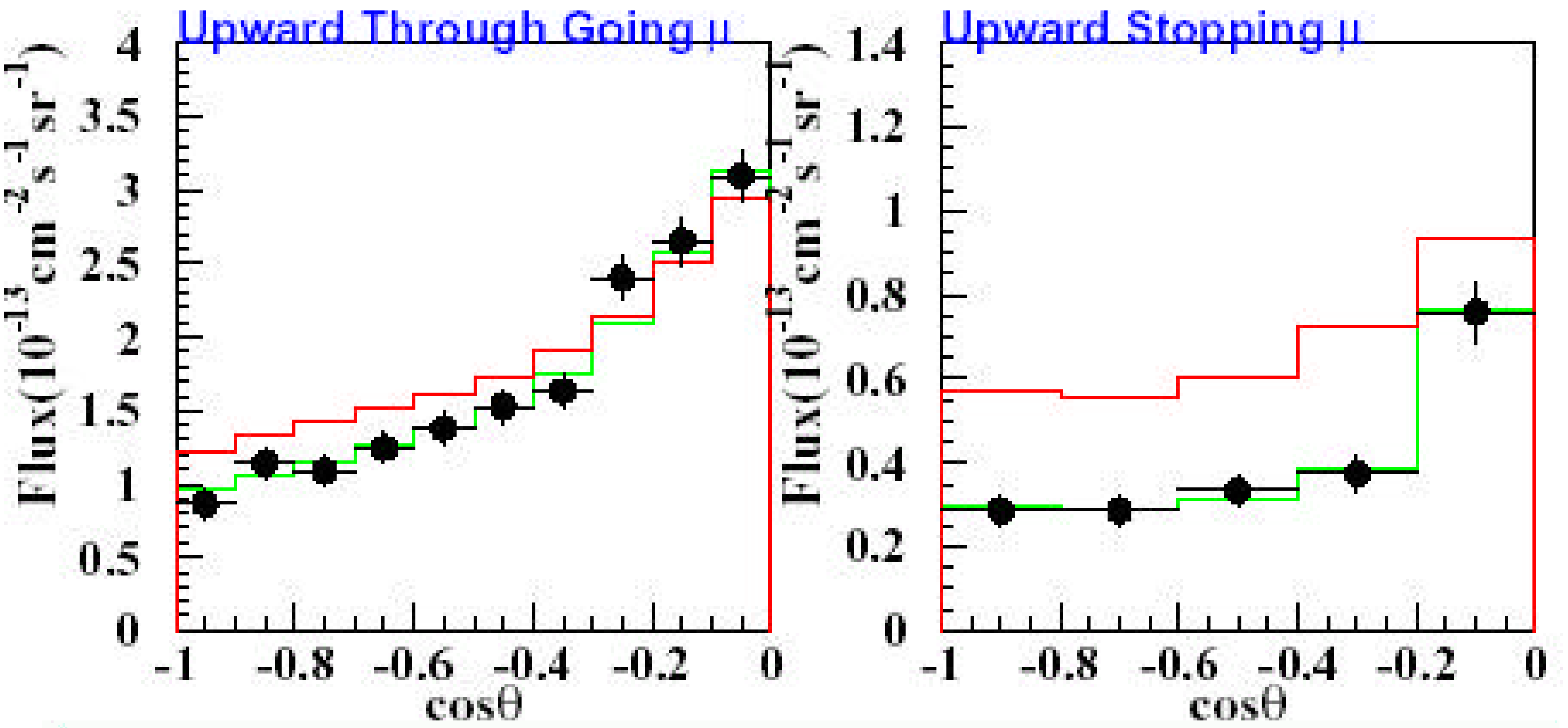
🟩 **$n_m - n_t$ oscillation**
best fit: $Dm^2 = 2.5 \times 10^{-3}$ eV^2
$\sin^2 2q = 1.0$
$(c^2 = 163.2 / 170$ dof)

Multi-ring event analysis



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

Zenith angle distributions of upward-going muons



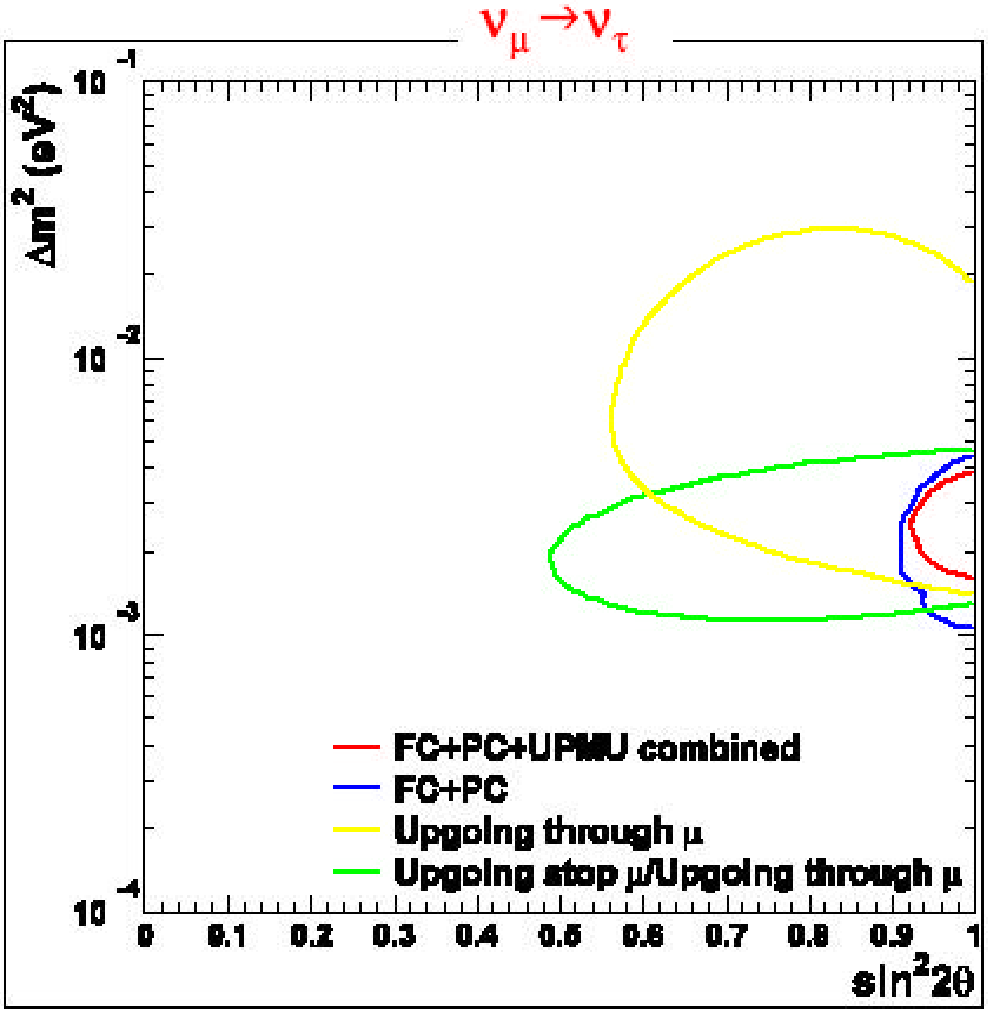
Up through-going μ, 1678days, Obs. 1.7 +- 0.04 +- 0.02 ($\times 10^{-13}$cm^{-2}s^{-1}sr^{-1})

Exp. 1.97+-0.44

Up stopping μ, 1657days, Obs. 0.41+-0.02+-0.02 ($\times 10^{-13}$cm^{-2}s^{-1}sr^{-1})

Exp. 0.73+-0.16

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



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

Best fit(Δm^2=2.5x10^{-3},$\sin^2 2\theta$=1.0

χ^2_{min}=163.2/170 d.o.f)

No oscillation

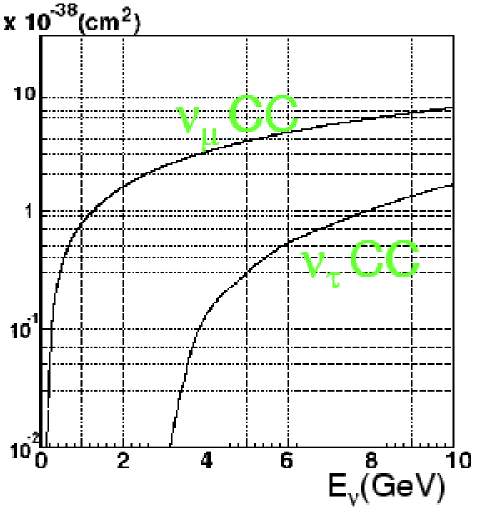
(χ^2 =456.5/172 d.o.f)

Δm^2 = (1.5~4.0)x10^{-3}eV^2

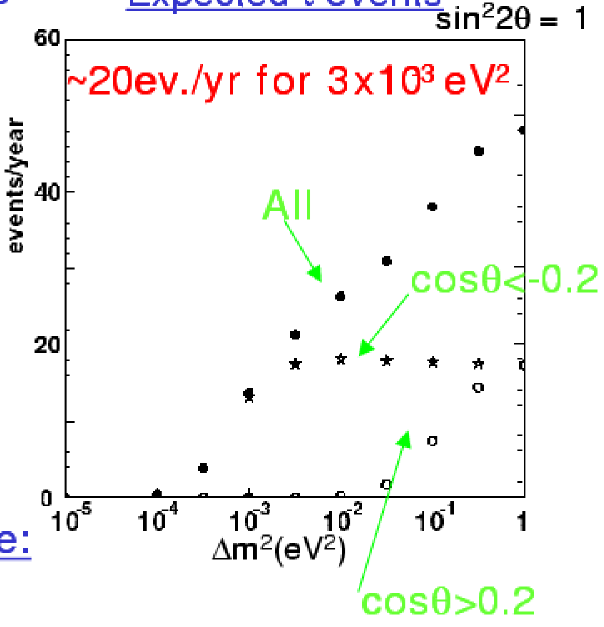
$\sin^2 2\theta$ > 0.92 @ 90%CL

τ appearance with atmospheric ν

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 μ→e decay signals
- More spherical event pattern

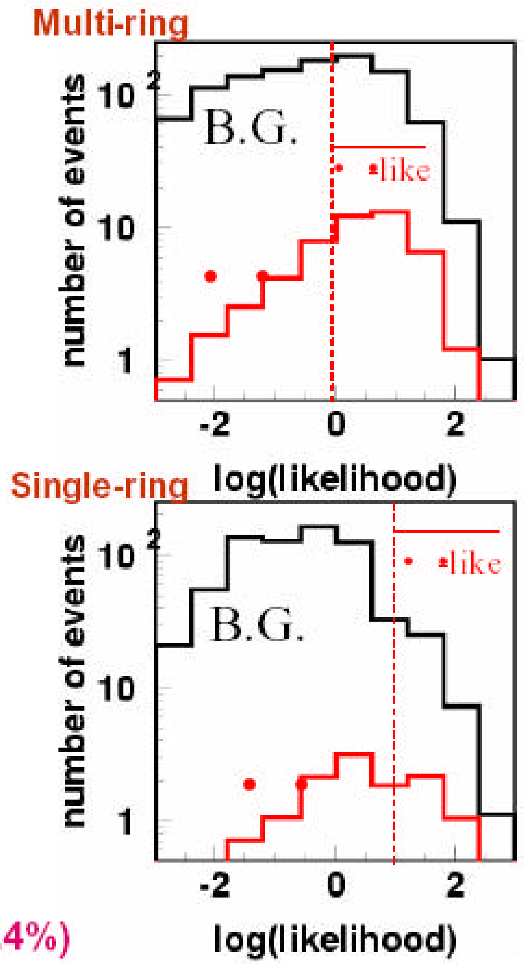
τ detection in atmospheric ν

Selection Criteria
- multi-GeV, multi-ring
- most energetic ring is e-like
- log(likelihood) > 0 (single-ring)
  > 1 (multi-ring)

τ likelihood is defined using;
- total energy
- number of rings
- number of decay electrons
- max(Ei)/• Ei
- distance between ν interaction point and decay-e point
- max(P_μ)
- $Pt/Evis^{3/4}$
- PID likelihood of most energetic ring

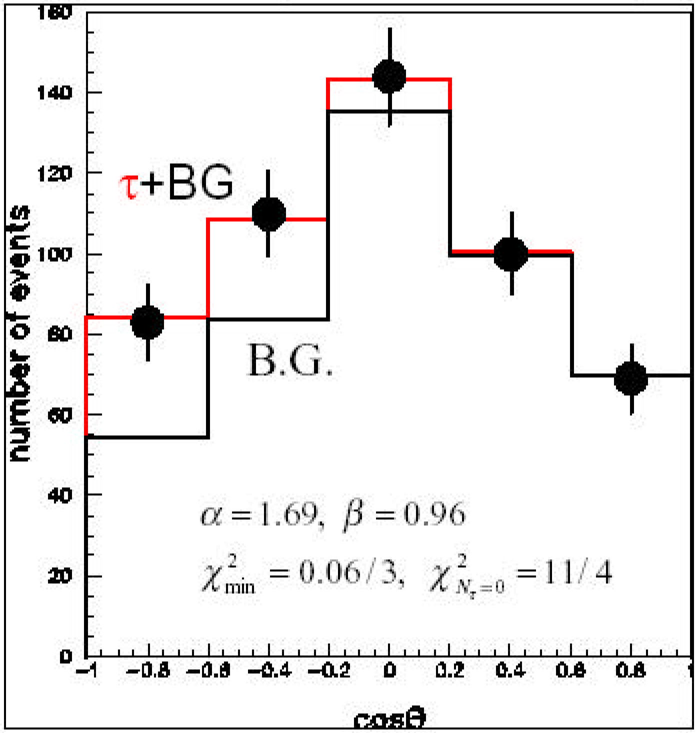
τ–like selection; effτ=44%, S/N=8%

observed τ–like events; 506
MC expectation; CC ν_τ 37 events,
BG 461 events (CCν_e 43.1%, CCν_μ 24.5%, NC 32.4%)



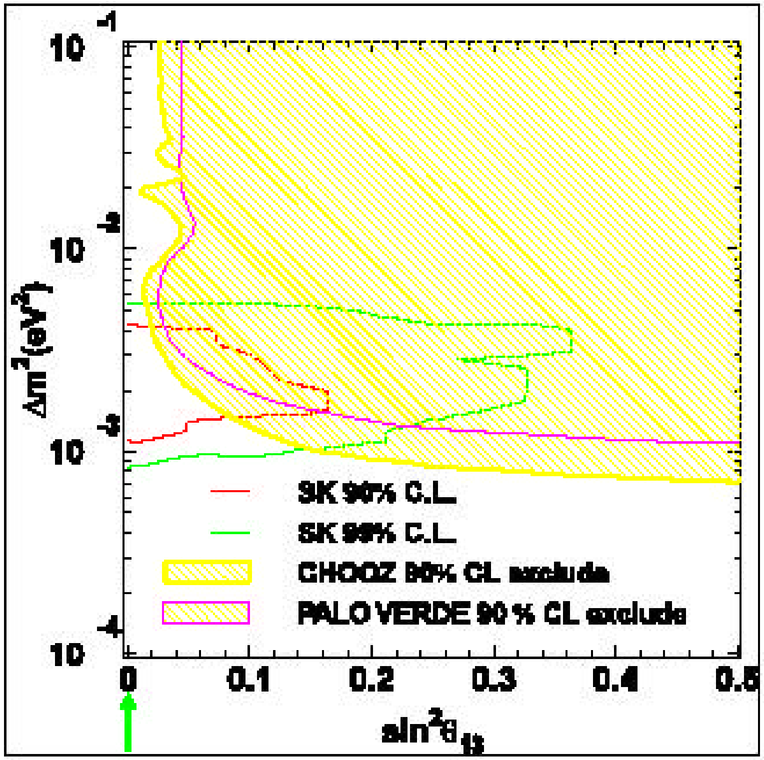
τ appearance analysis

$$\chi^2 = \sum_{\cos\Theta}^{5} \left(\frac{N_{data} - \left(\alpha N^{\tau}_{MC} + \beta N^{BG}_{MC} \right)}{\sigma} \right)^2$$



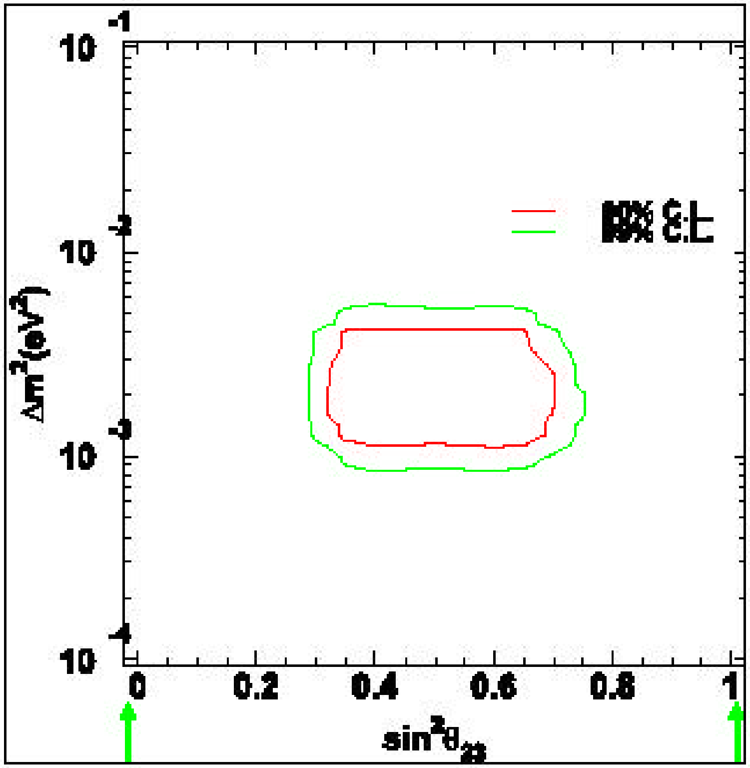
- N^{FC}_{τ}= αN^{τ}_{MC}/(eff.=0.44)
  =145+-44(stat.)
  +11/-16(sys.)
  N_{exp}=86
- consistent with $\nu_\mu \leftrightarrow \nu_\tau$
- other two analysis give similar results:
  *analysis-2(neural network)
  N^{FC}_{τ}=99+-39(stat.)
  +-13(Δm^2)
  +0/-16(3-flavor)
  *analysis-3(energy flow)
  N^{FC}_{τ}=135+47-44(stat.+sys.)

Allowed region for active 3-flavor oscillations



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

getting close to CHOOZ's limit on θ_{13}

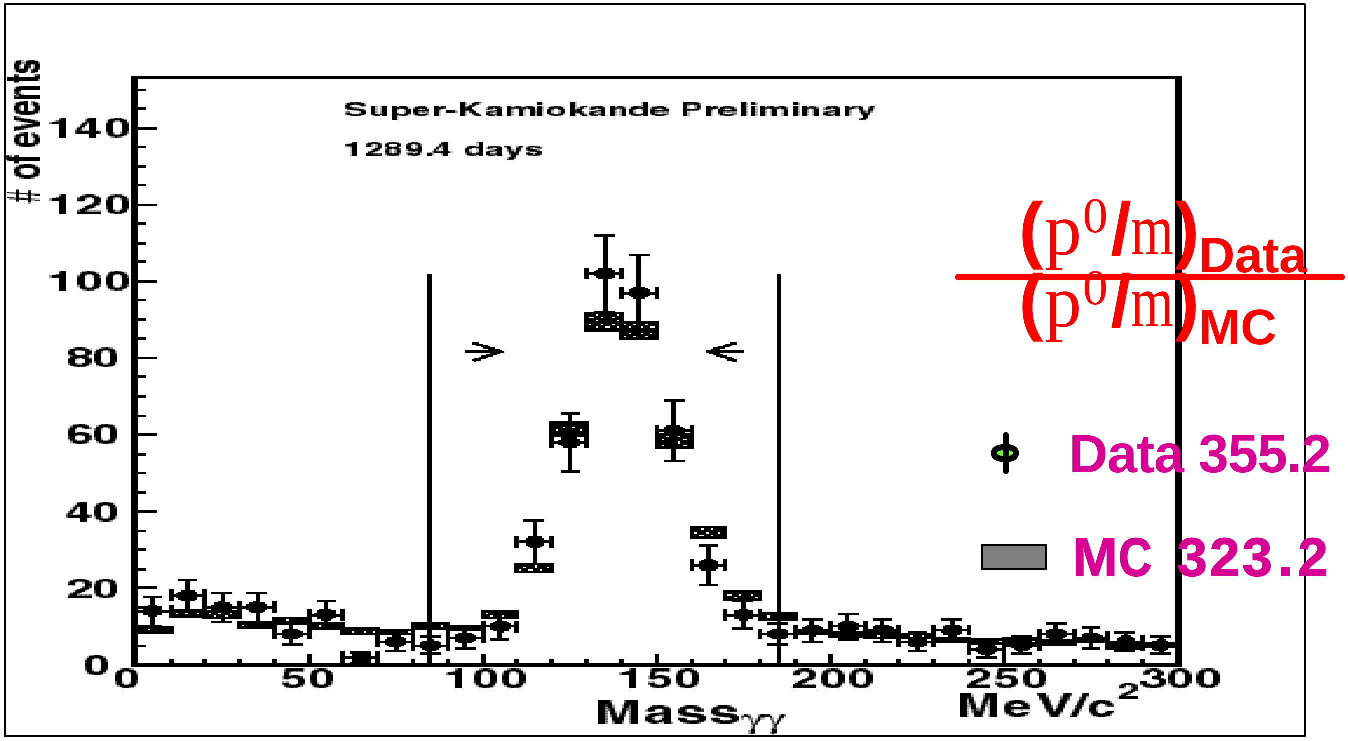


Pure $\nu_e \leftrightarrow \nu_\tau$

Pure $\nu_e \leftrightarrow \nu_\mu$

consistent with CHOOZ's excluded region

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

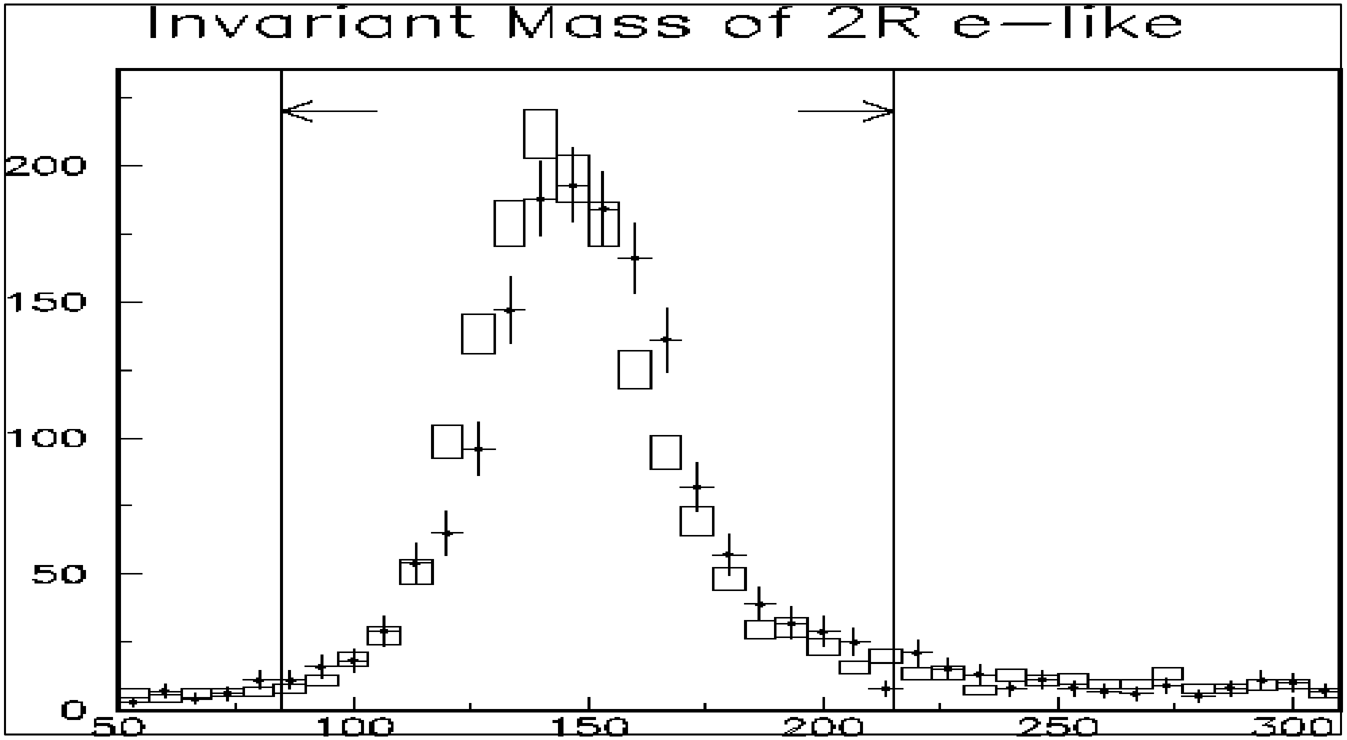


$$\frac{(p^0/m)_{Data}}{(p^0/m)_{MC}} \begin{cases} > 1 \text{ for } n_m \text{®} n_t \\ \text{»} \ 1 \text{ for } n_m \text{®} n_s \end{cases}$$

- ● Data 355.2 events (BG subt.)
- ▬ MC 323.2 events

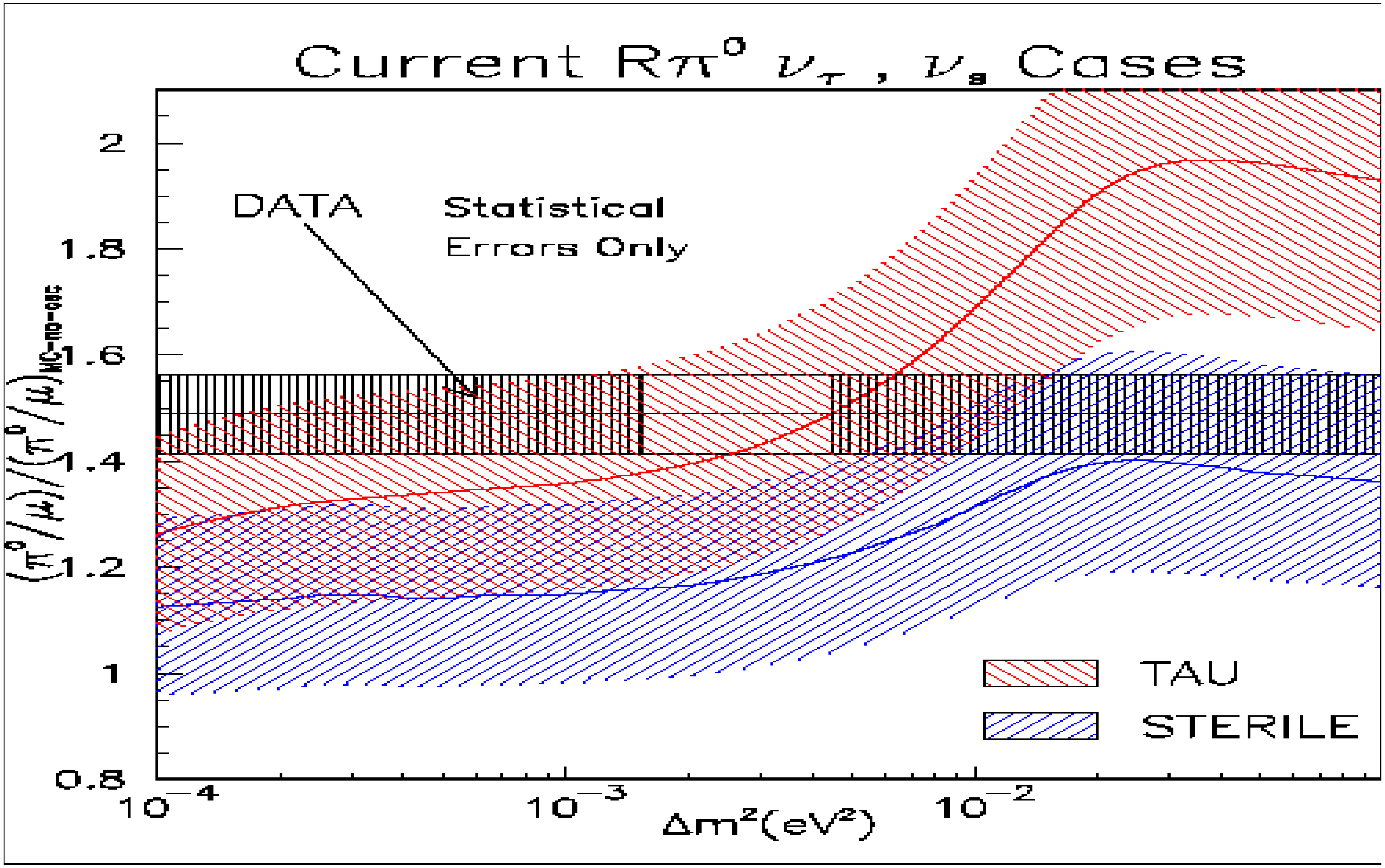
$$\frac{(p^0/m)_{Data}}{(p^0/m)_{MC}} = 1.49 \pm 0.08(\text{stat.}) \pm 0.11(\text{sys.})$$

π^0 info from K2K-1kt



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

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



$\nu_\mu \to \nu_{\text{sterile}}$ (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

$$\begin{pmatrix} n_m \\ n_t \end{pmatrix} = \begin{pmatrix} \cos J_m & \sin J_m \\ -\sin J_m & \cos J_m \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \end{pmatrix}$$

Neutrino oscillation in matter

$$\sin^2 2J_m = \frac{\sin^2 2J}{(z - \cos 2J)^2 + \sin^2 2J}$$

$$z = \frac{2\sqrt{G_F}\, n_n E_n}{\Delta m^2}$$

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

For $\sin^2 2\theta = \sim 1$

and for E_ν = 30~100 GeV

$\sin^2 2\theta_m \sim 1/(\zeta^2+1) \Rightarrow$ $\zeta \gg 1$ and $\sin^2 2\theta_m \ll 1$

Suppression !

Strategy:

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

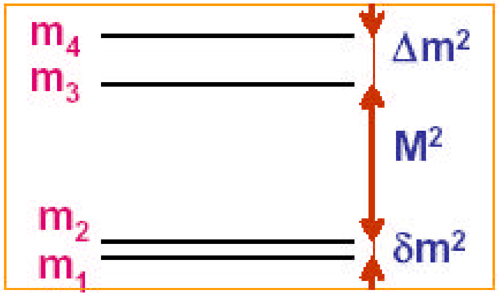
⇨Test zenith angle of NC enriched events, high energy PC and through-going muon events.

Tau vs Sterile Neutrino analysis

analyses following to Fogli, Lisi, Marrone (PRD63,053008)

assuming 3 active ν + 1 sterile ν having

$\delta m^2(\text{solar}) << \Delta m^2(\text{atm}) << M^2(\text{LSND})$



simplifies to 3 parameters;

$\Delta m^2(\text{atm})$, $\sin^2 2\theta$, $\sin^2\xi$

$$\boxed{\nu_\mu \to \cos\xi\,\nu_\tau + \sin\xi\,\nu_s}$$

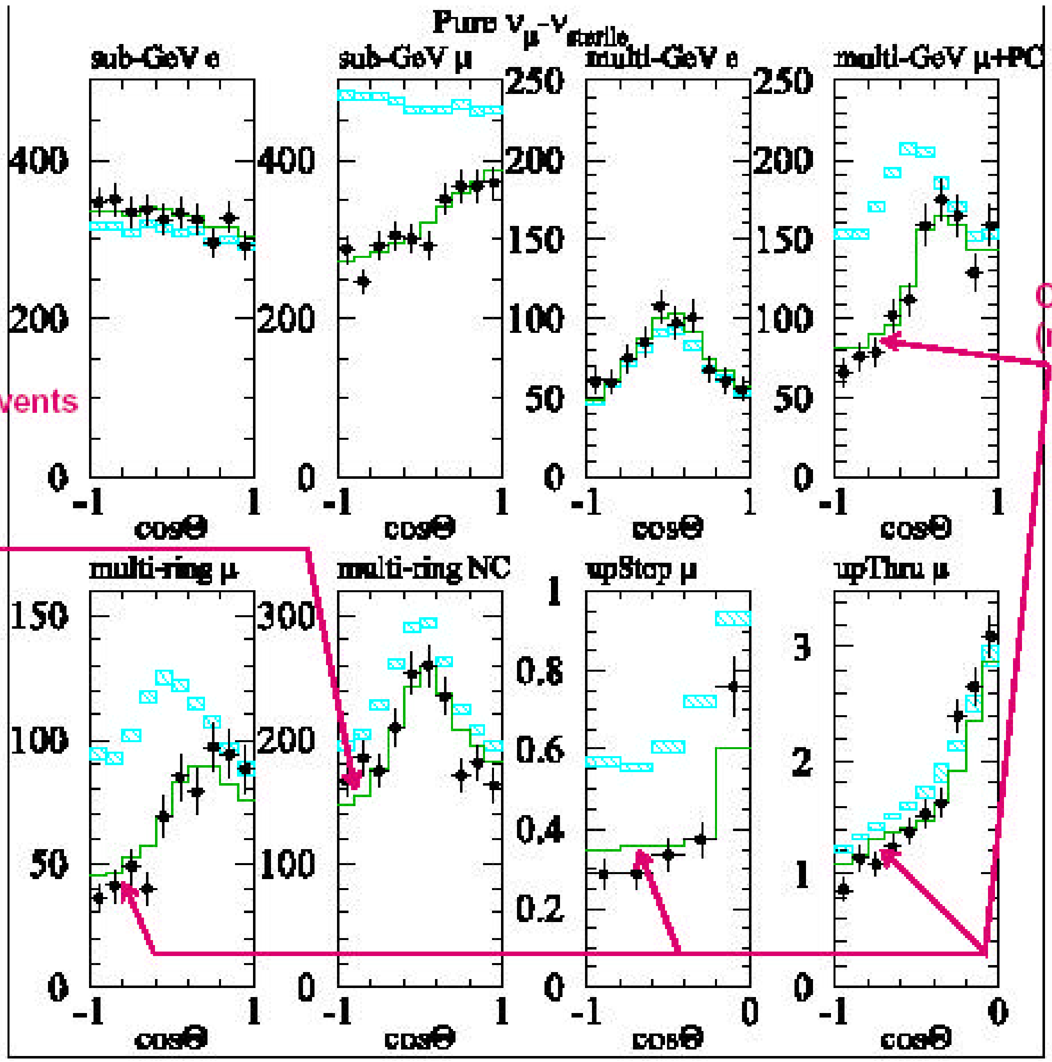
$\sin^2\xi=0$; pure $\nu_\mu \to \nu_\tau$

$\sin^2\xi=1$; pure $\nu_\mu \to \nu_s$

nonzero $\sin^2\xi$

- oscillation suppression happens at multi-GeV region due to matter effect
- deficit of NC events in upward bins is expected

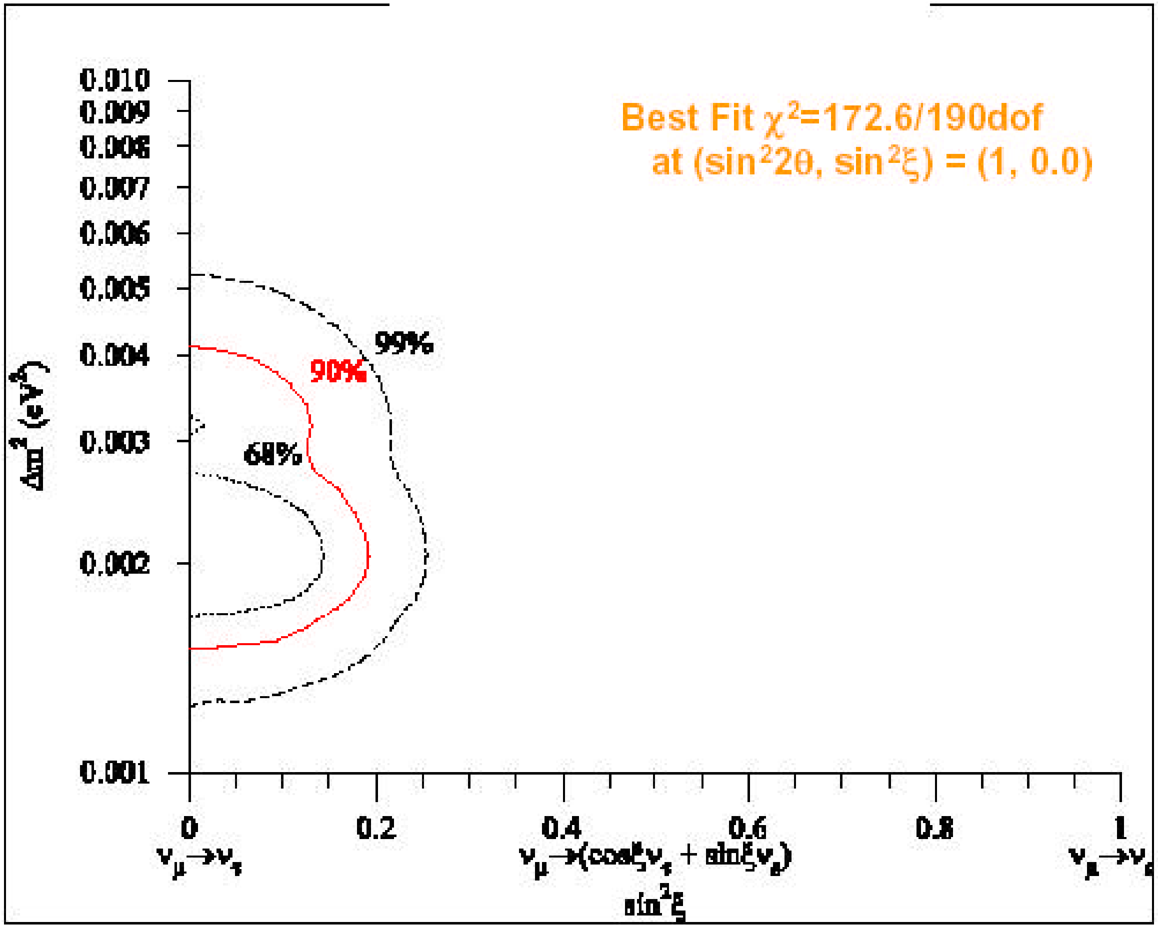
Shape of pure $\nu_\mu \rightarrow \nu_s$



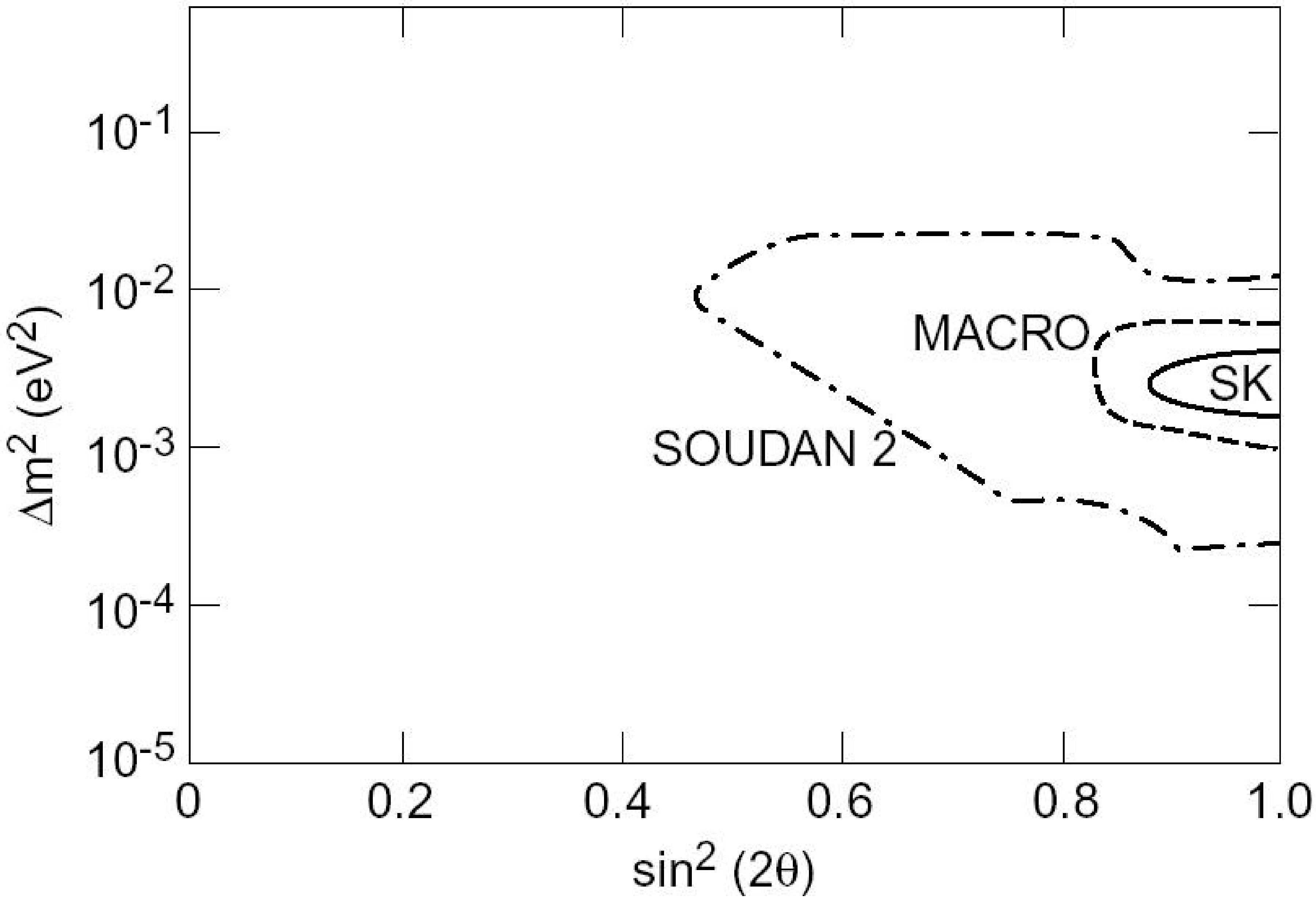
deficit of NC events

Oscillation suppression (matter effect)

Limit on $\nu_\mu \rightarrow \nu_s$ add mixture



Soudan-2 & MACRO

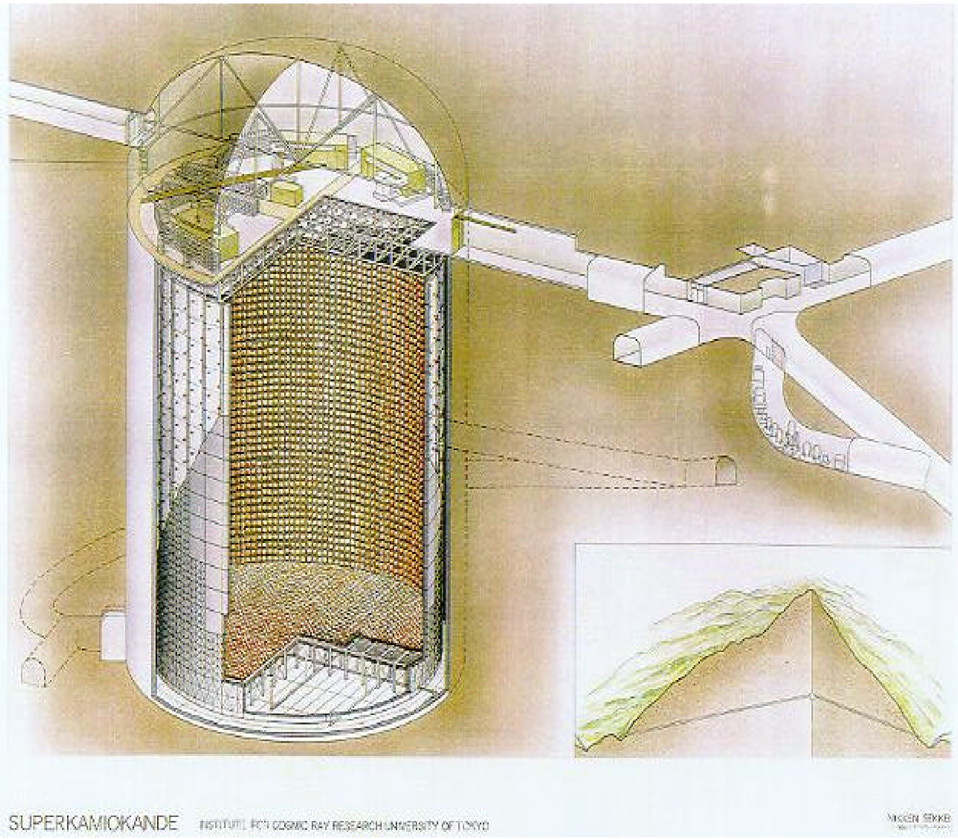


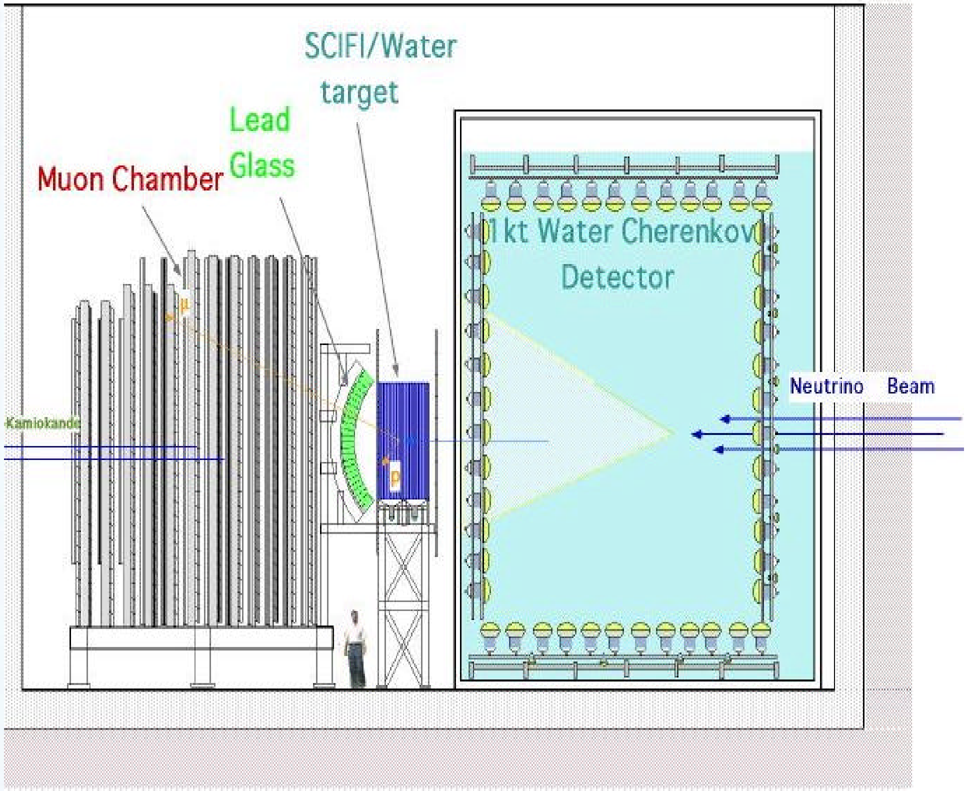
Conclusions on atmospheric neutrinos

- ✓ Oscillation parameters for $\nu_\mu \rightarrow \nu_\tau$:
  $\Delta m^2 = 1.5 \sim 4 \times 10^{-3}$ eV^2, $\sin^2 2\theta > 0.92$ (90%CL)
- ✓ Excess from τ leptons ~ 1σ
- ✓ $\nu_\mu \rightarrow \nu_s$ is strongly disfavored
- ✓ π^0/μ ratio is consistent with $\nu_\mu \rightarrow \nu_\tau$

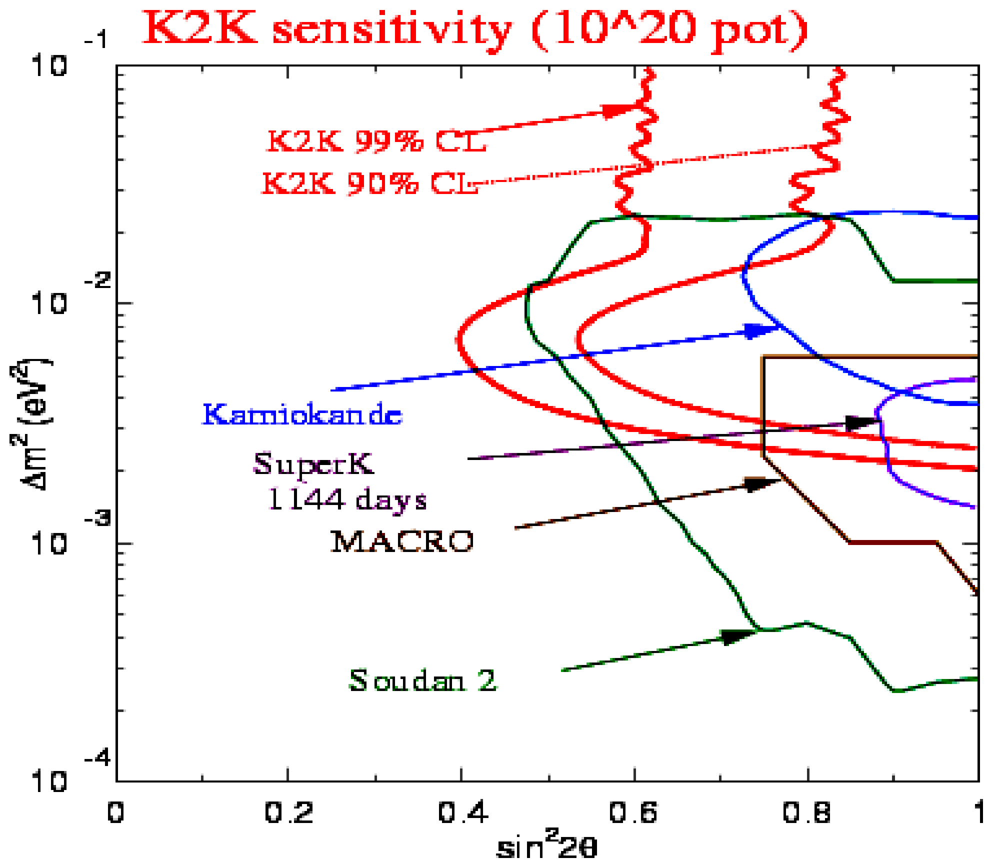
Far Detector

Close Detectors (CD)



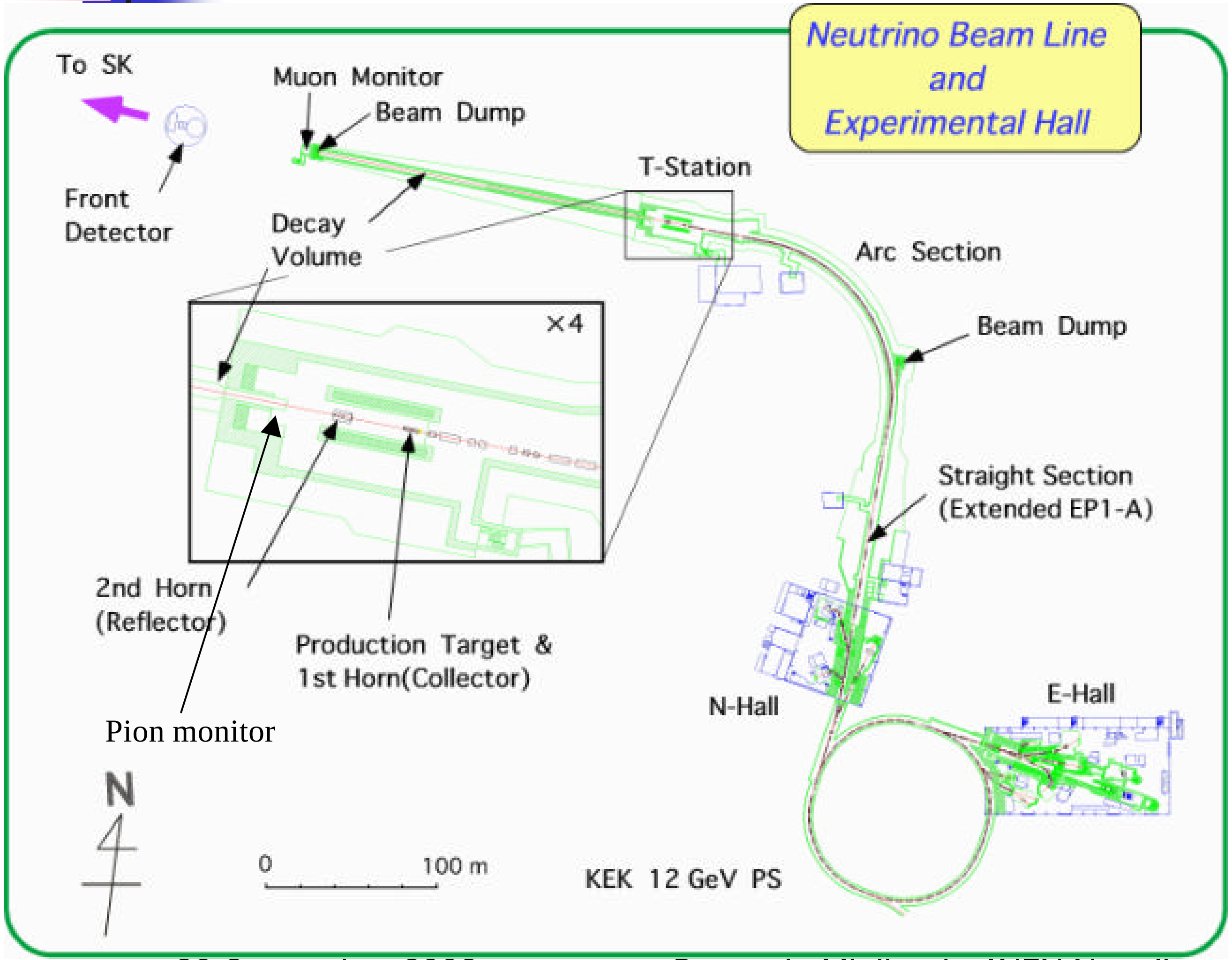


Sensitivity of the experiment



Sensitive to Δm^2 above 2×10^{-3} eV^2!

The neutrino beam



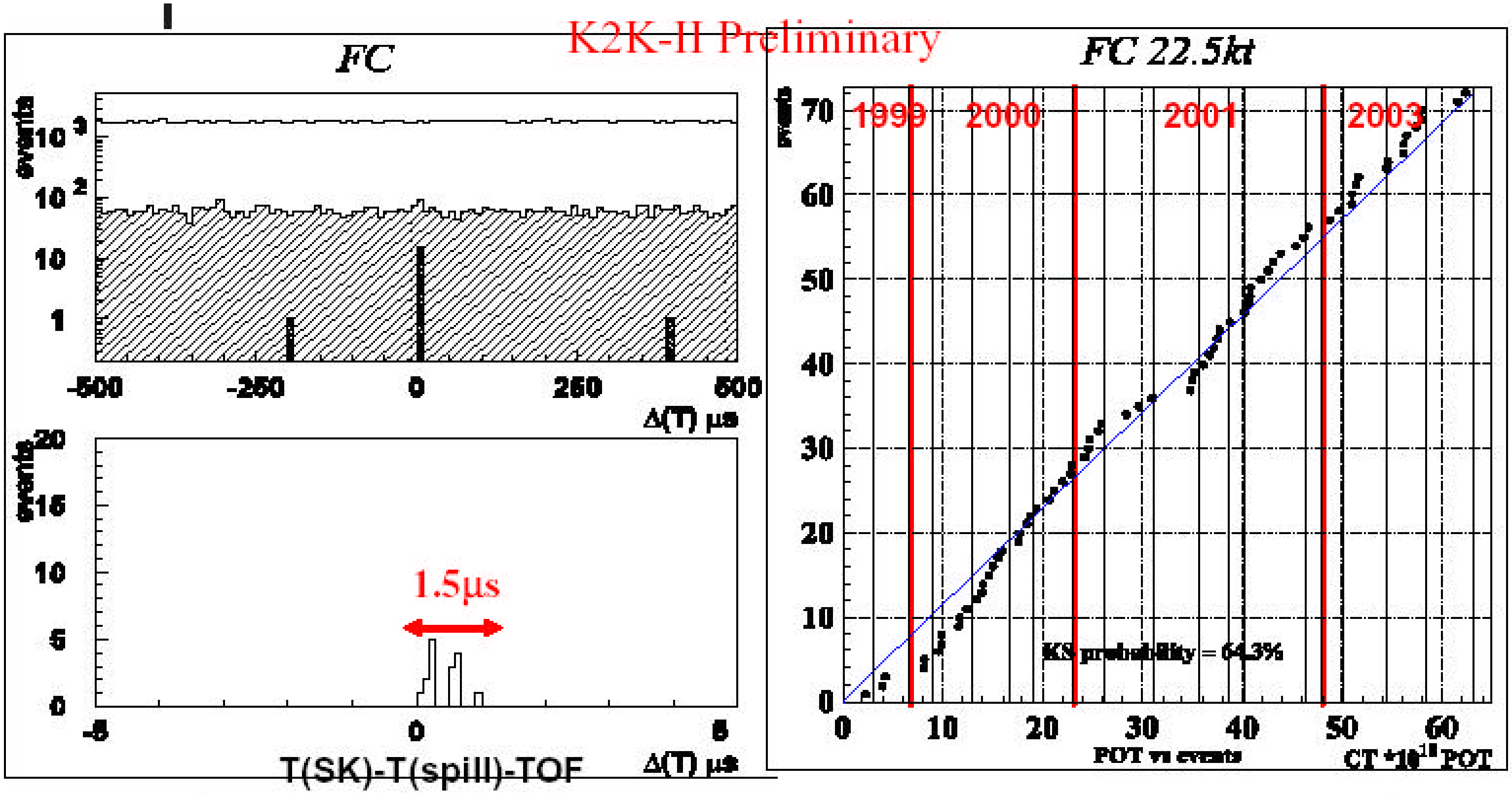
Target/Horn system
Al alloy
250 kA current

Proton intensity
~5.5x10^{12}/spill

Decay pipe
200 m long and filled with Helium @1atm

Average ν energy
$\langle E_\nu \rangle \sim 1.3$ GeV

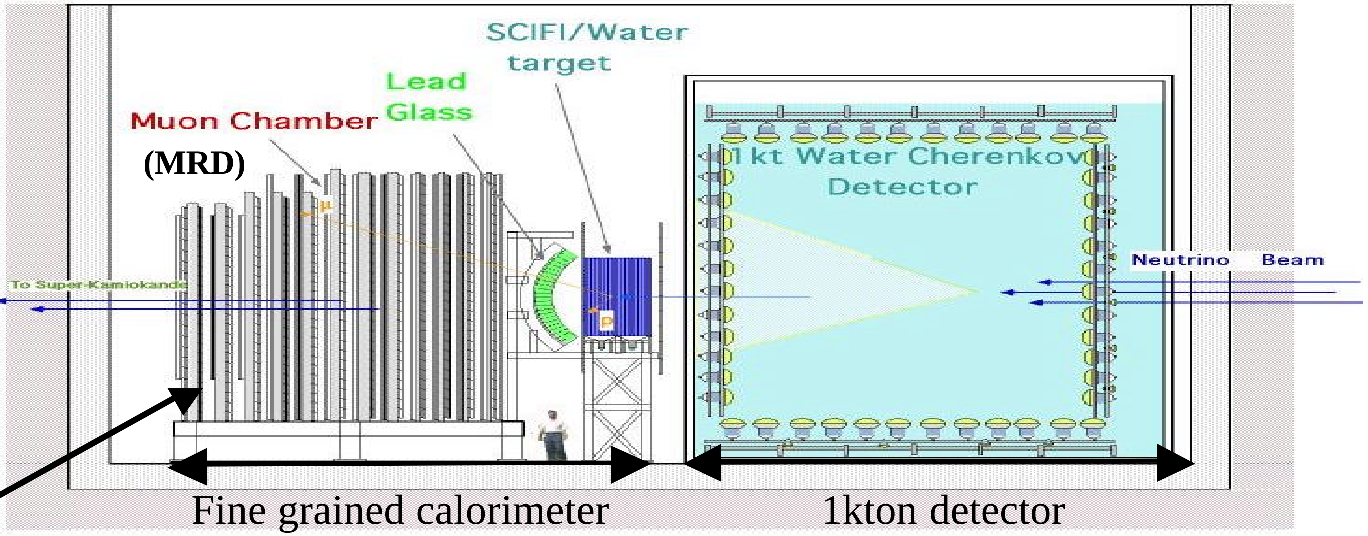
The neutrino beam



K2K-II experiment successfully observed SK events

K2K-I close detector

ν to SK



MRD consists

- ✓ **Drift tubes + 12 layers of Fe (10cm x4 + 20cm x8)**
- ✓ **Fiducial mass 312 ton**
- ✓ **200k νevts/2.1x10^{19}pot**

Features

- ✓ Good vertex resolution
- ✓ Good angular resolution
- ✓ Good momentum resolution for high energy muons

Aim

- ✓ Measure ν energy
- ✓ Measure ν profile

Features

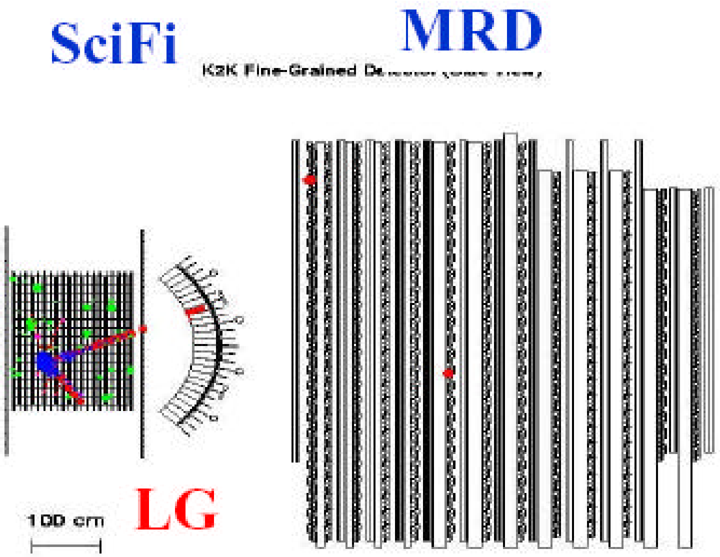
- ✓ Similar systematics as Super-Kamiokande

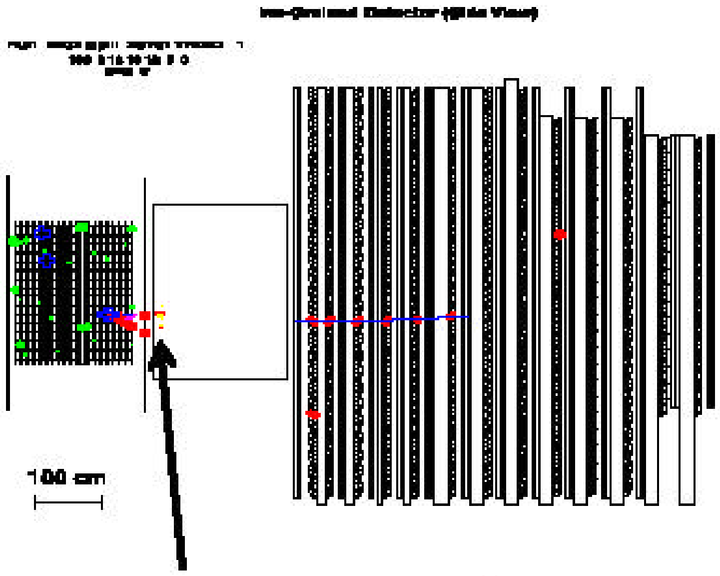
Aim

- ✓ Measure ν rate
- ✓ Measure π^0 production

K2K-II close detector

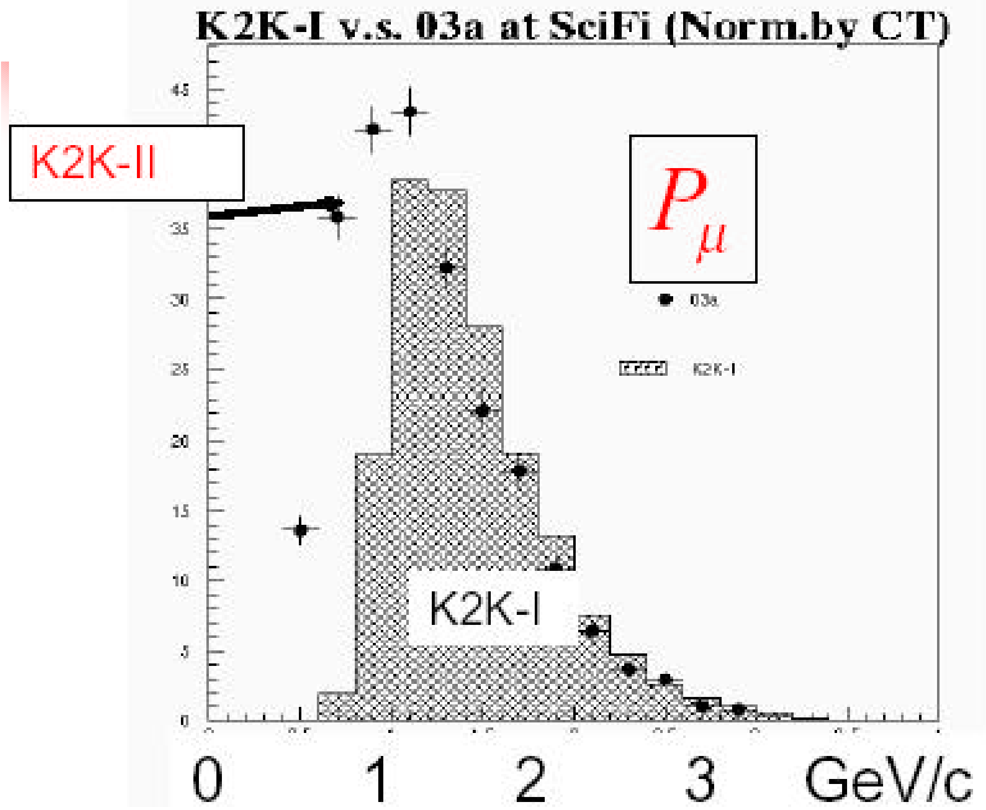
K2K-I → K2K-II

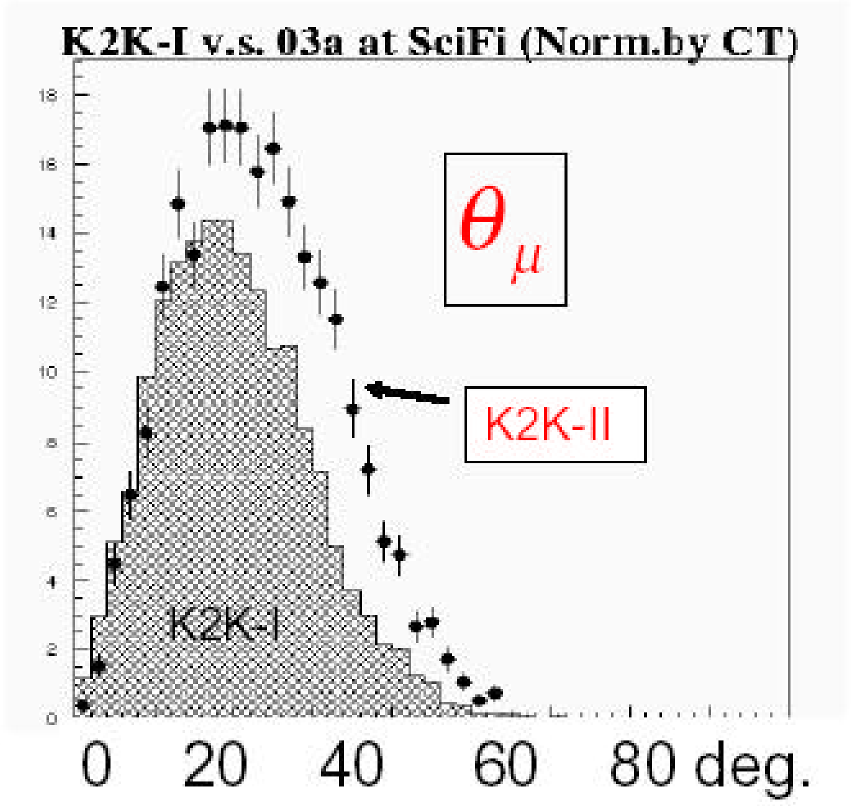




Scibar 4layers exists.
Full installation this summer.

Improved Acceptance

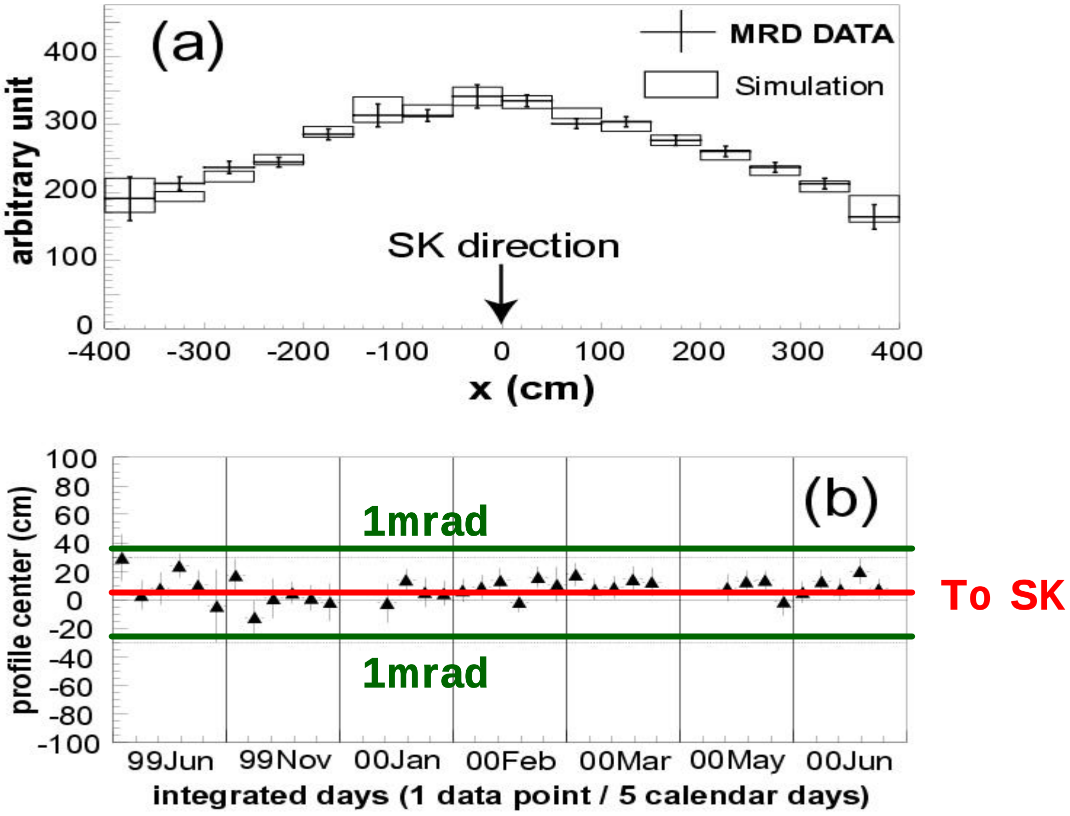




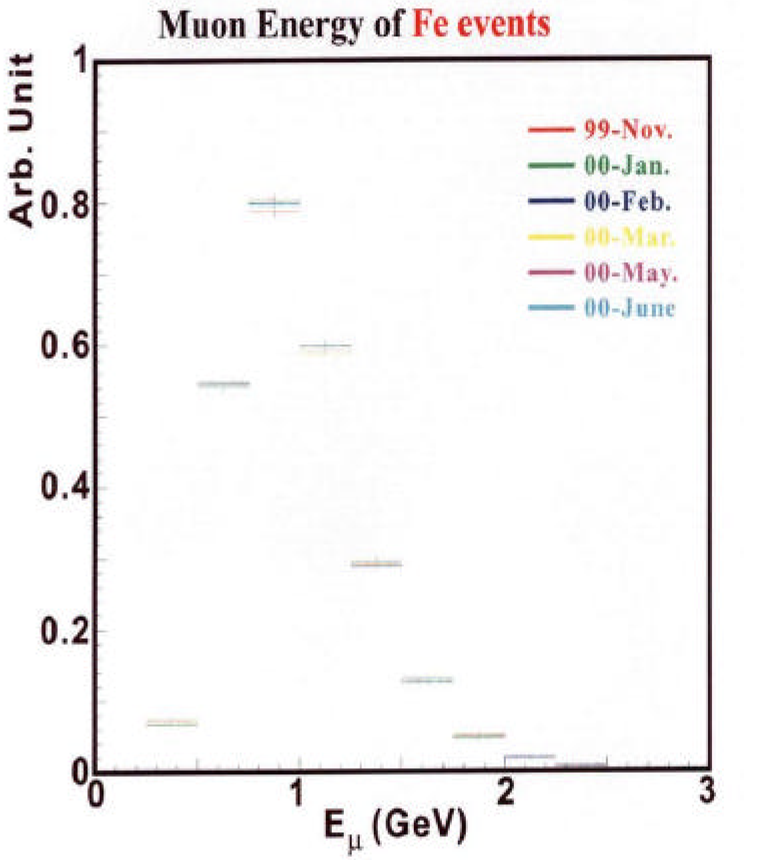
- Increased acceptance at low energy
  - Important for the oscillation analysis
- Increased acceptance at large angle

Profile and spectrum stability monitored with the MRD

Stability of the profile

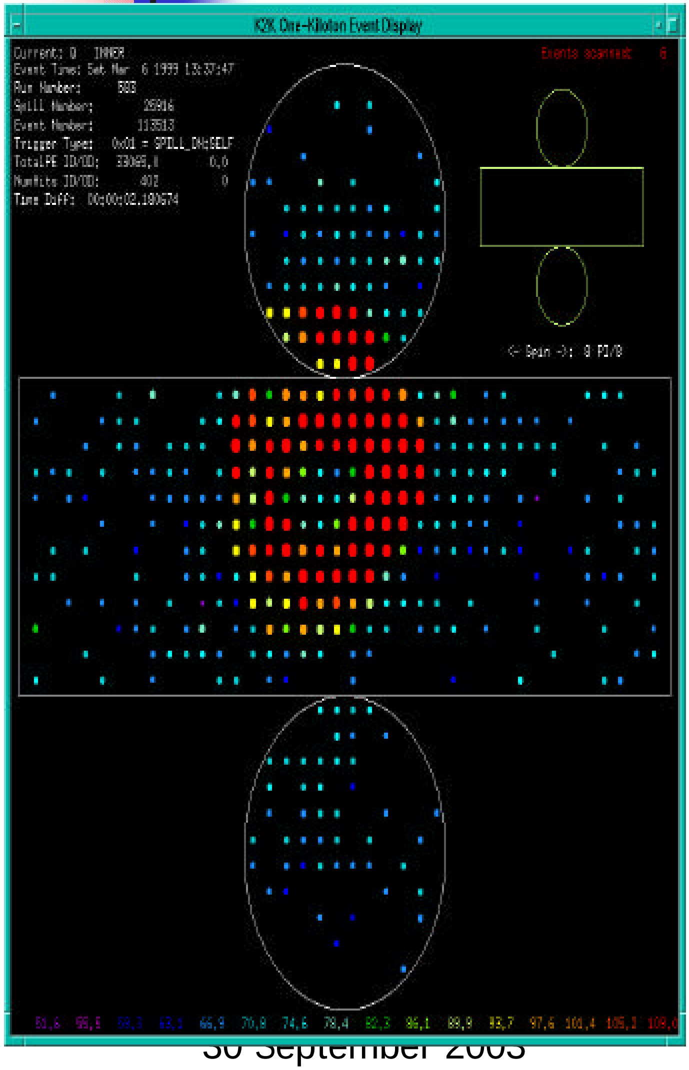


Stability of the spectrum

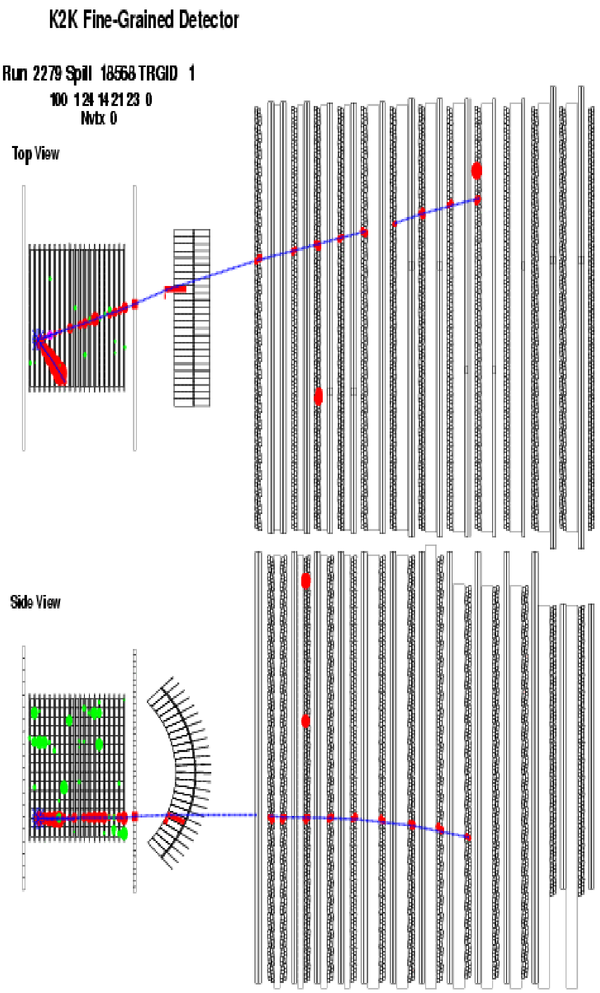


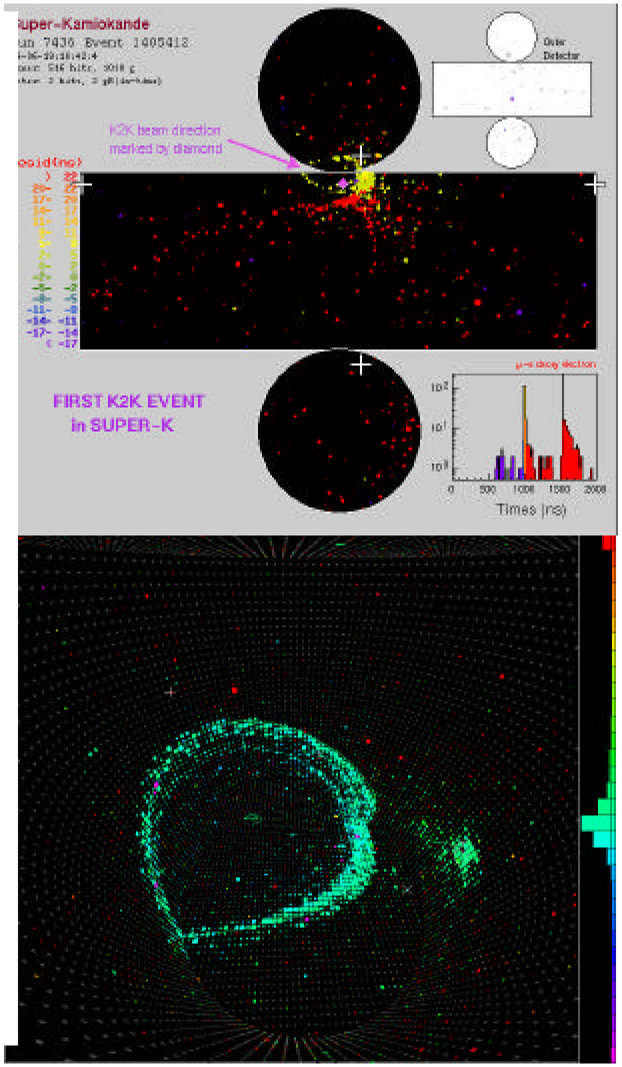
- **beam direction is stable within 1 mrad**

ν interaction @ different locations



```
Current: 0   INNER
Event Time: Sat Mar  6 1999 13:37:47
Run Number:        583
Spill Number:        25916
Event Number:       113513
Trigger Type:   0x01 = SPILL_ONLSELF
TotalPE ID/OD:   33065,1        0,0
NumHits ID/OD:      402          0
Time Diff:  00:00:02.180674
```





Event selection at SK

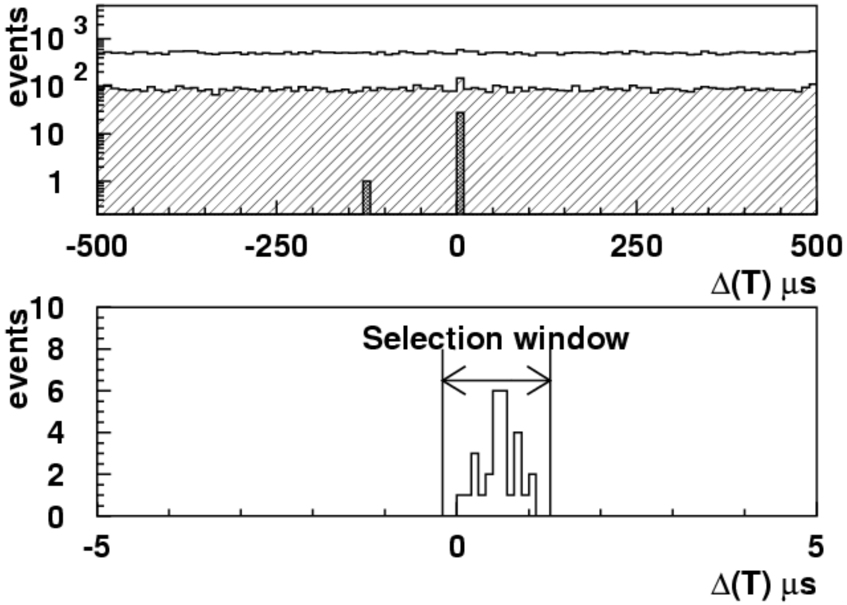
Using GPS timing

$$\Delta T \equiv T_{SK} - T_{KEK} - TOF$$

require

$$-0.2 < \Delta T < 1.3ms$$

56 evts fully contained in the fiducial volume have been observed



10^{-3} background events up to now mainly from atmospheric ν events

Trigger similar to the one used for atmospheric neutrino induced events

Expected #ν evts at SK (1)

$$N_{\text{expected}} = \underbrace{N_{\text{observed}} \times \frac{1}{e_{CD}}} \times R_{FD/CD} \times e_{SK} \times \frac{L.T._{SK}}{L.T._{CD}}$$

#evts expected at SK
assuming null oscillations

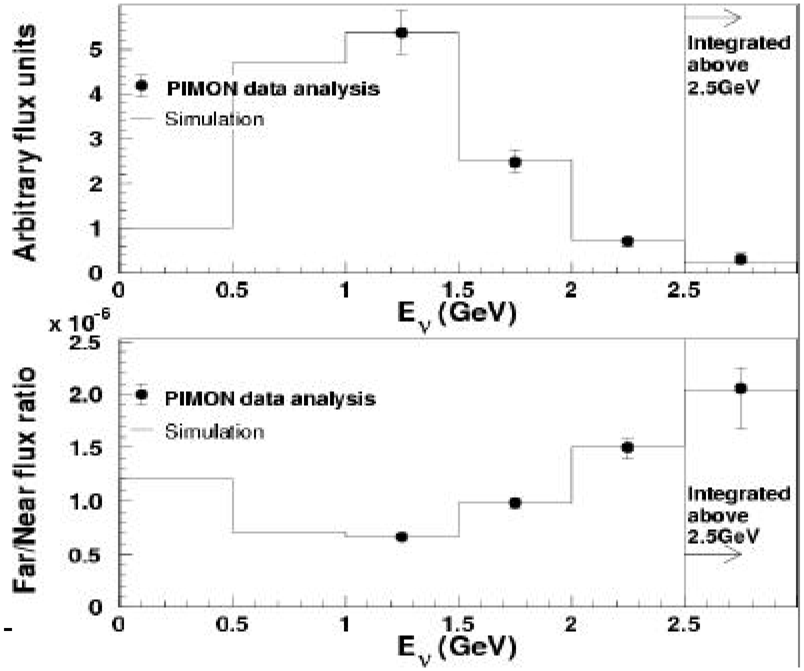
#evts observed in the
near detector

Live time correction
using **p**roton **o**n **t**arget

$$R_{FD/CD} = \frac{\int \Phi_{SK} s_{SK} \mathrm{d}E}{\int \Phi_{CD} s_{CD} \mathrm{d}E} \times \frac{N_{SK}^{\text{target}}}{N_{CD}^{\text{target}}}$$

Event ratio R from MC calculation but

Φ_{SK} and Φ_{CD} confirmed by
pion monitor ($E_\nu > 1$ GeV)



Expected #ν evts at SK (2)

The 1kton water Cerenkov detector is used as reference CD detector

- ✓ same neutrino interaction target
  (cross section uncertainty cancels out)
- ✓ same detection energy threshold
- ✓ same event reconstruction scheme

⇨ small systematic error

The MRD and Scifi/Water detectors are used to check the consistency of the 1kton detector results

Expected #ν evts at SK (3)

Beam–associated events in Super-K

June 1999 – July 2001 (4.8×10^{19} protons on target)

FCFV events, $E_{vis} > 30$ MeV: **Expected ($P_{osc} = 0$): $80.1^{+6.2}_{-5.4}$ events**

Observed: 56 events

(probability of a statistical fluctuation ~3% if $P_{osc} = 0$)

Nov 1999 – July 2001 (stable beam conditions)

Main source of sys. Error

✓ Sys. error from 1kton meas.
(mainly due to fid. vol.) **5%**

✓ Sys. error from SK meas. **3%**

✓ Sys. Error from extrapolation

✓Far/Close **7%**

✓ Statistical error **1%**

Null Oscillation Probability

Null Oscillation Probability

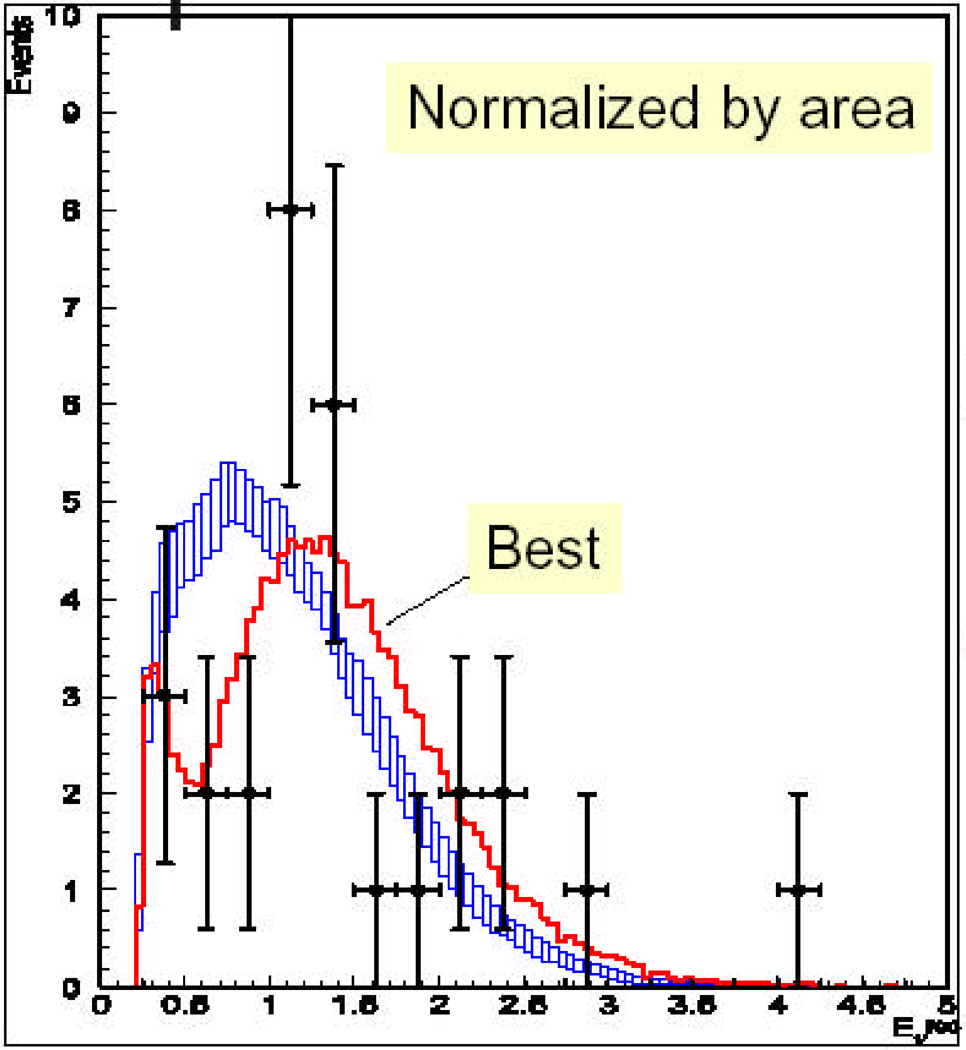
	analysis-1	analysis-2
N_{SK}only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK}+Shape	0.7%	0.4%

Best fit ($\sin^2 2\theta$, Δm^2)

Shape only	(1.0, 3.0x10^{-3}eV^2)	(1.0, 3.2x10^{-3}eV^2)
(Allowing unphys.)	(1.09, 3.0x10^{-3}eV^2)	(1.05, 3.2x10^{-3}eV^2)
N_{SK} +Shape	(1.0, 2.8x10^{-3}eV^2)	(1.0, 2.7x10^{-3}eV^2)
(Allowing unphys.)	(1.03, 2.8x10^{-3}eV^2)	(1.05, 2.7x10^{-3}eV^2)

Both Shape and N_{SK} +Shape indicate consistent parameter region

Best fit 1Rμ spectrum & Nsk



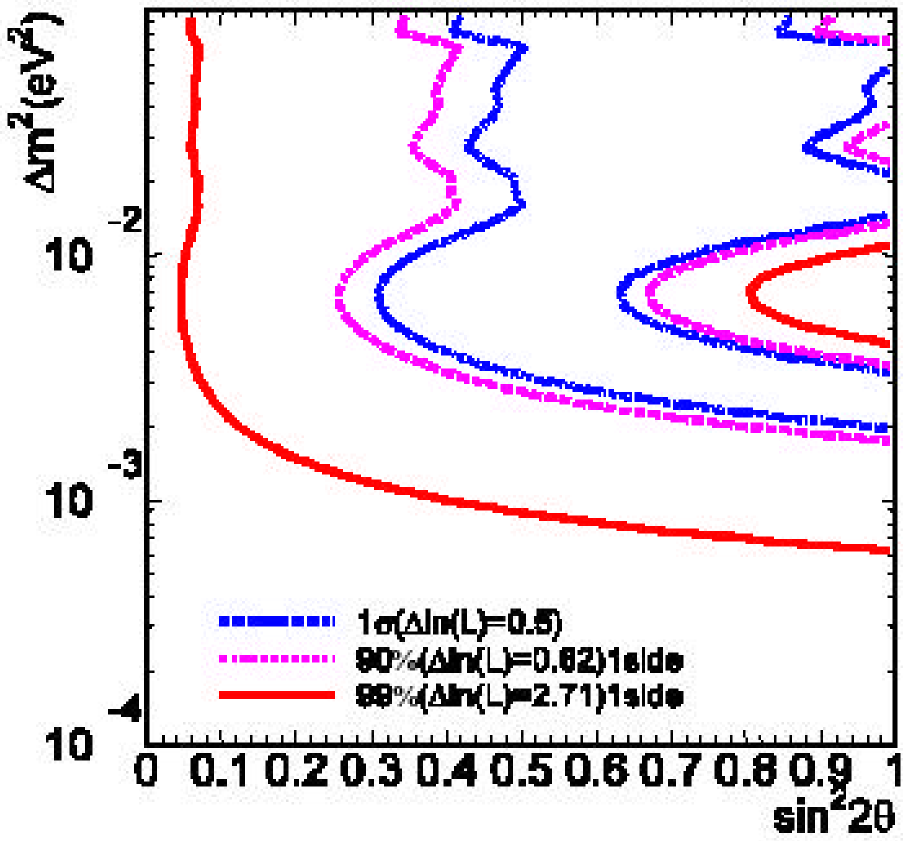
Best fit point ($\sin^2 2\theta$, Δm^2) = (1.0, $2.8\times10^{-3}\text{eV}^2$)

KS test prob.(shape): 79%

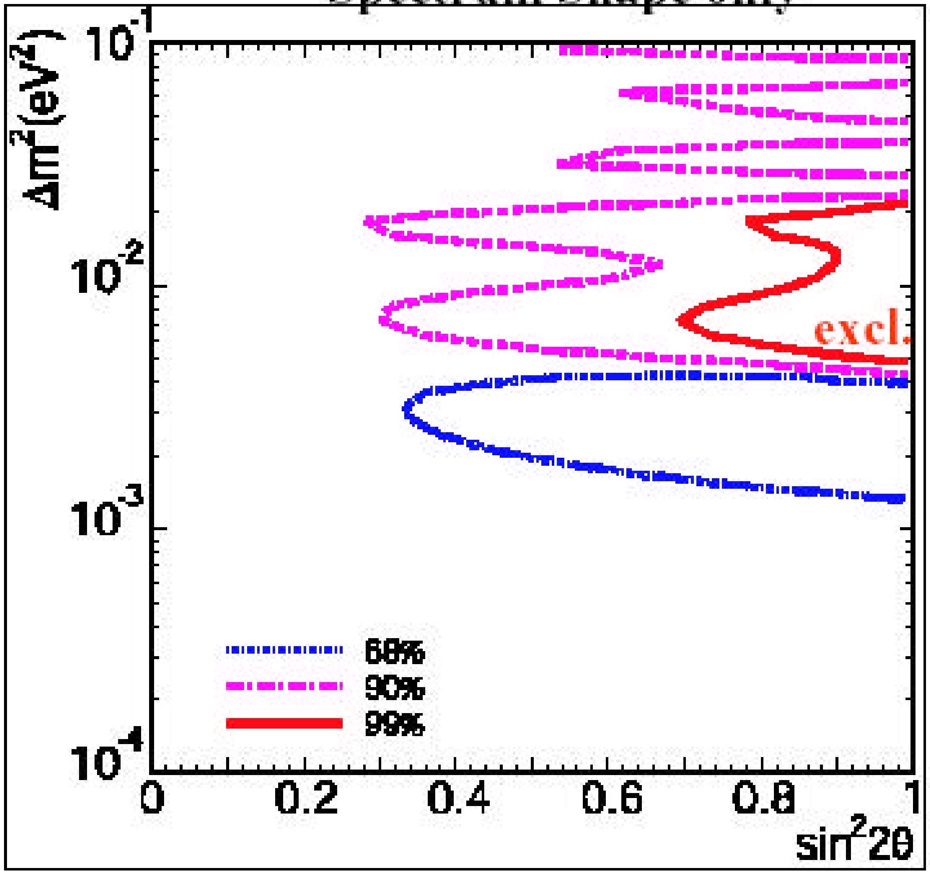
N_{SK}=54 (Obs.=56)

Very good agreement Shape & N_{SK}

Allowed regions



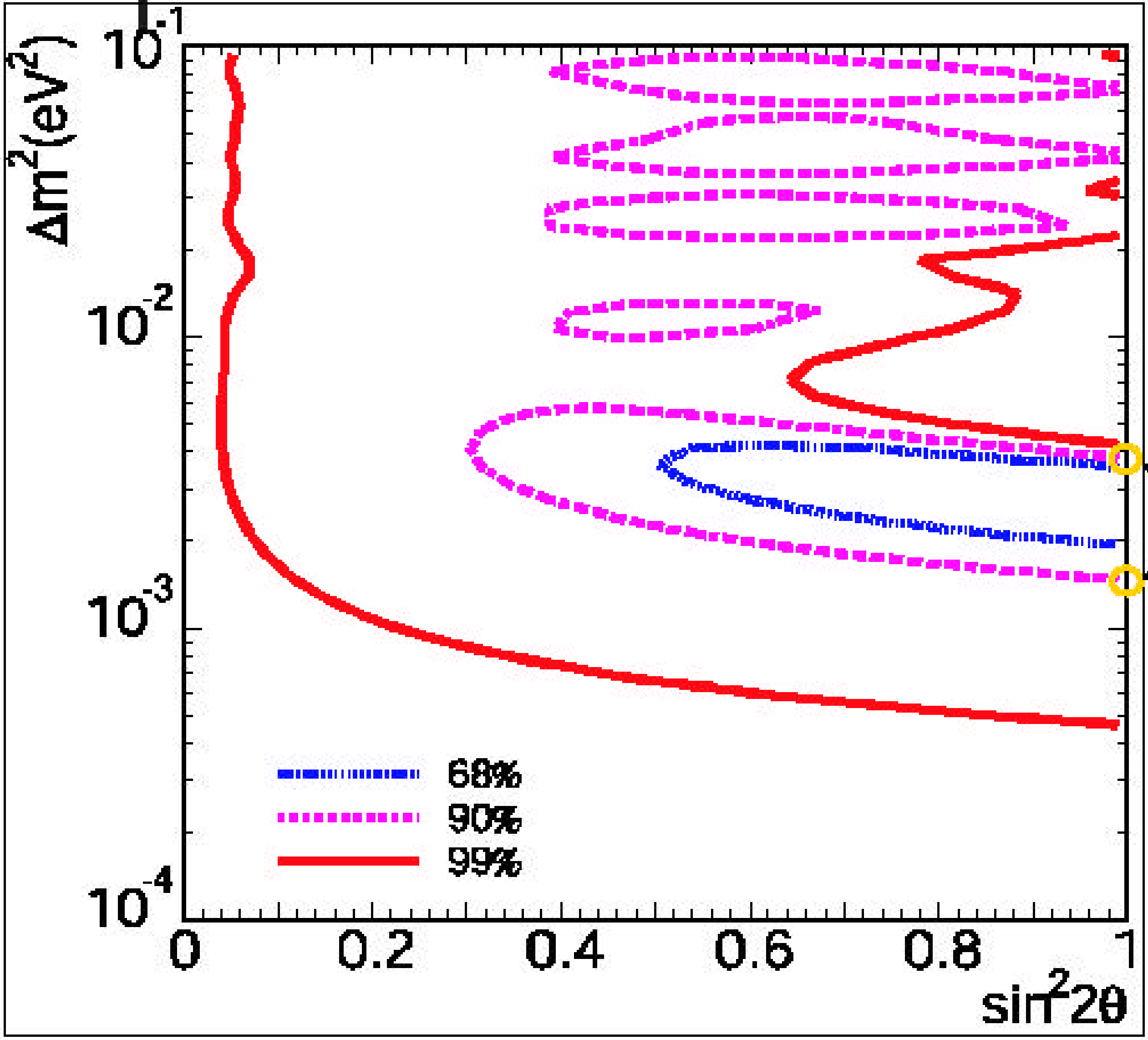
Total no. of Events only



Spectrum Shape only

Both indicate consistent Δm² region

Allowed region (Shape+Norm)

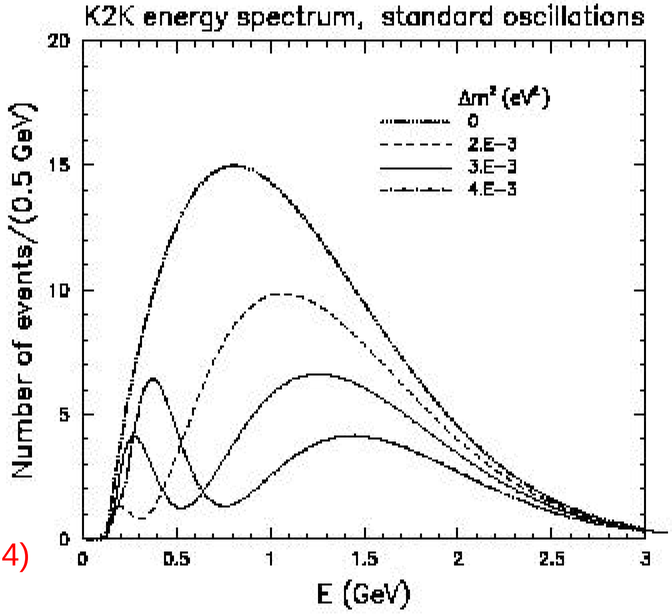


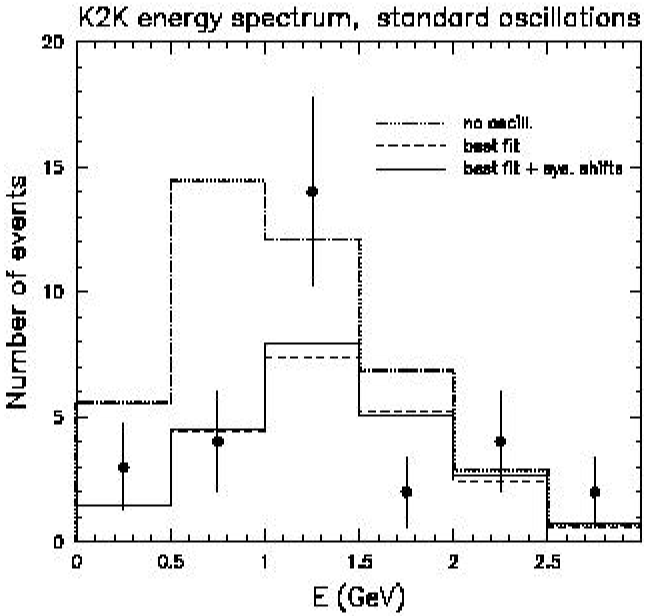
Δm^2=
$1.5\text{~}3.9\times10^{-3}eV^2$
@ $\sin^2 2\theta=1$
@90%CL

K2K energy spectrum

The value of Δm^2 determines the oscillation minimum, giving the maximum event rate suppression

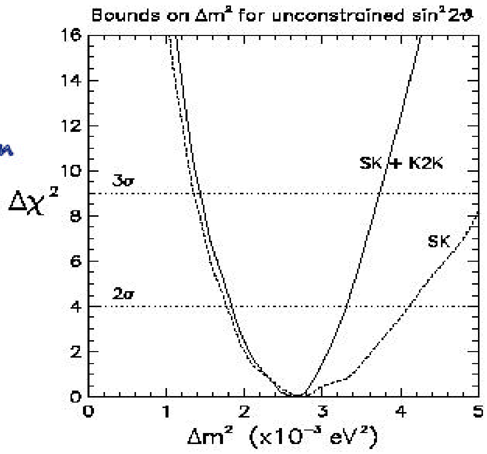
(GL Fogli, E. Lisi, A. Marrone and D. Montanino, hep-ph/0303064)



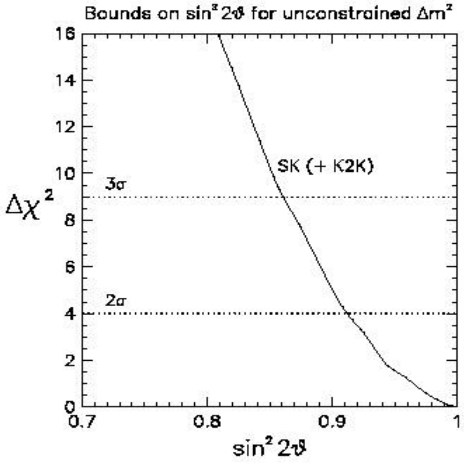


The combination SK+K2K gives an almost parabolic χ^2 in Δm^2 so that a well defined 1σ error can be quoted:

$$\Delta m^2 = (2.6 \pm 0.4) \times 10^{-3}\,\mathrm{eV}^2$$



jlio:



Also in this case the fit gives an almost parabolic χ^2 resulting in the following limit at 1σ:

$$\sin^2 2\theta_{23} = 1.00^{+0.00}_{-0.05}$$

(The impact of K2K is negligible in this case)

Impact of atmospheric and K2K neutrinos

Δm^2, θ_{23} can be basically taken from the 2ν analysis of SK data, K2K

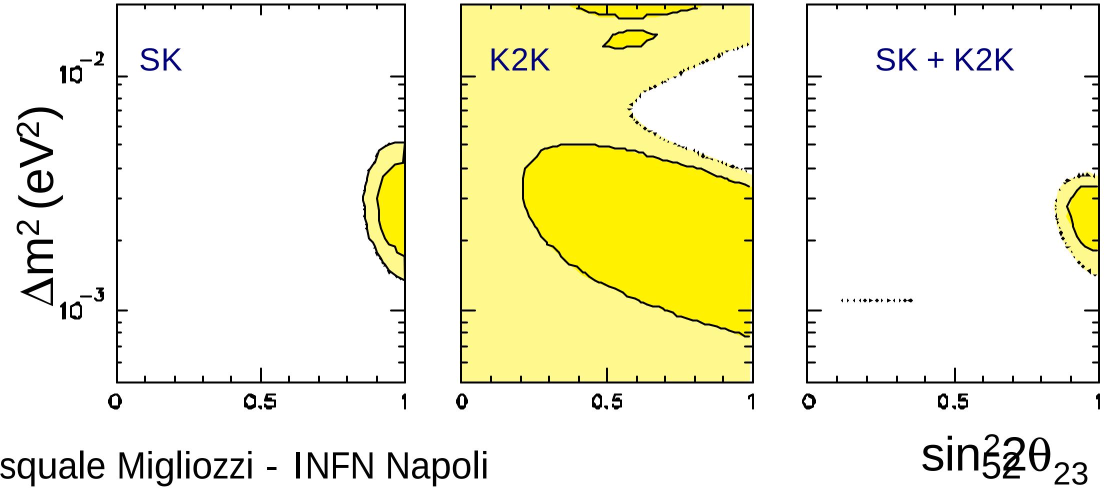
since they are not significantly perturbed by 3ν effects induced by small θ_{13} or $\delta m^2/\Delta m^2$ (at least within the current picture).

this also implies no real sensitivity to sign(Δm^2) or δ

$$\Delta m^2 = (2.6 \pm 0.4) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00\ ^{+0.00}_{-0.05}$$

(GL Fogli, E. Lisi, A. Marrone and D. Montanino, hep-ph/0303064)



However this is not the end of the story!

A new analysis of the available SK data has been recently presented

Atmospheric ν oscillation analysis updates

- New neutrino flux (Honda 2001)

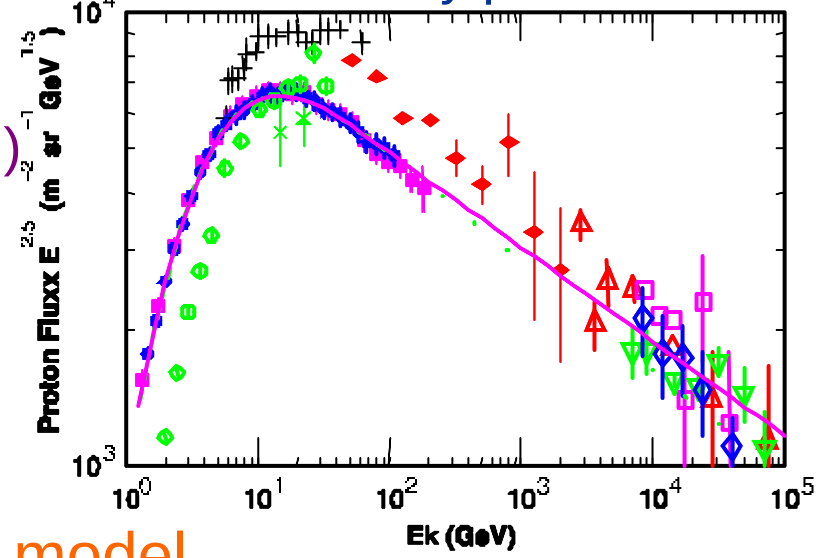
  Updated primary cosmic ray flux

  (Based on new precise measurements.)

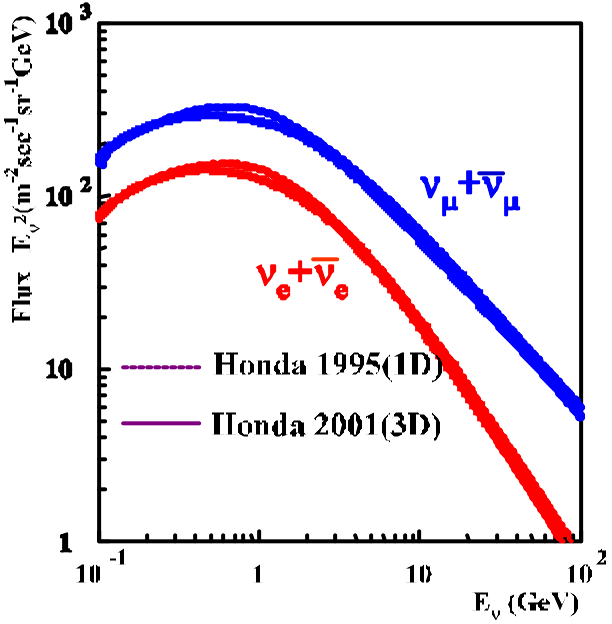
  3d calculation has been done.

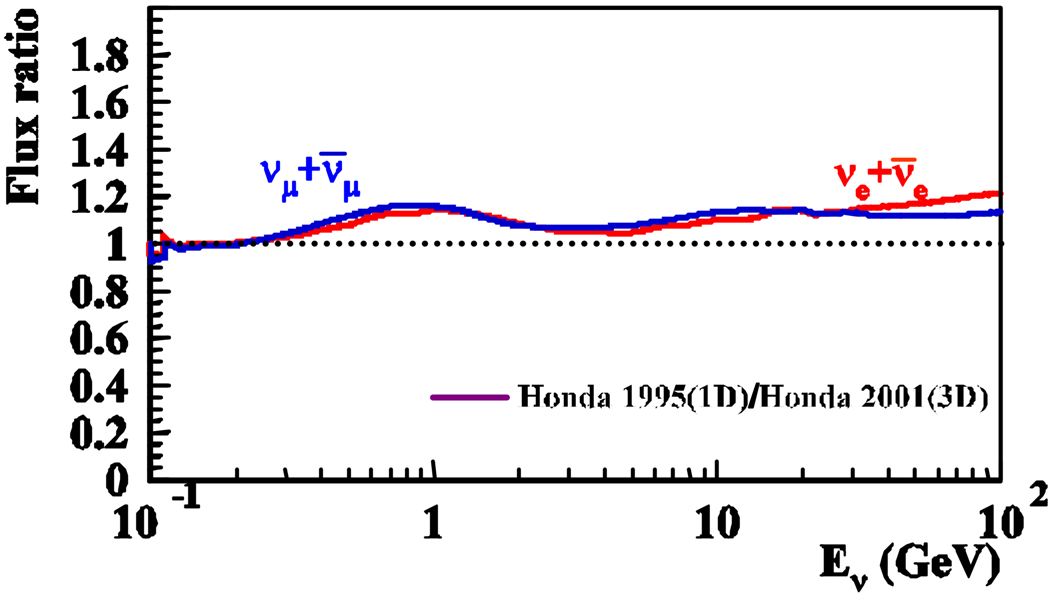
  (In the previous calculation,
  direction of ν was assumed to be
  as same as the primary particle.)

cosmic-ray proton flux



New improved hadron interaction model

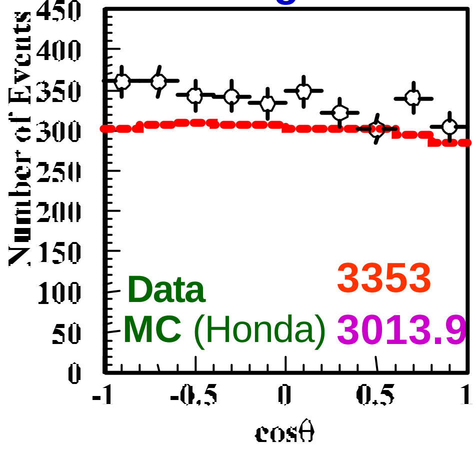




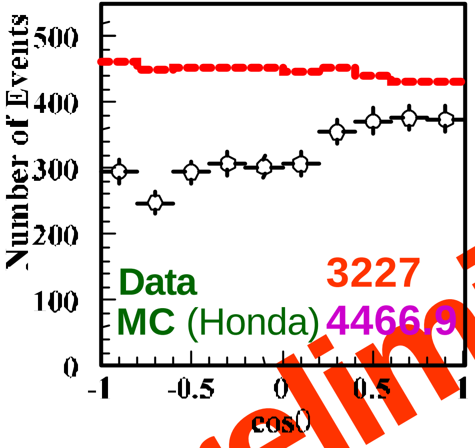
Summary of the atmospheric ν events
1.contained events

(complete SK-I dataset)

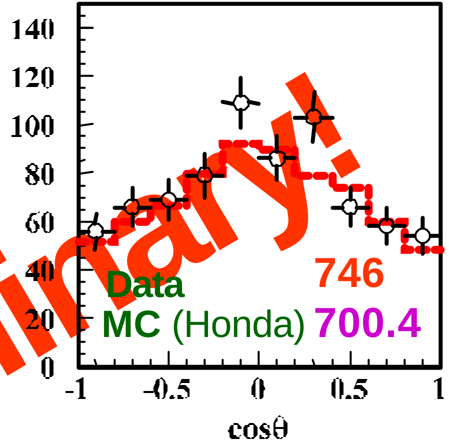
Sub GeV
1ring e-like



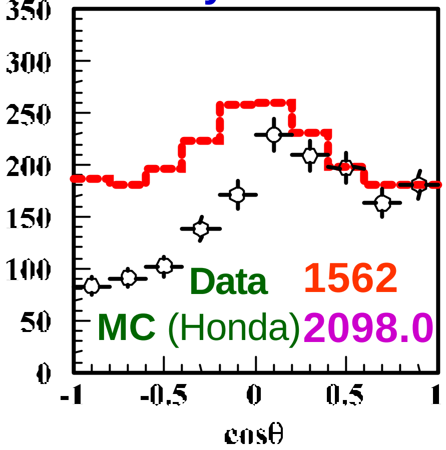
Sub GeV
1ring m-like



Multi GeV
1ring e-like



Multi-GeV 1ring m-like
+ Partially Contained



Preliminary!

Sub GeV

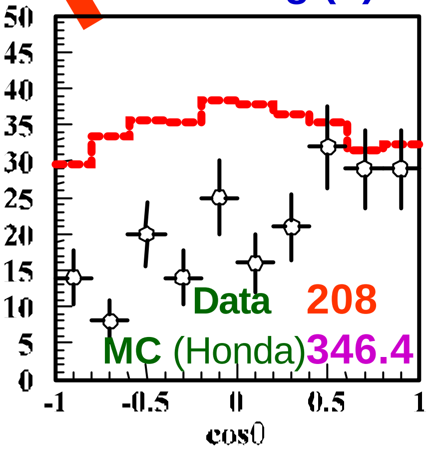
$$\frac{(m/e)_{data}}{(m/e)_{MC}} = 0.649 \pm 0.016$$

(stat.)

$$\pm 0.051$$

(syst.)

Sub GeV
Multi ring (m)



Multi GeV+PC

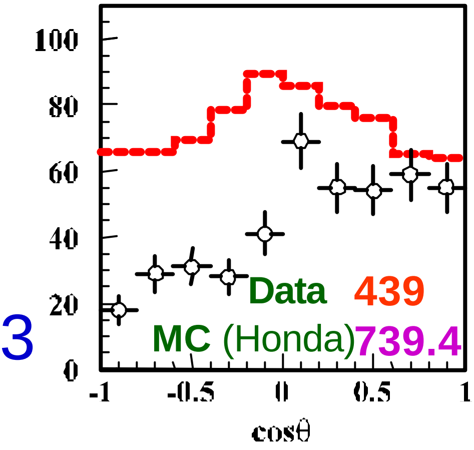
$$\frac{(m/e)_{data}}{(m/e)_{MC}} = 0.699 \pm^{0.032}_{0.030}$$

(stat.)

$$\pm 0.083$$

(syst.)

Multi GeV
Multi ring (m)



Summary of the atmospheric ν events
2.up-going μ events

(complete SK-I dataset)

Up through going m

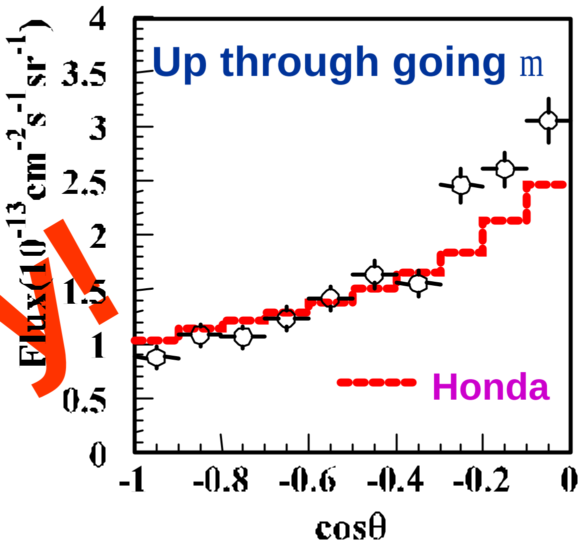
Measured flux

$1.70 \pm 0.02 \pm 0.04 \times 10^{-13} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$
(stat.) (syst.)

Theoretical calc. (Honda)

$1.57 \pm 0.35 \times 10^{-13} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$
(theo.)

Preliminary!



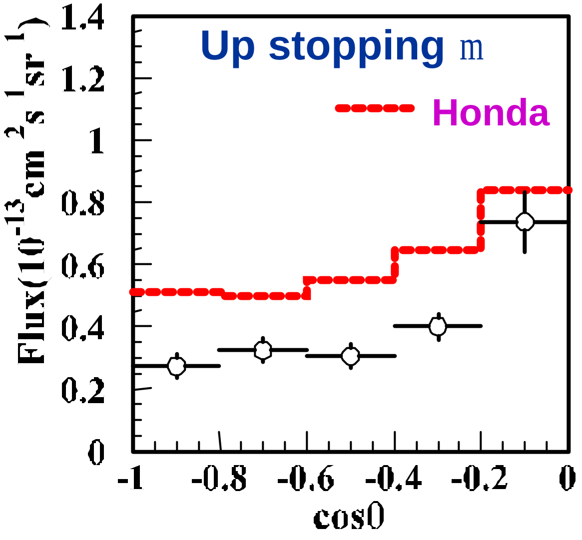
Up stopping m

Measured flux

$0.41 \pm 0.02 \pm 0.02 \times 10^{-13} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$
(stat.) (syst.)

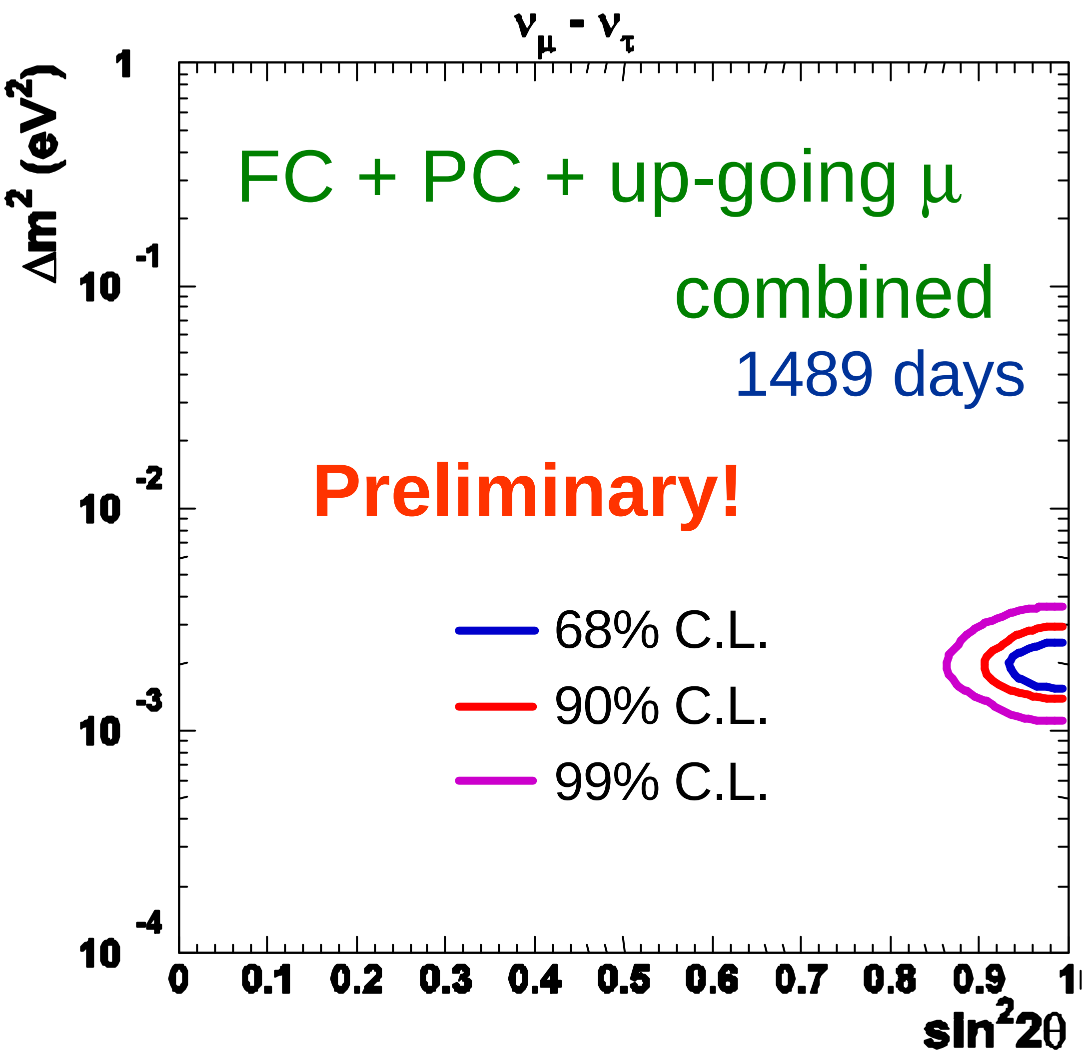
Theoretical calc. (Honda)

$0.61 \pm 0.14 \times 10^{-13} \mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{sr}^{-1}$
(theo.)



Allowed region of the oscillation parameters from atmospheric ν data

(complete SK-I dataset)



Assuming $\nu_\mu \Leftrightarrow \nu_\tau$ oscillation

Best fit

c^2_{min} = 170.8/170 d.o.f.

at ($\sin^2 2\theta$, Δm^2)

= (1.0,2.0 x 10^{-3} eV^2)

90% confidence level allowed region

$\sin^2 2\theta > 0.9$

$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ (eV^2)

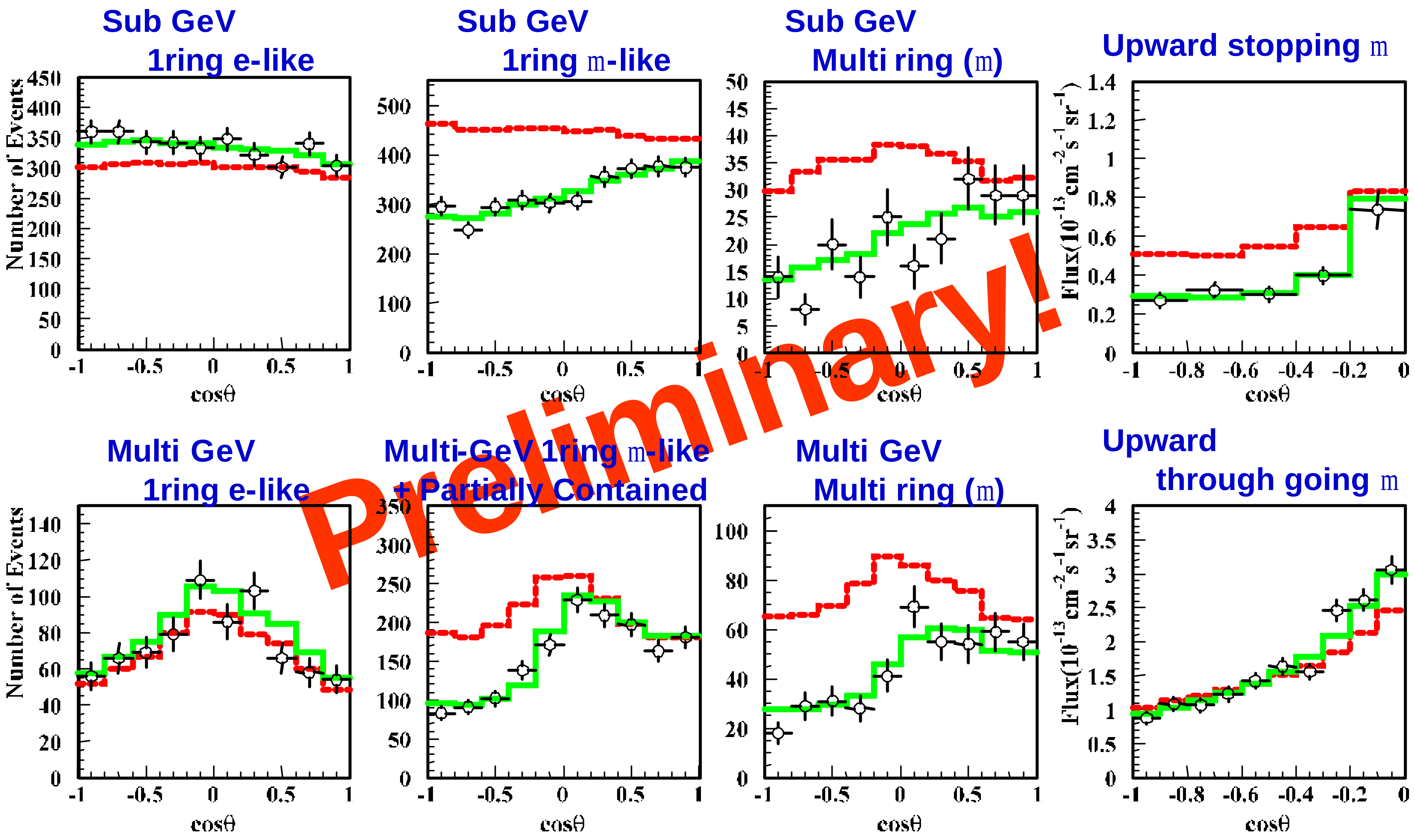
Assuming null oscillation

c^2 = 445.2/172 d.o.f.

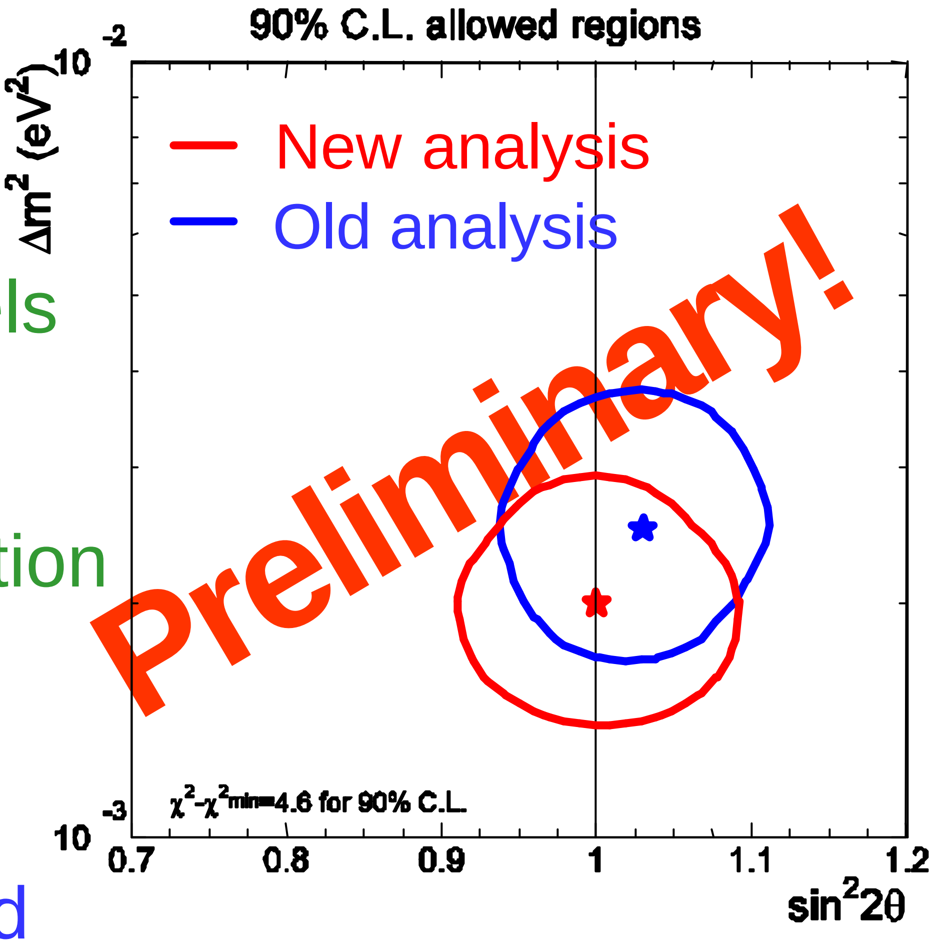
Atmospheric ν zenith angle distribution

Honda

Best fit($\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2)



Comparison between old and new results from atmospheric ν data

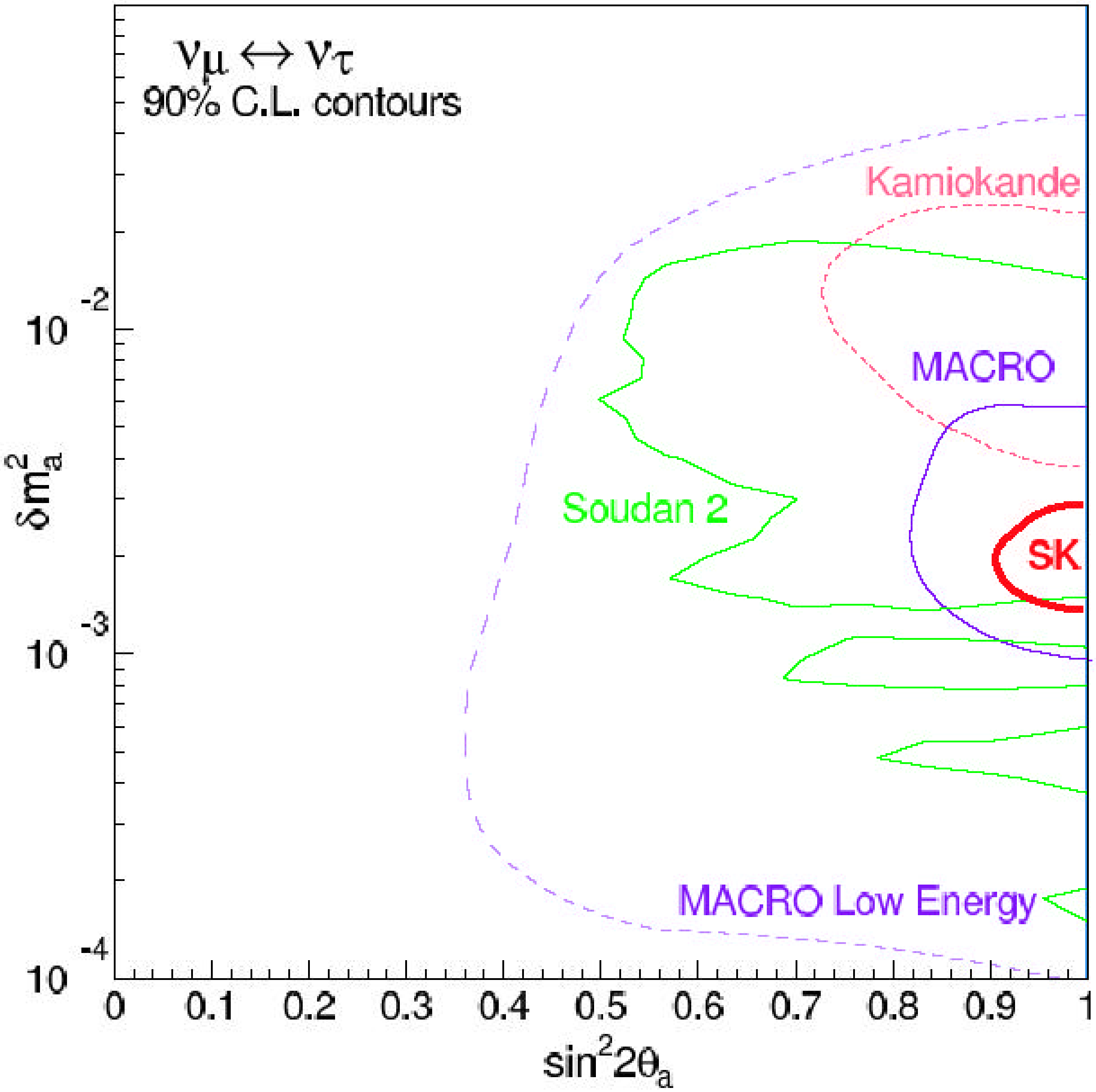


- Neutrino flux

  (Honda 1995 → Honda 2001)
- Neutrino interaction models

  (several improvements,
  agree with K2K near data)
- Improved detector simulation
- Improved event reconstruction tools

Each change slightly shifted the allowed region to lower Δm^2


$\nu_\mu \leftrightarrow \nu_\tau$
90% C.L. contours
Kamiokande
MACRO
Soudan 2
SK
MACRO Low Energy
δm_a^2
10^{-2}
10^{-3}
10^{-4}
$\sin^2 2\theta_a$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1