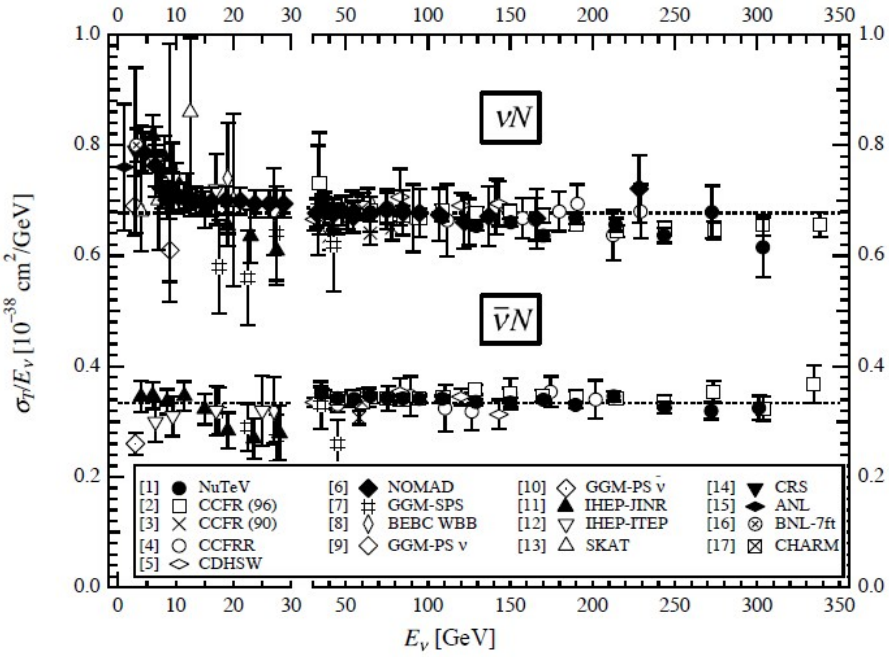


PMNS mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $s_{ij} = \sin\theta_{ij}$ $\quad c_{ij} = \cos\theta_{ij}$

α_1, α_2 *Majorana phases*

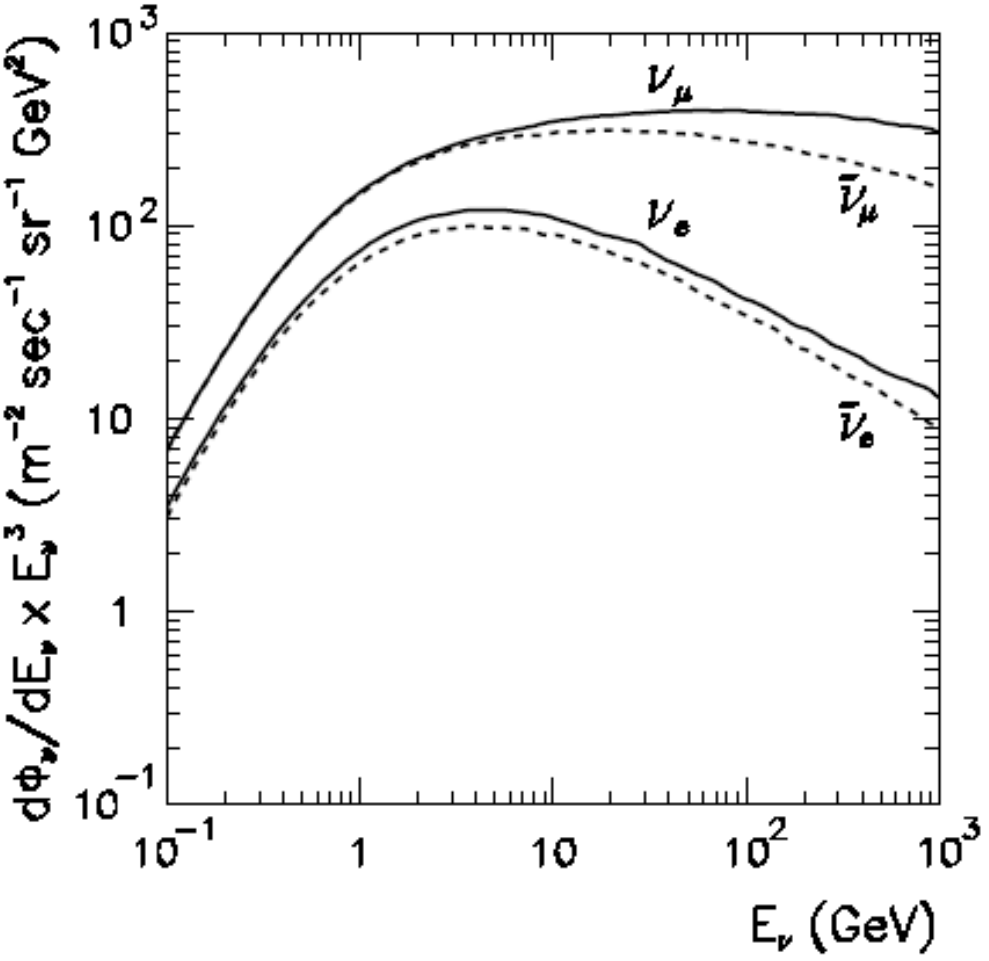
δ *Dirac* (CP) *phase*

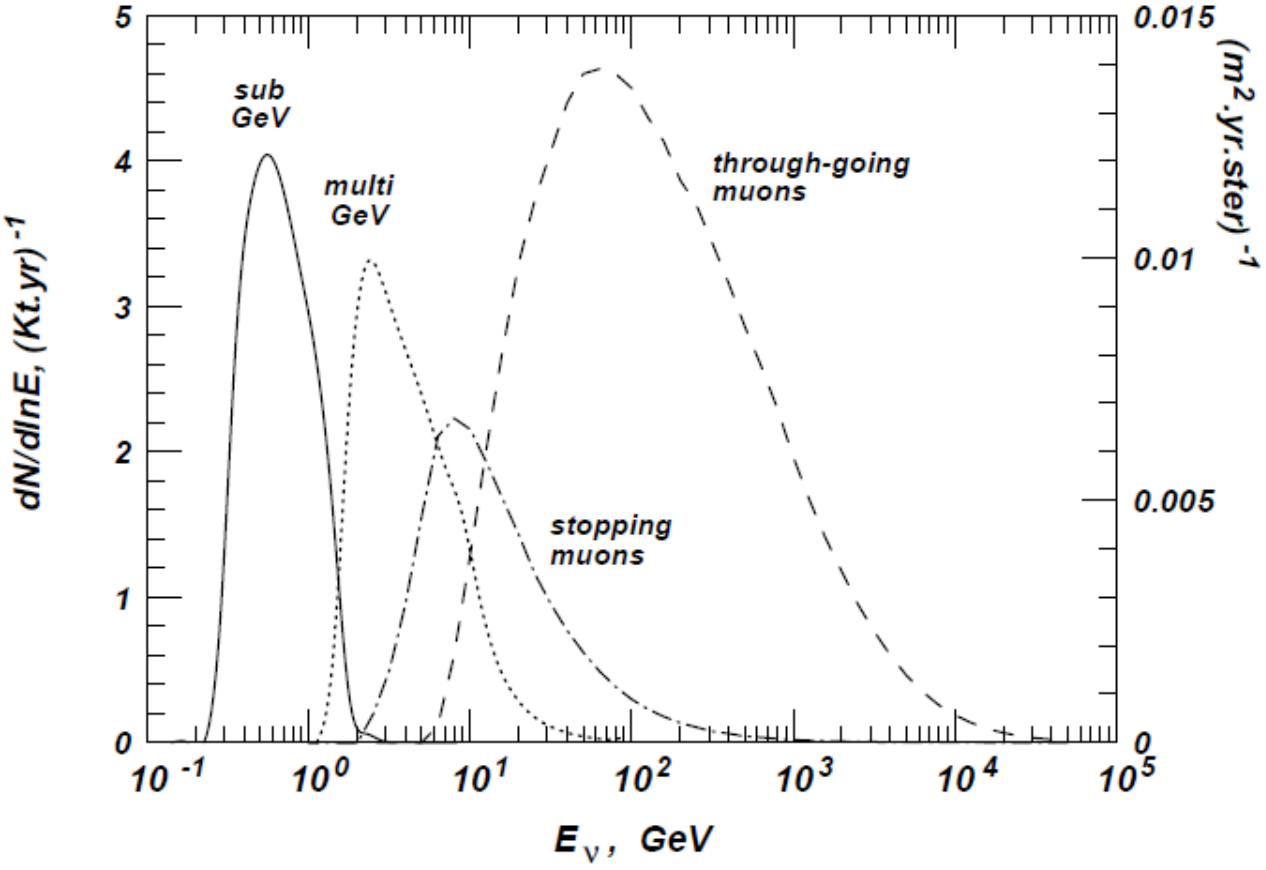
$\sin^2 2\theta_{12} = 0.87 \pm 0.03$ $\quad \Delta m^2_{12} = \left(7.59^{+0.19}_{-0.21}\right) \times 10^{-5}\ \text{eV}^2$

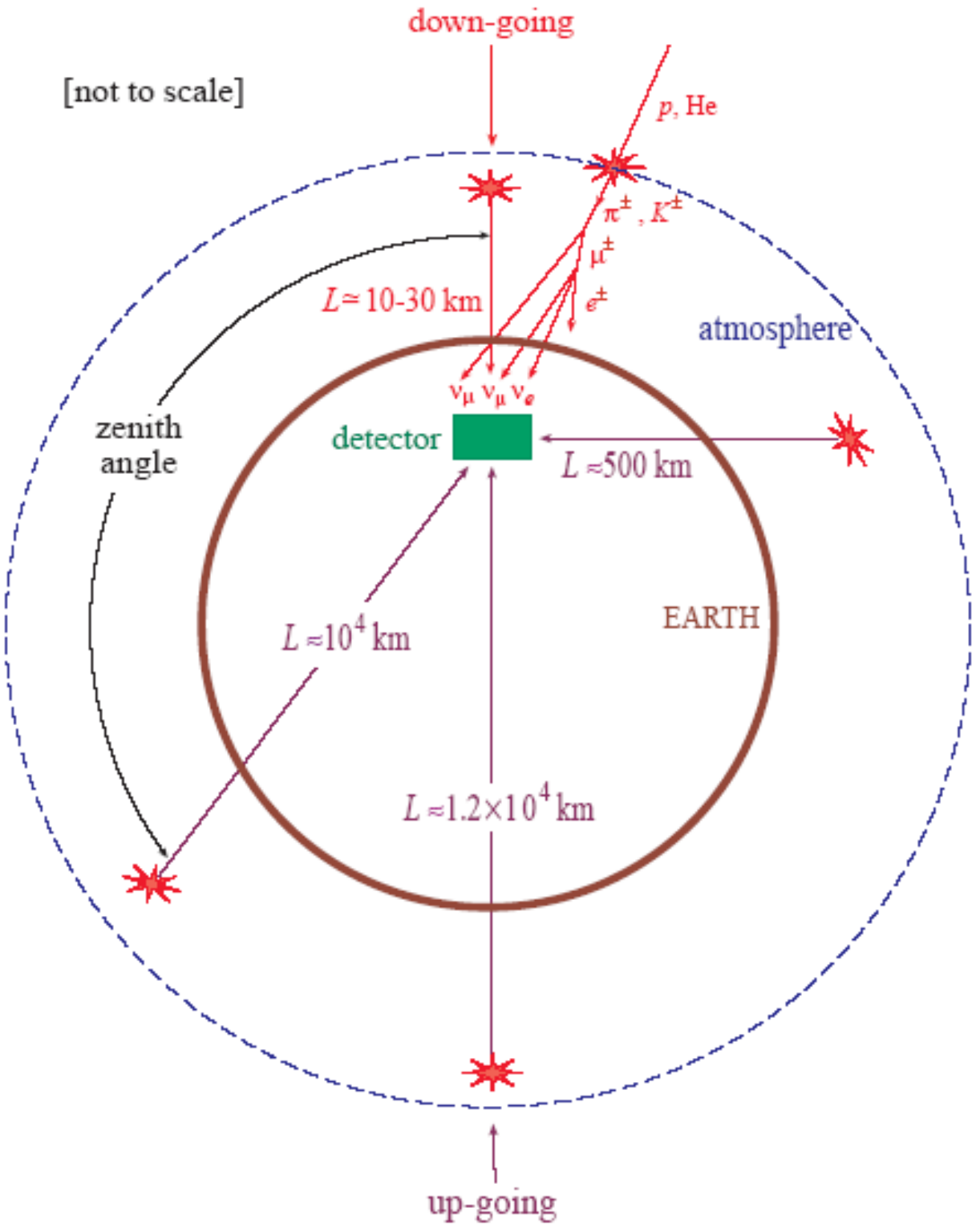
$\sin^2 2\theta_{23} > 0.92$ $\quad \Delta m^2_{23} = (2.43 \pm 0.13) \times 10^{-3}\ \text{eV}^2$

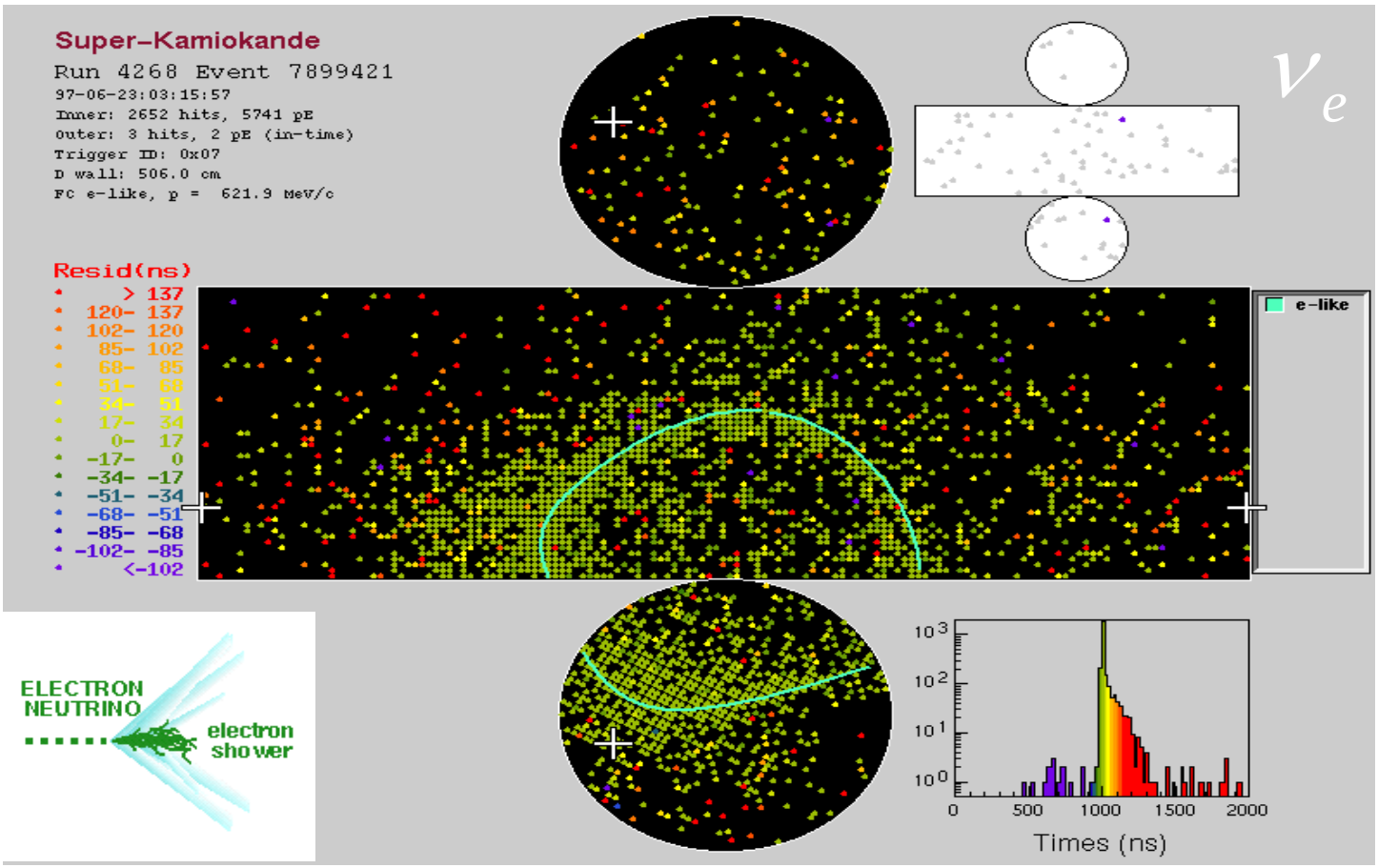
$\sin^2 2\theta_{13} < 0.15$

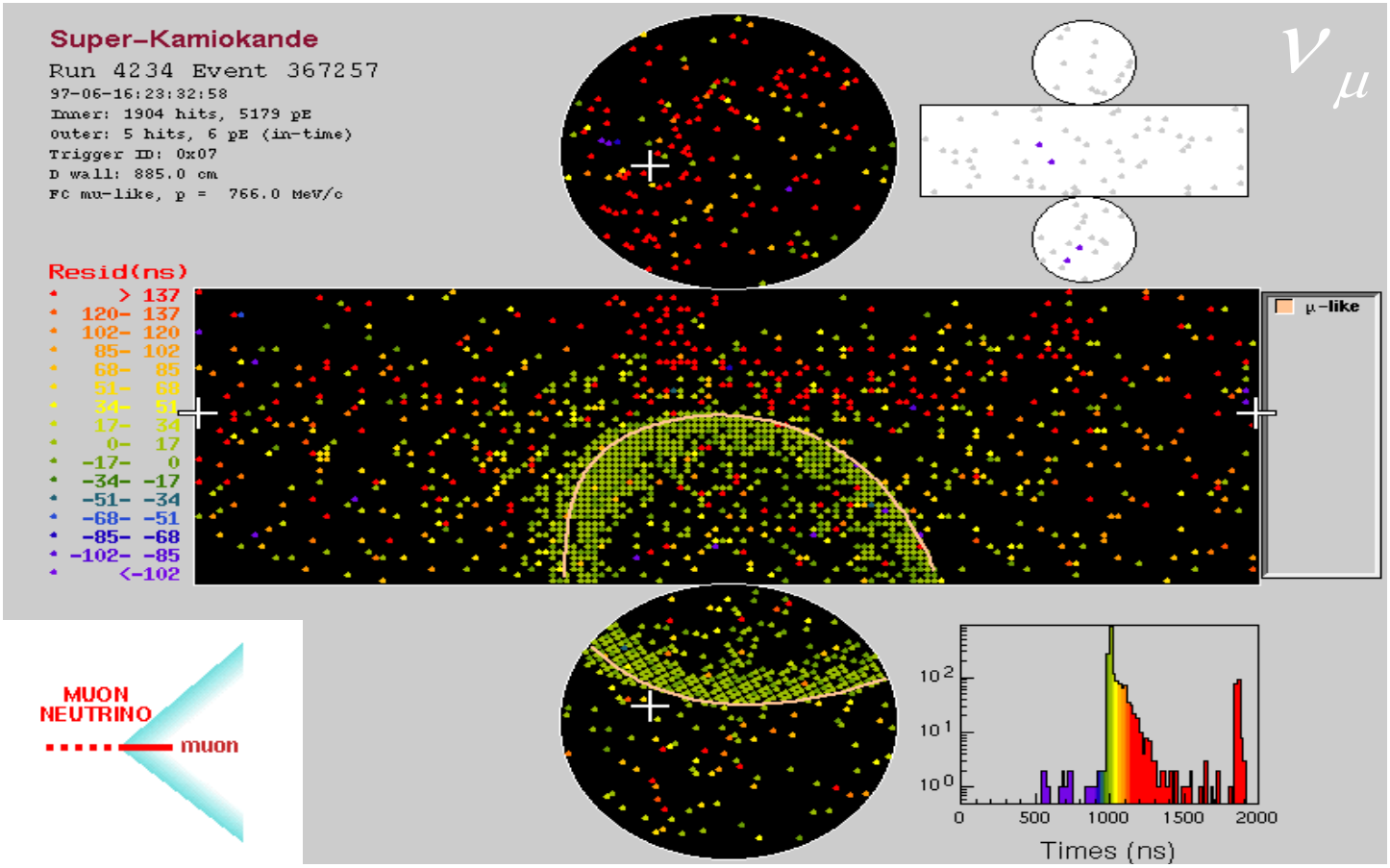
Valori dal PDG 2010

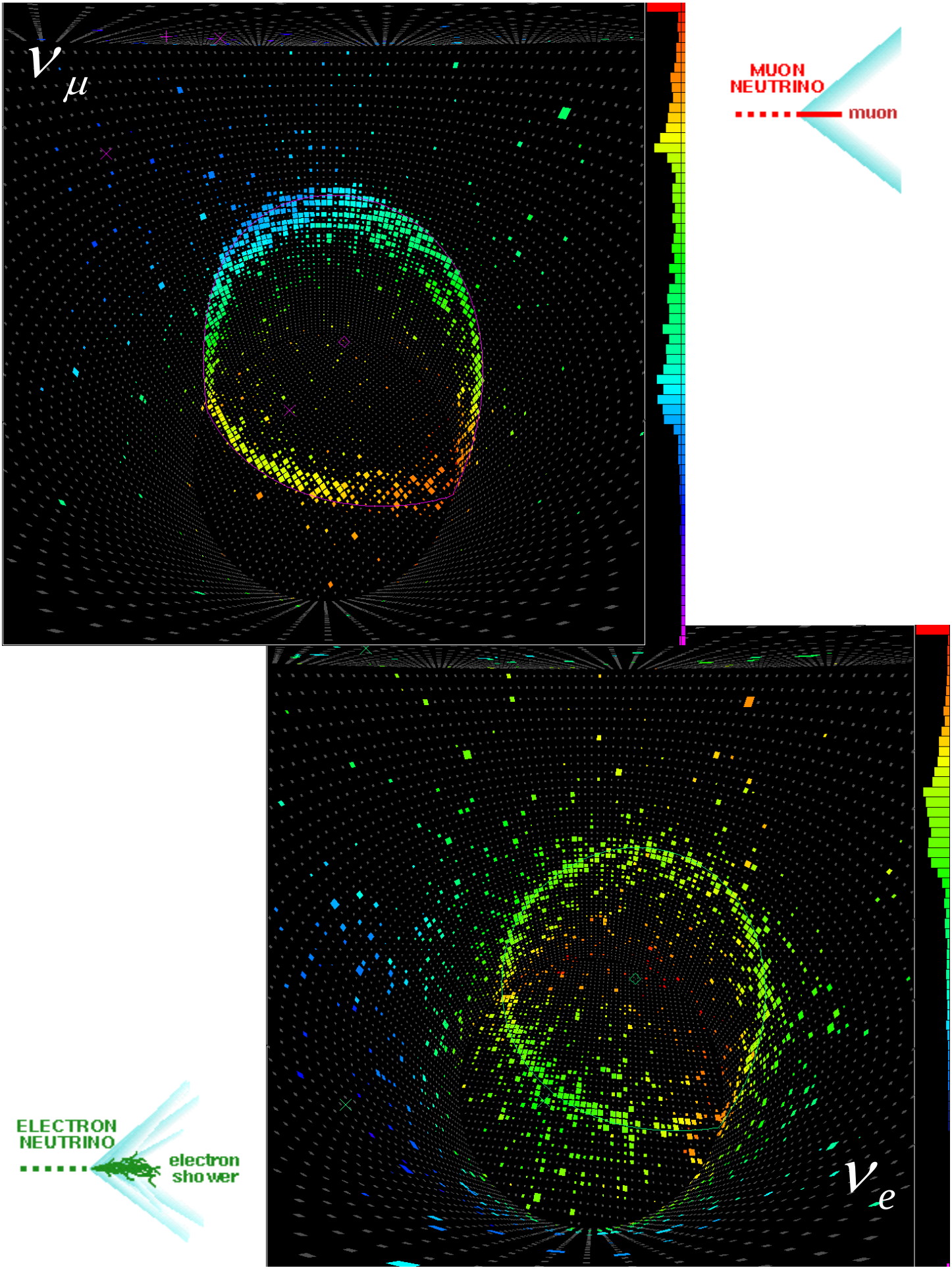

ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
$d\Phi_\nu/dE_\nu \times E_\nu^3$ (m^{-2} sec^{-1} sr^{-1} GeV^2)
E_ν (GeV)


sub GeV
multi GeV
through-going muons
stopping muons
dN/dlnE, (Kt.yr)$^{-1}$
$(m^2.yr.ster)^{-1}$
E_ν, GeV

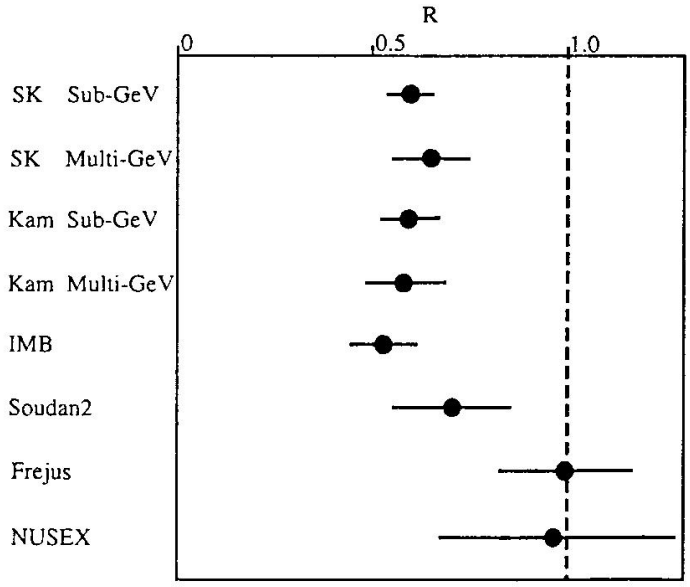

down-going
[not to scale]
p, He
π±, K±
μ±
e±
L≈10-30 km
atmosphere
νμ νμ νe
zenith
angle
detector
L≈500 km
L≈10^4 km
EARTH
L≈1.2×10^4 km
up-going

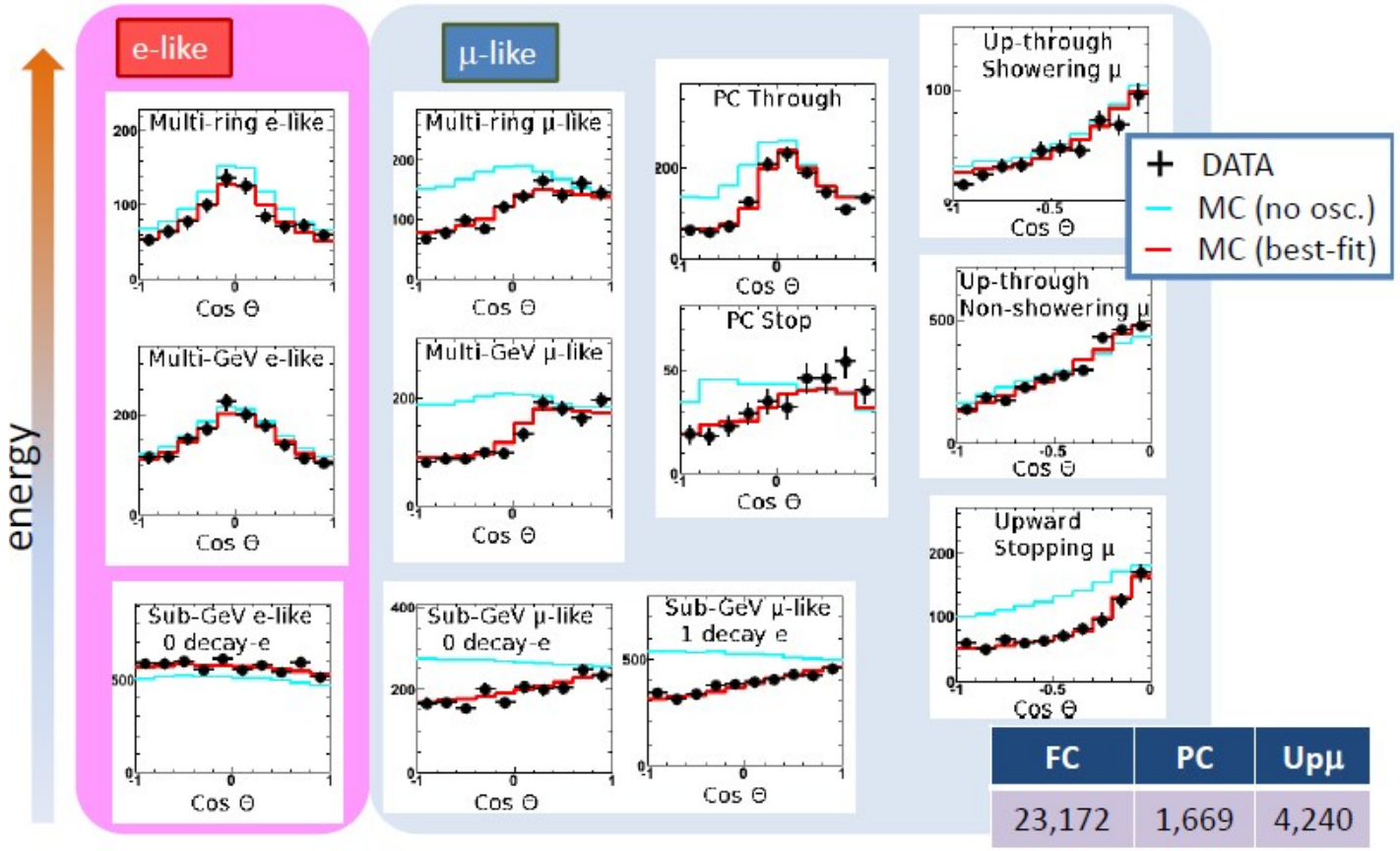

Super-Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p = 621.9 MeV/c
ν_e
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
e-like
ELECTRON NEUTRINO
electron shower
10^3
10^2
10^1
10^0
0
500
1000
1500
2000
Times (ns)


Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p = 766.0 MeV/c
ν_μ
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
μ-like
MUON NEUTRINO
muon
10^2
10^1
10^0
0
500
1000
1500
2000
Times (ns)


ν_μ
MUON NEUTRINO
muon
ELECTRON NEUTRINO
electron shower
ν_e

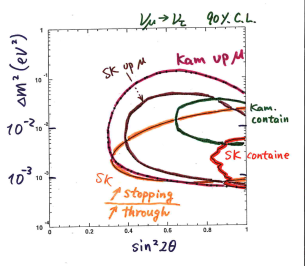
$$R = \frac{\left(\frac{\mu}{e}\right)_{DATA}}{\left(\frac{\mu}{e}\right)_{MC}}$$





FC	PC	Upμ
23,172	1,669	4,240

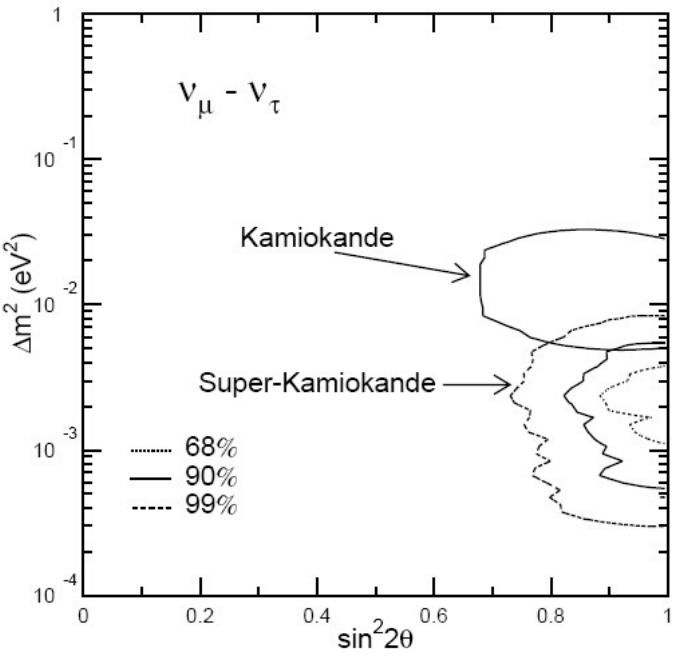
Evidence for ν_μ oscillations

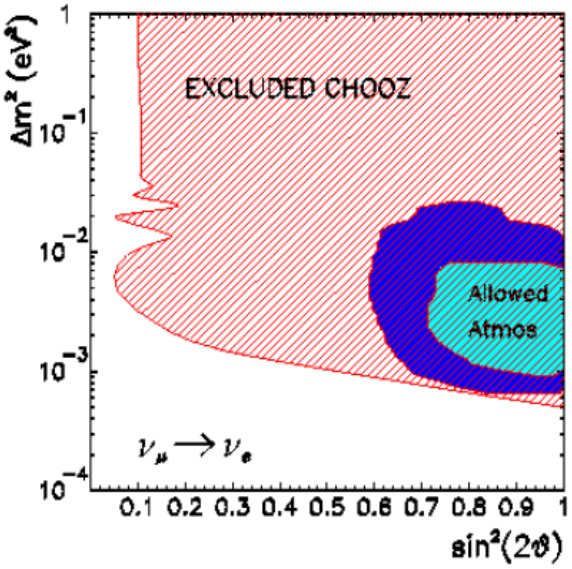


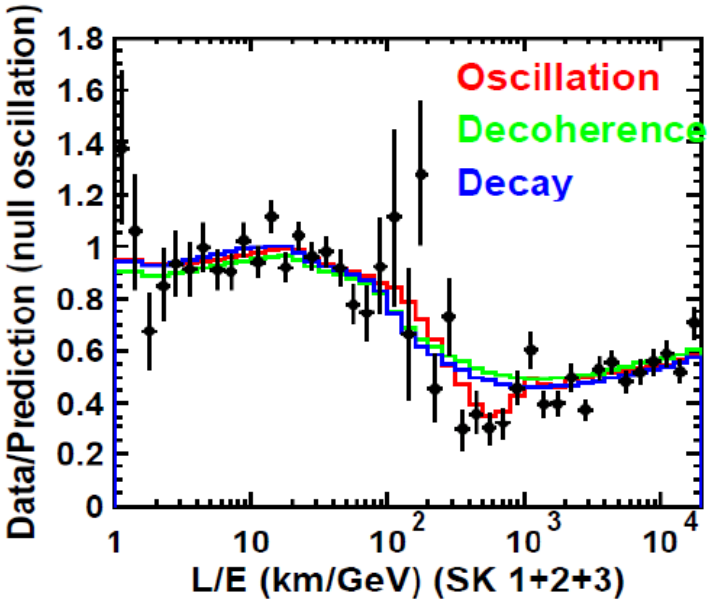
- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

($\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Kajita: Neutrino 98







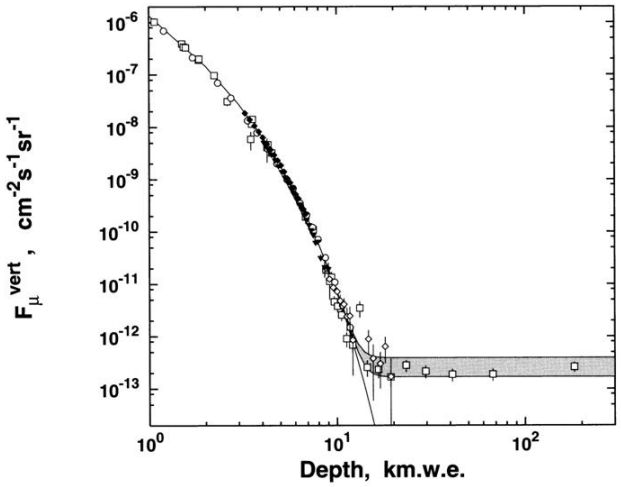
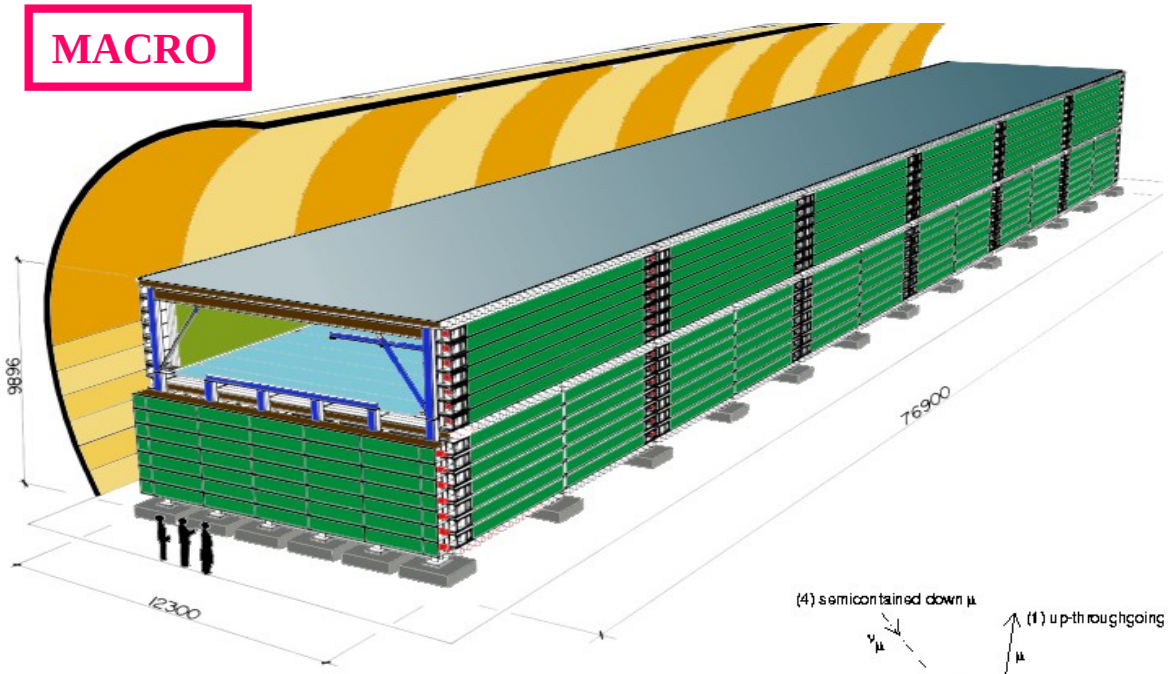
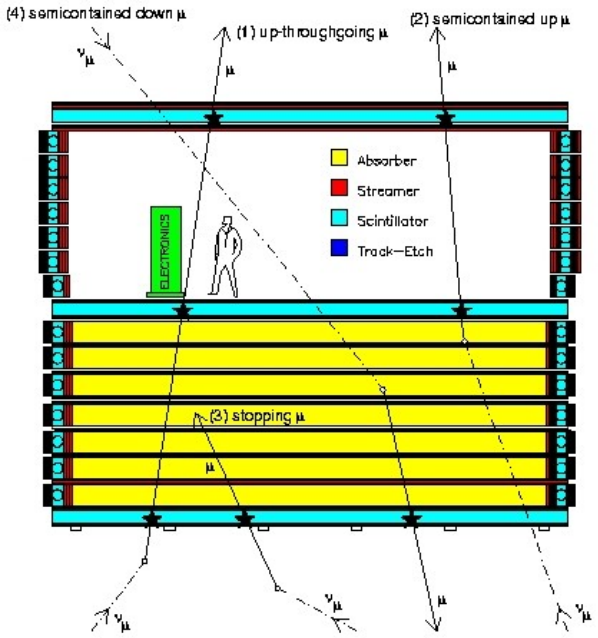
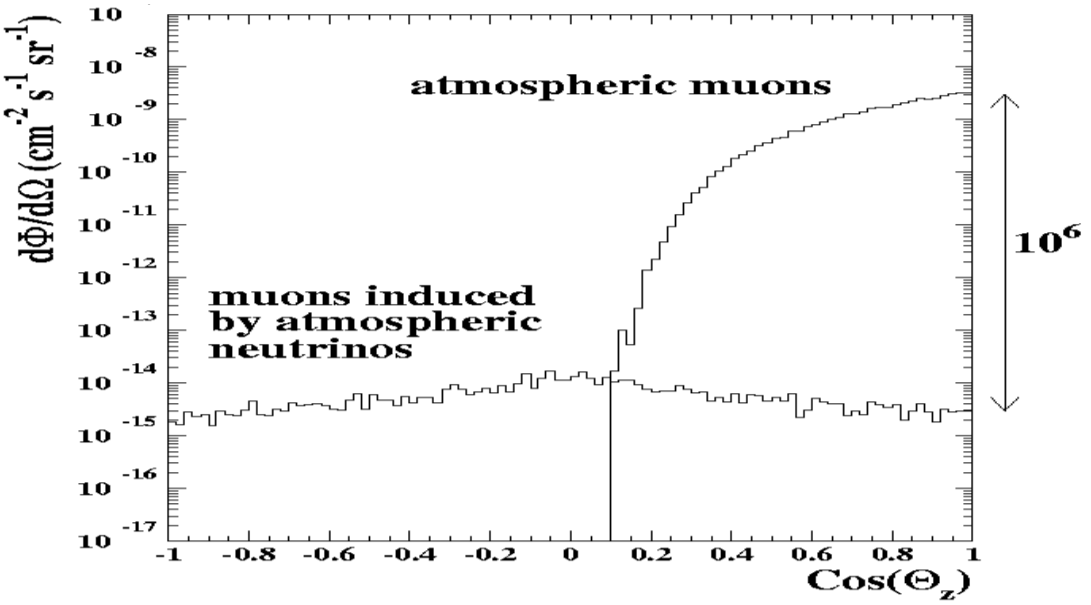


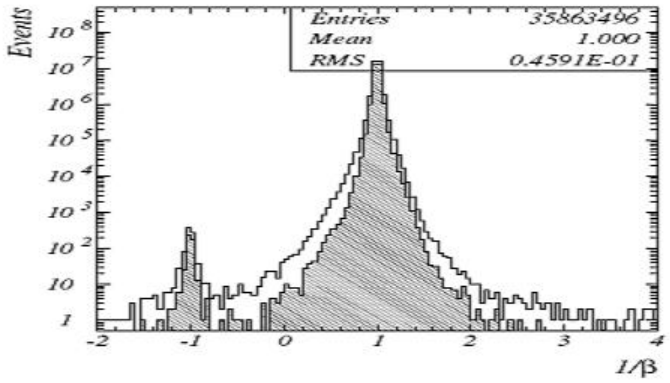
Fig. 7.1. Depth–intensity relation – the integral muon flux measured at different depths and angles and converted to vertical muon flux is compared to predictions. See text for the references to different data sets.

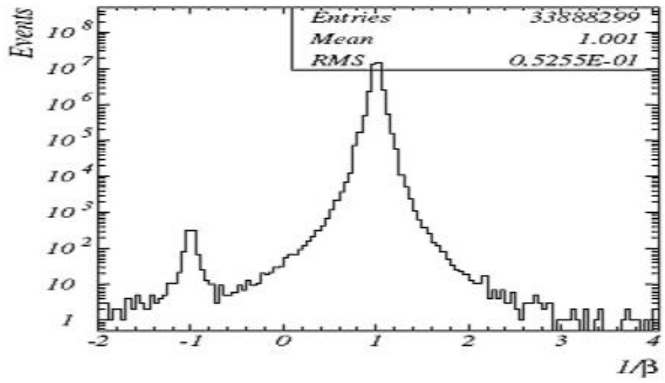
MACRO











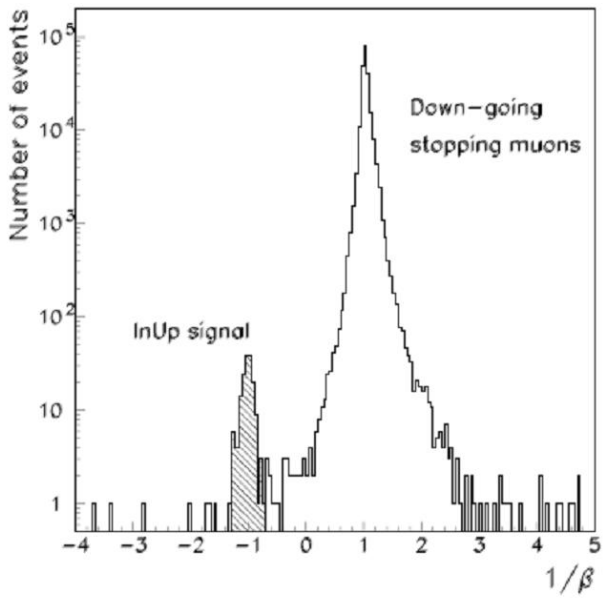


Fig. 9. The $1/\beta$ distribution of partially-contained events. The peak at $1/\beta \sim +1$ is due to downward-going muons stopping in the apparatus

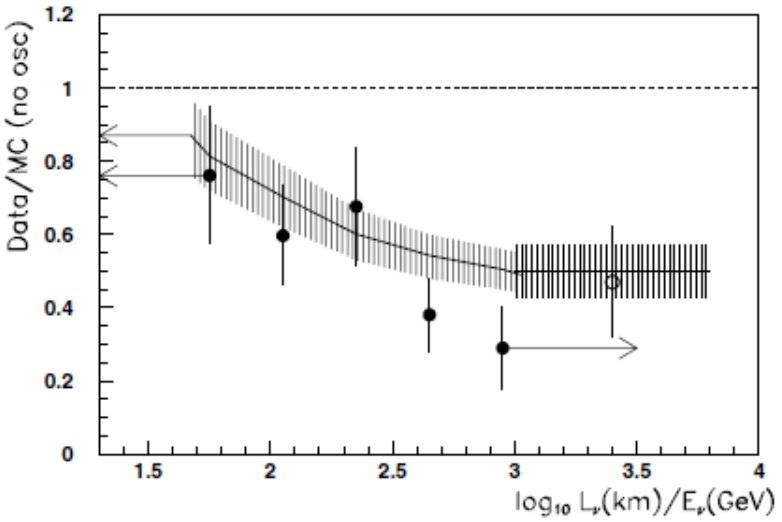
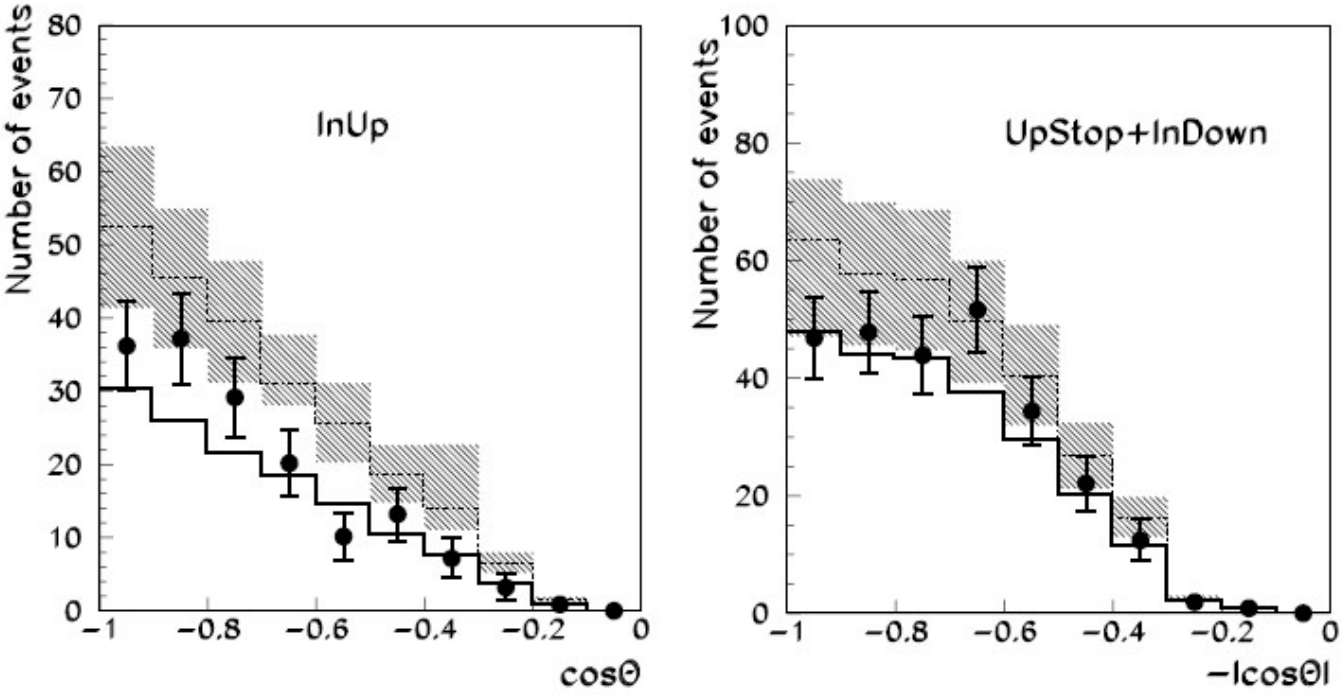


Fig. 8. Ratio data/MC (no oscillations) as a function of the estimated L_ν/E_ν for the *UpThrough* muon sample (black points). The solid line is the MC expectation assuming $\Delta m^2 = 0.0023\,\mathrm{eV}^2$ and $\sin^2 2\theta_m = 1$. The last point (empty circle) is obtained from the *InUp* sample



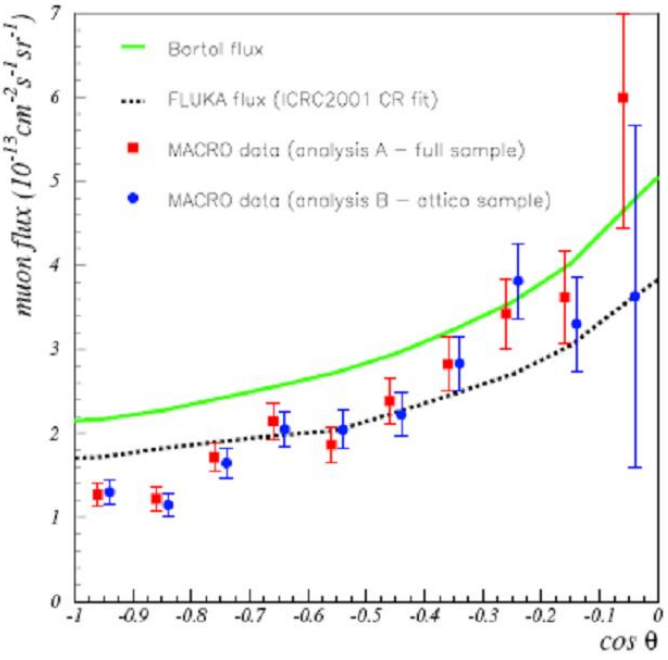
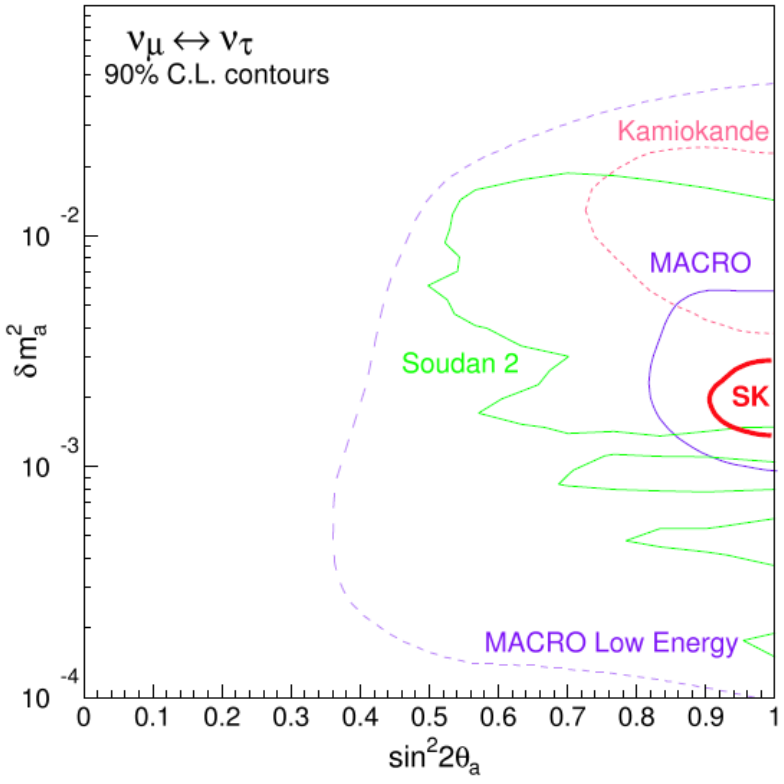
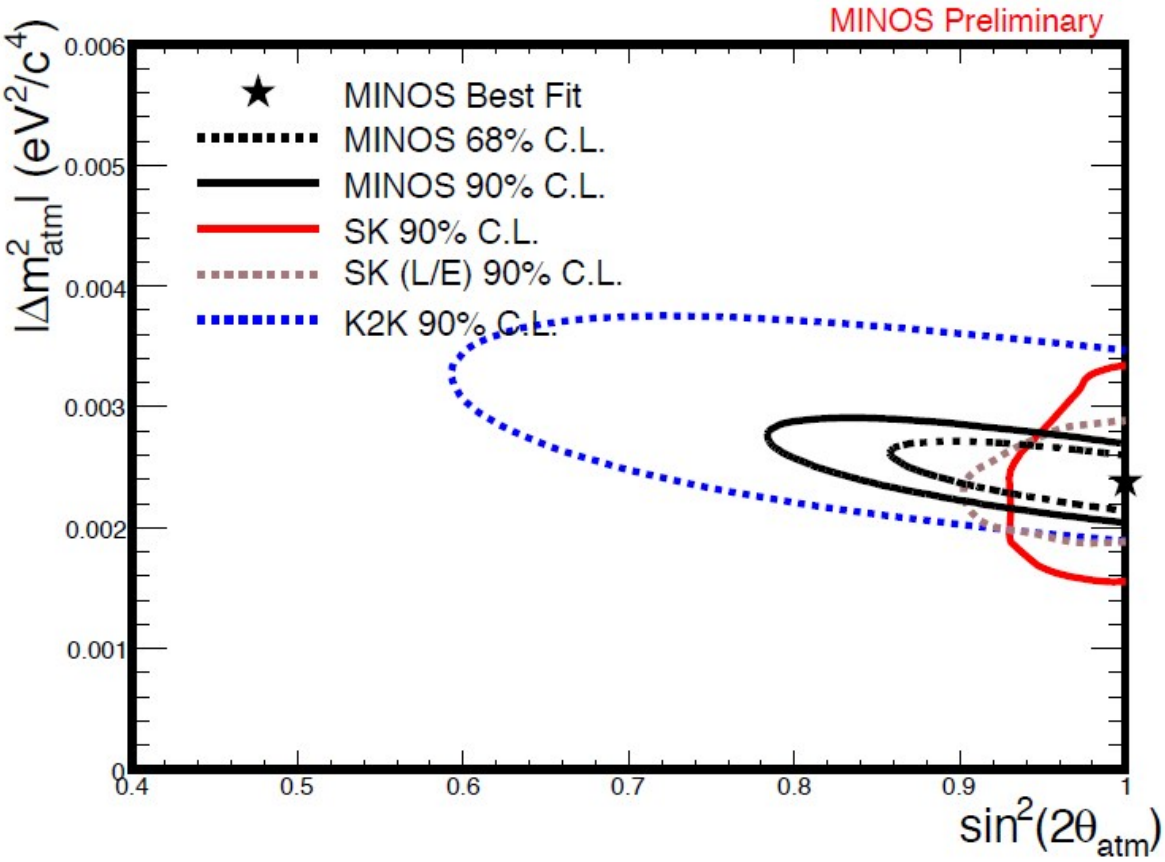
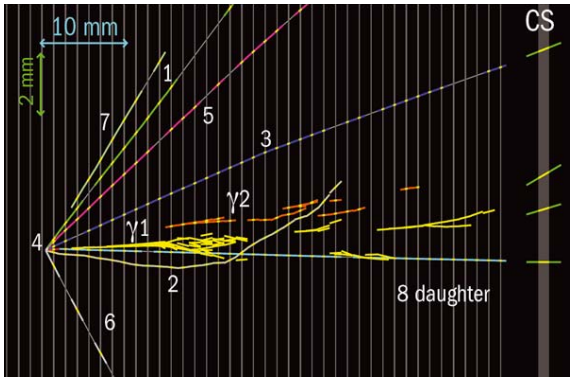
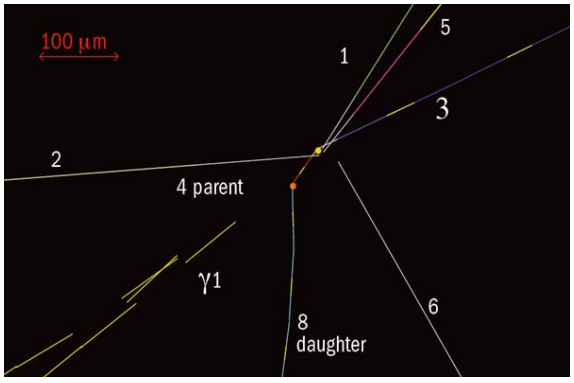


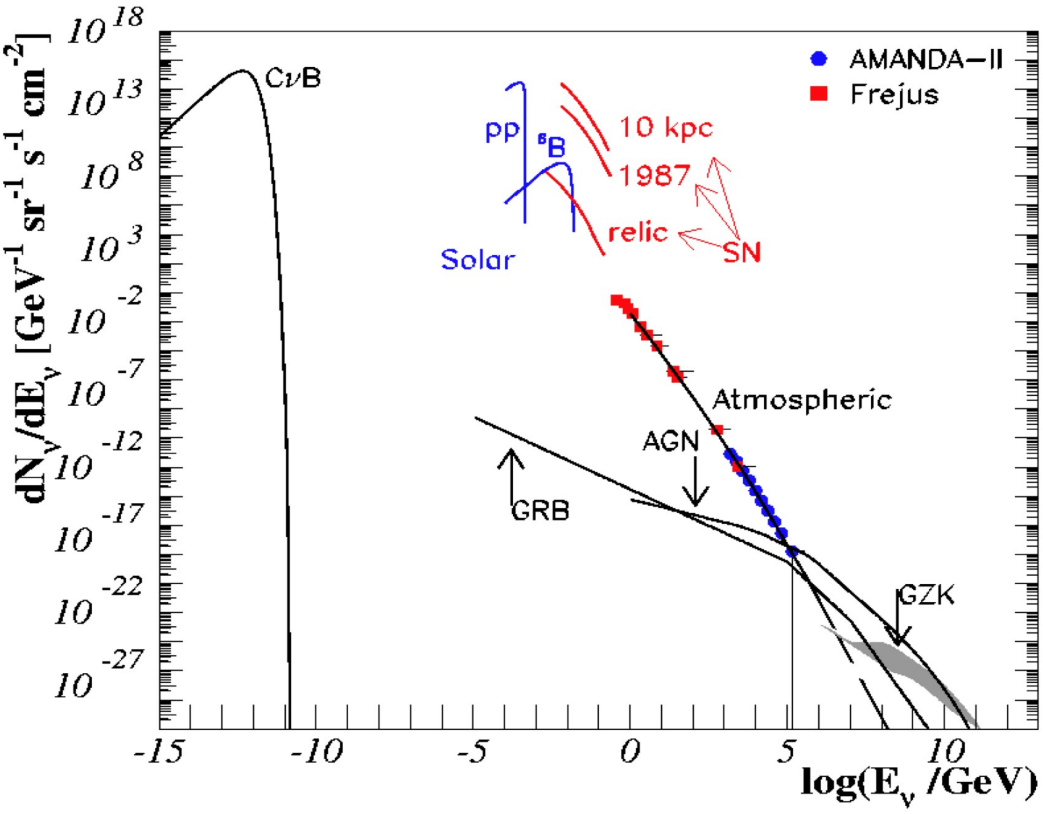
Fig. 3. Comparison of the *UpThrough* muon fluxes measured by means of the different analysis procedures, A and B. The experimental points are slightly shifted horizontally to distinguish the two analyses. Statistical and systematic errors are displayed. The non–oscillated Bartol [31] and FLUKA [34] fluxes, assuming $E_\mu > 1\,\mathrm{GeV}$, are shown (the theoretical error is not displayed). The fit to the new CR measurements [37] is used for the FLUKA flux

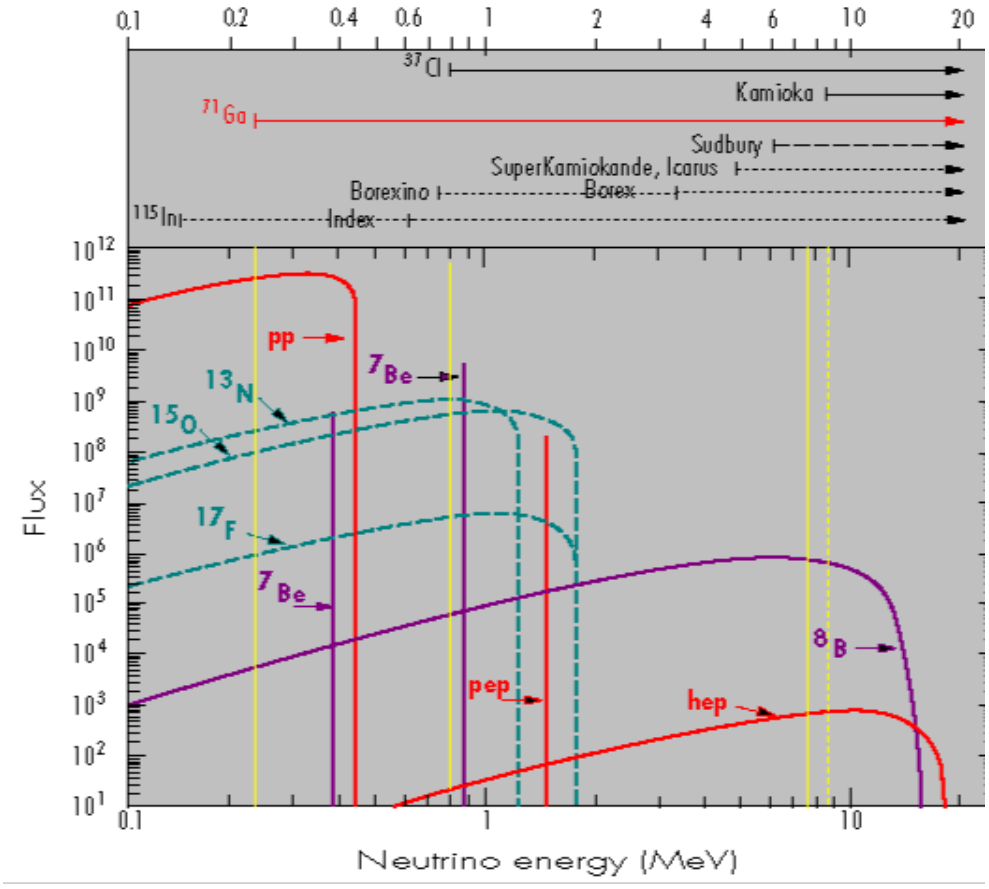



MINOS Preliminary
MINOS Best Fit
MINOS 68% C.L.
MINOS 90% C.L.
SK 90% C.L.
SK (L/E) 90% C.L.
K2K 90% C.L.
$|\Delta m^2_{atm}|$ (eV^2/c^4)
$\sin^2(2\theta_{atm})$
0.006
0.005
0.004
0.003
0.002
0.001
0
0.4
0.5
0.6
0.7
0.8
0.9
1

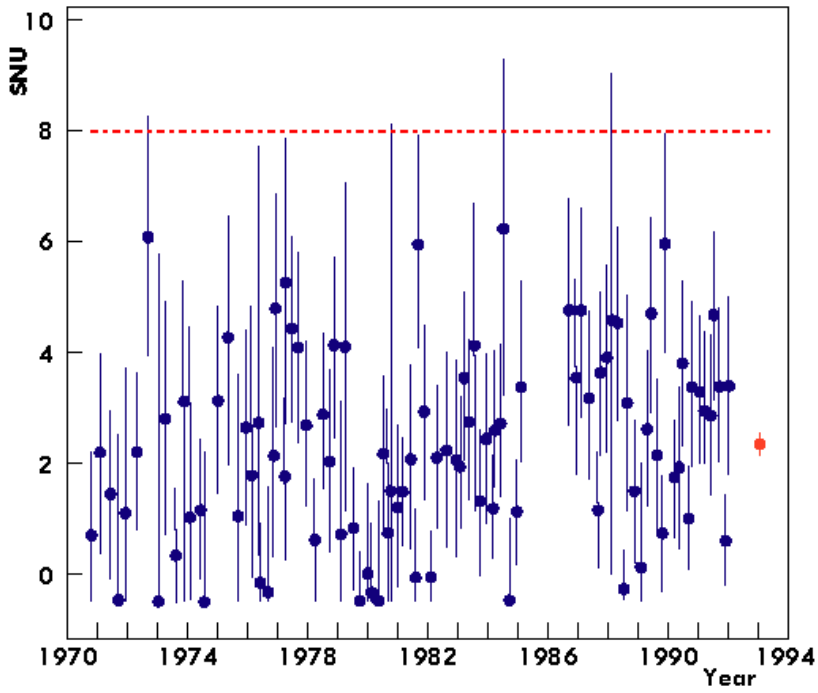

10 mm
2 mm
CS
1
7
5
3
γ2
γ1
4
2
8 daughter
6


100 μm
1
5
3
2
4 parent
γ1
8
daughter
6

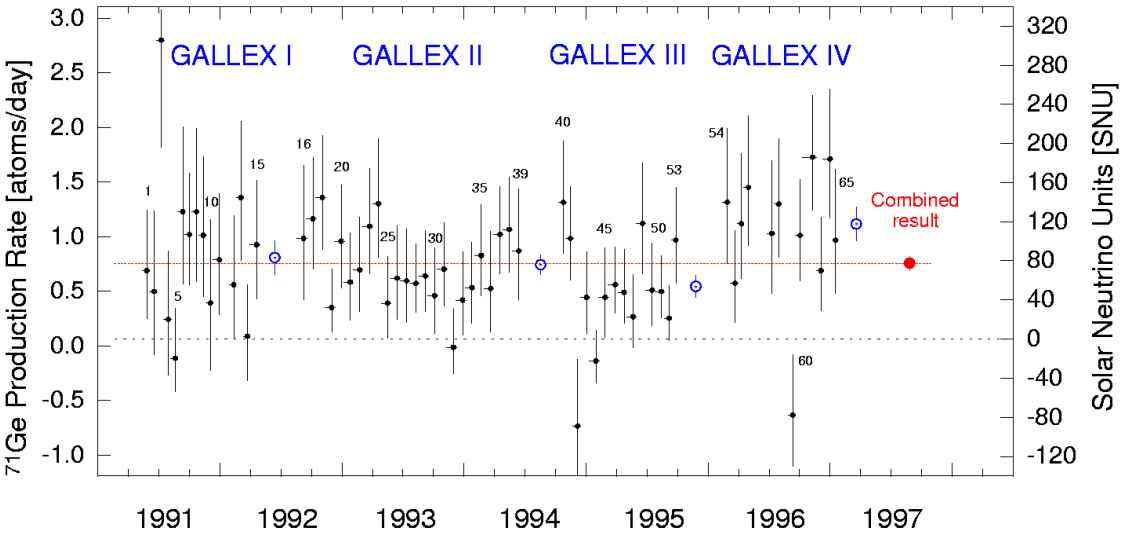

AMANDA−II
Frejus
CνB
pp
⁸B
10 kpc
1987
relic
SN
Solar
Atmospheric
AGN
GRB
GZK
dN_ν/dE_ν [GeV⁻¹ sr⁻¹ s⁻¹ cm⁻²]
log(E_ν /GeV)


³⁷Cl
Kamioka
⁷¹Ga
Sudbury
SuperKamiokande, Icarus
Borexino
Borex
¹¹⁵In
Index
pp
⁷Be
¹³N
¹⁵O
¹⁷F
⁷Be
⁸B
pep
hep
Flux
Neutrino energy (MeV)

Homestake



$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$



KAMIOKANDE

$$\nu_e + e^- \rightarrow e^- + \nu_e$$

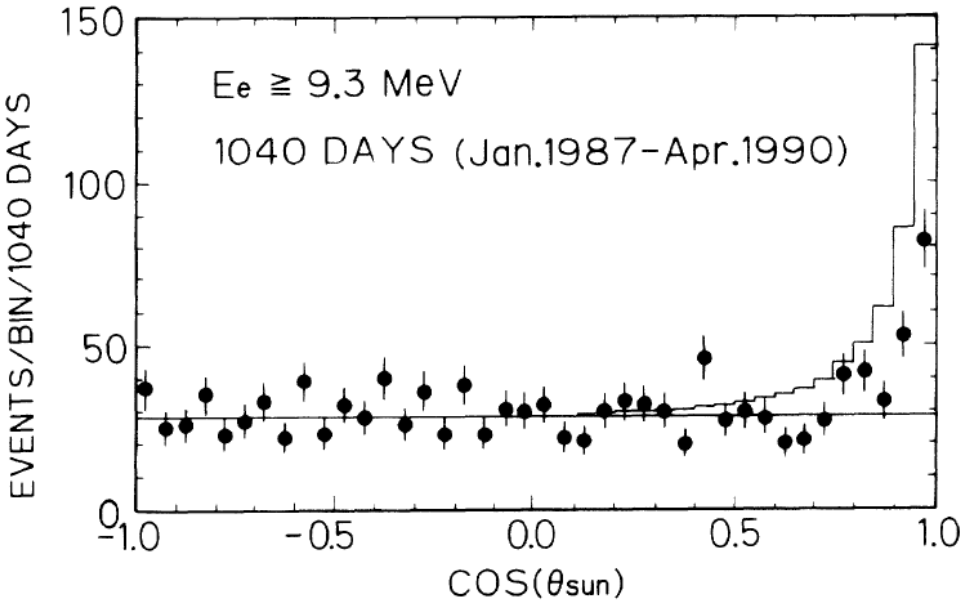
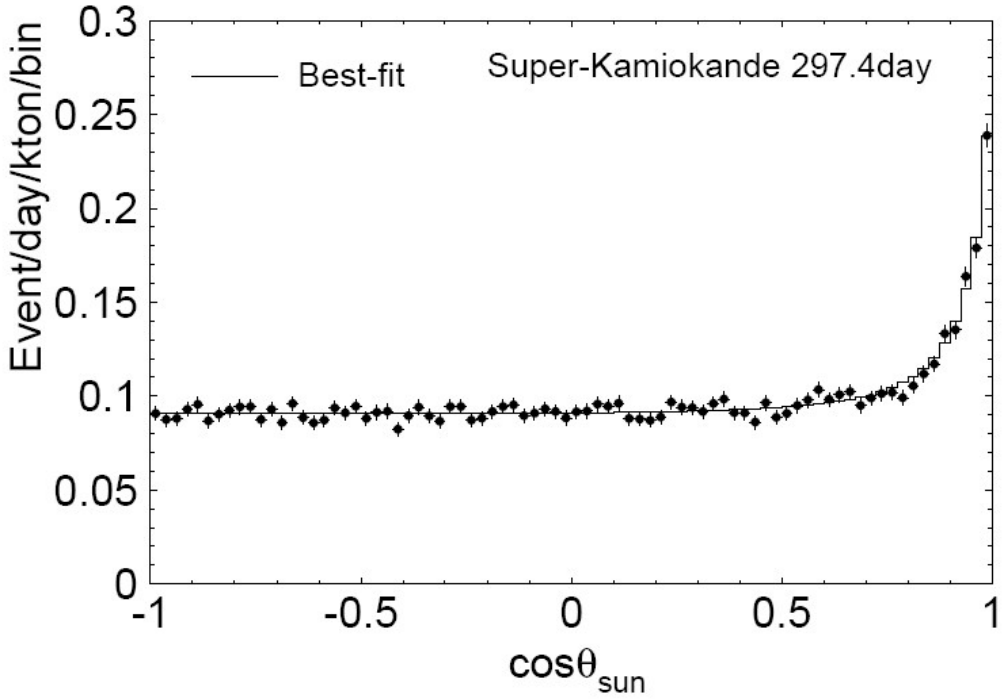
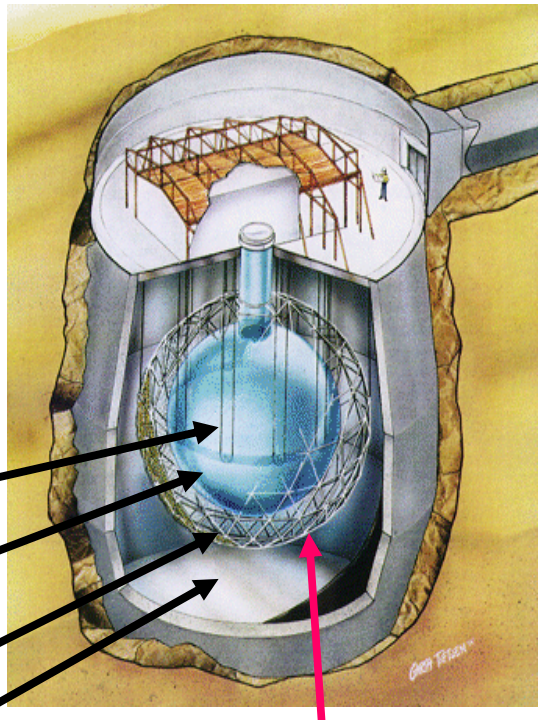


FIG. 3. Distribution in $\cos\theta_{\mathrm{Sun}}$ of the combined 1040-day sample for $E_e \geq 9.3$ MeV. The value of the ratio data/SSM from this figure is 0.43 ± 0.06.



Sudbury Neutrino Observatory



1000 tonnellate D_2O

contenitore acrilico

1700 tonnellate H_2O

5300 tonnellate H_2O

9500 PMT
(copertura 60%)

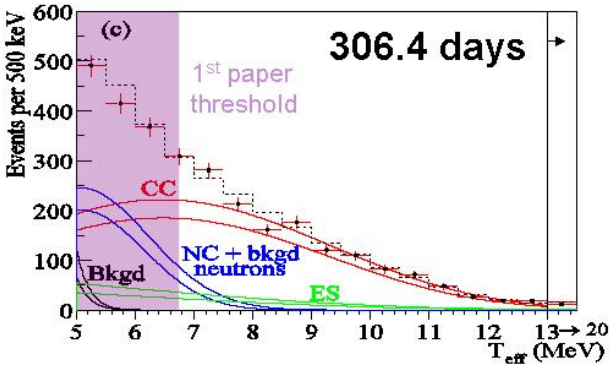
SNO Pure D_2O Results (2002)

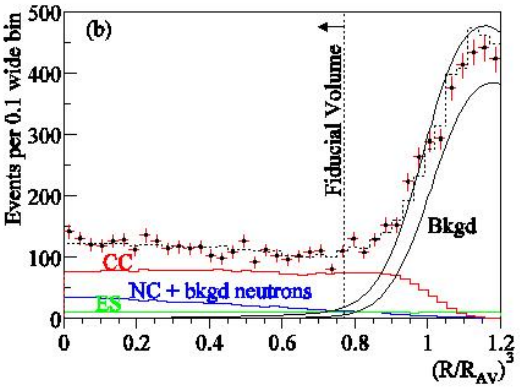
#EVENTS

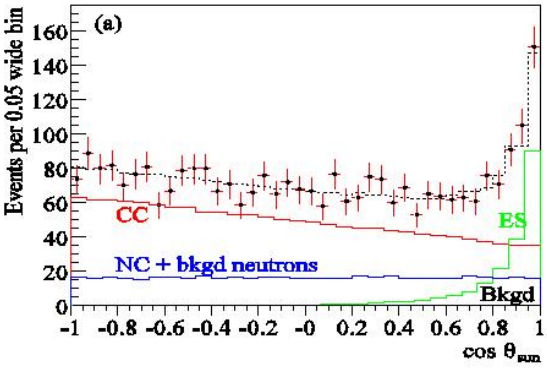
CC $1967.7^{+61.9}_{+60.9}$

ES $263.6^{+26.4}_{+25.6}$

NC $576.5^{+49.5}_{+48.9}$







Salt Phase (254.2 live-days)

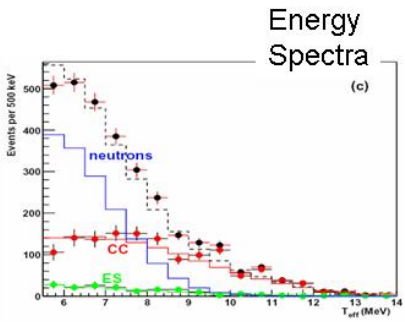
$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.306 \pm 0.026\ (stat) \pm 0.024\ (syst)$$

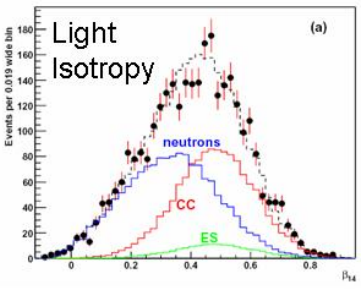
#EVENTS

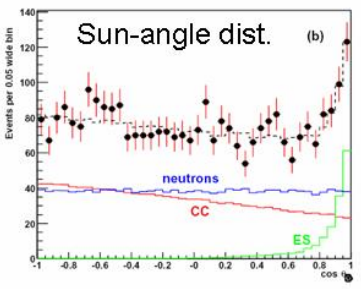
CC $1339.6^{+63.8}_{-61.5}$

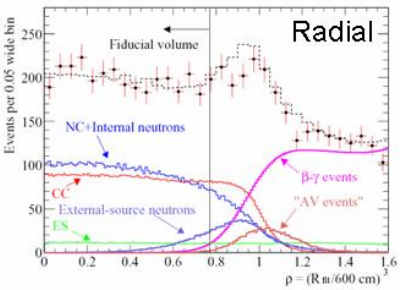
ES $170.3^{+23.9}_{-20.1}$

NC $1344.2^{+69.8}_{-69.0}$









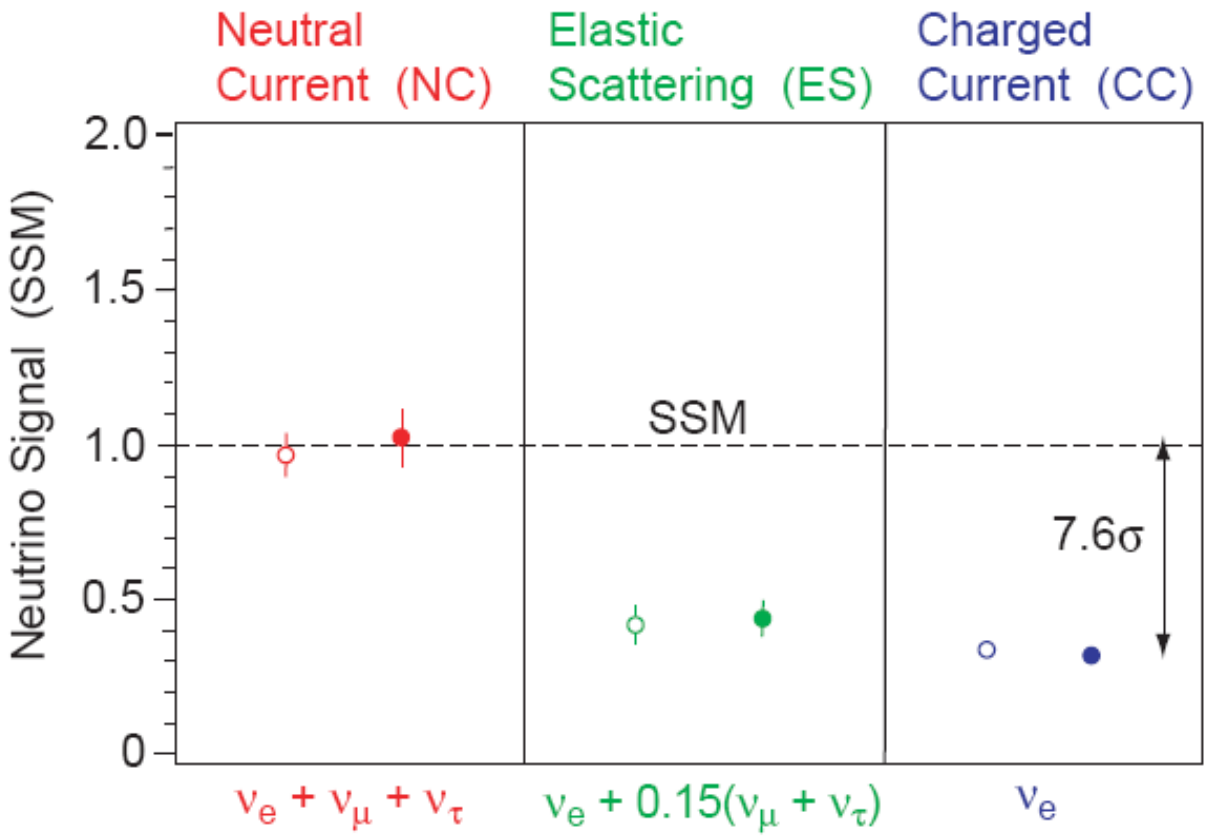
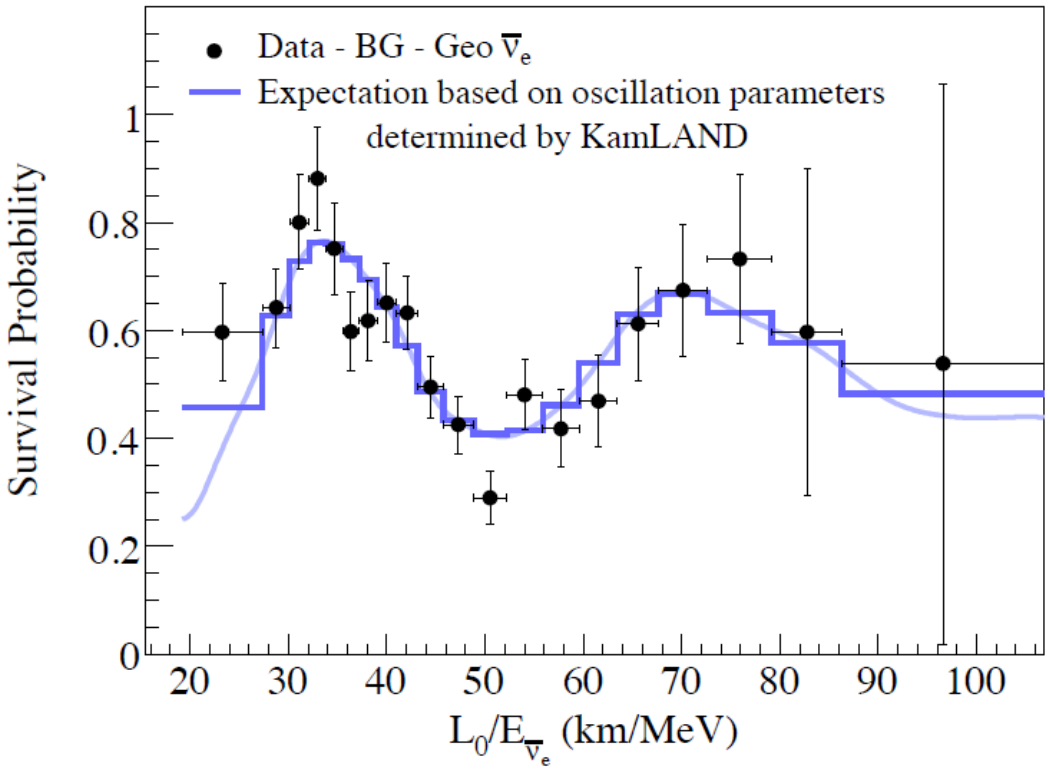
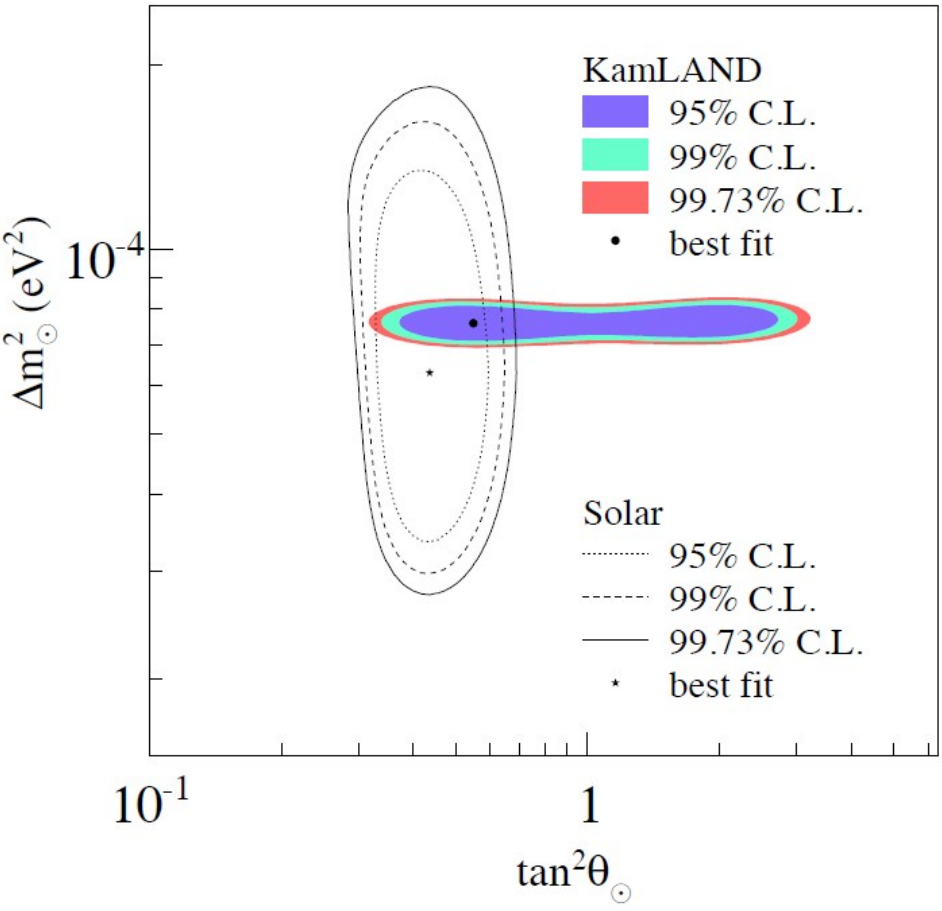


Figure 8: Evidence for neutrino flavor change seen by SNO. The open (filled) circles represent the 2003 SNO flux results, relative to the SSM, under the assumption of an undistorted (unconstrained) ^{8}B neutrino energy spectrum.


Data - BG - Geo $\bar{\nu}_e$
Expectation based on oscillation parameters
determined by KamLAND
Survival Probability
1
0.8
0.6
0.4
0.2
0
20
30
40
50
60
70
80
90
100
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

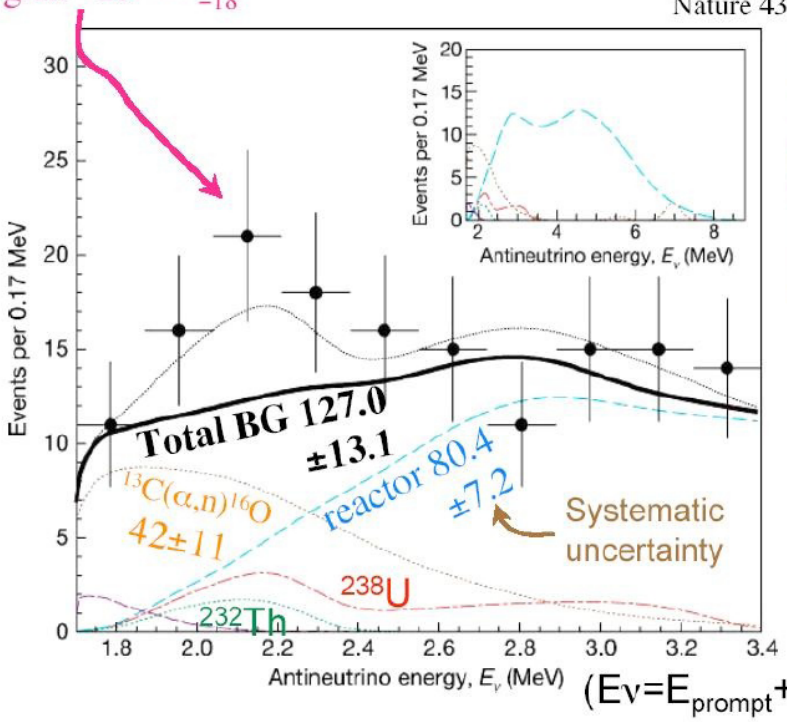

KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best fit
Solar
95% C.L.
99% C.L.
99.73% C.L.
best fit
$\Delta m^2_{\odot}$ (eV^2)
10^{-4}
10^{-1}
1
$\tan^2\theta_{\odot}$

152 events observed

"signal" 25^{+19}_{-18}

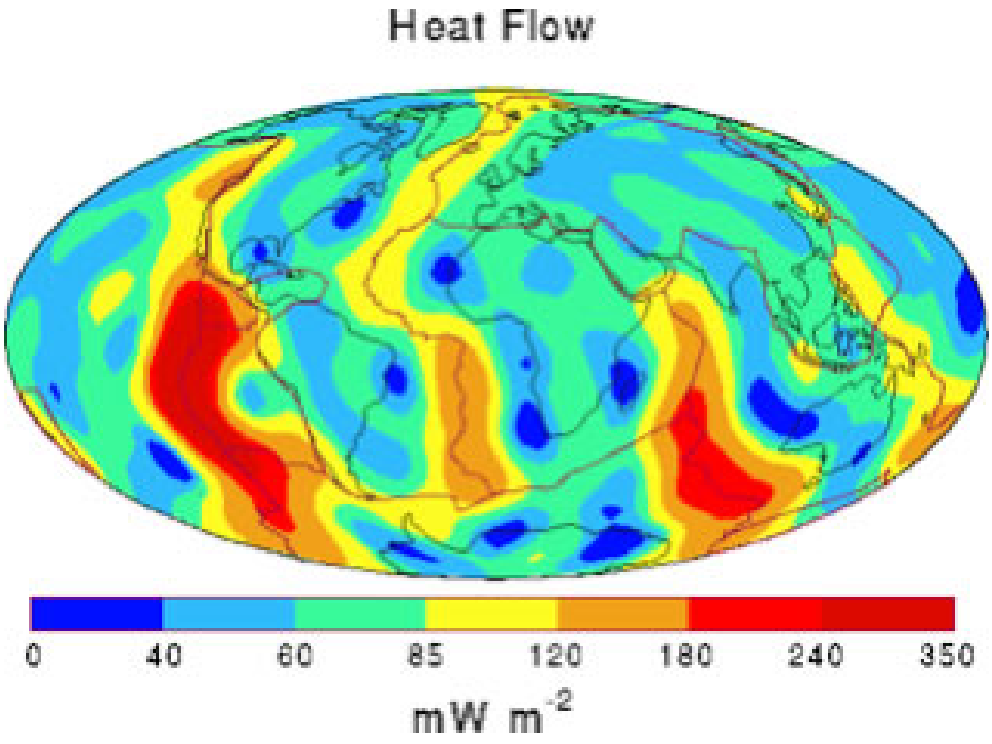
Geoneutrino results

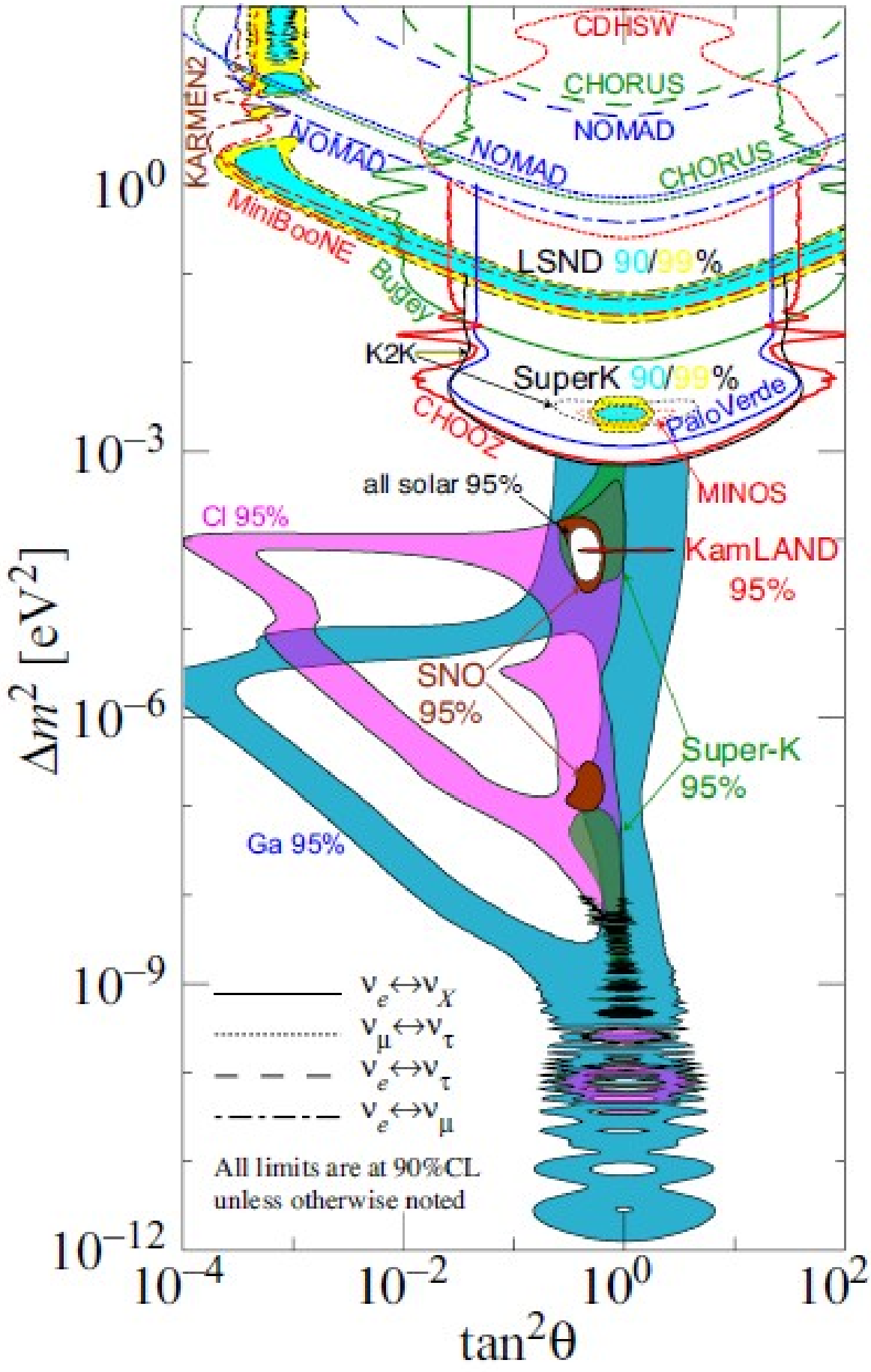
Nature 436, 28 July 2005

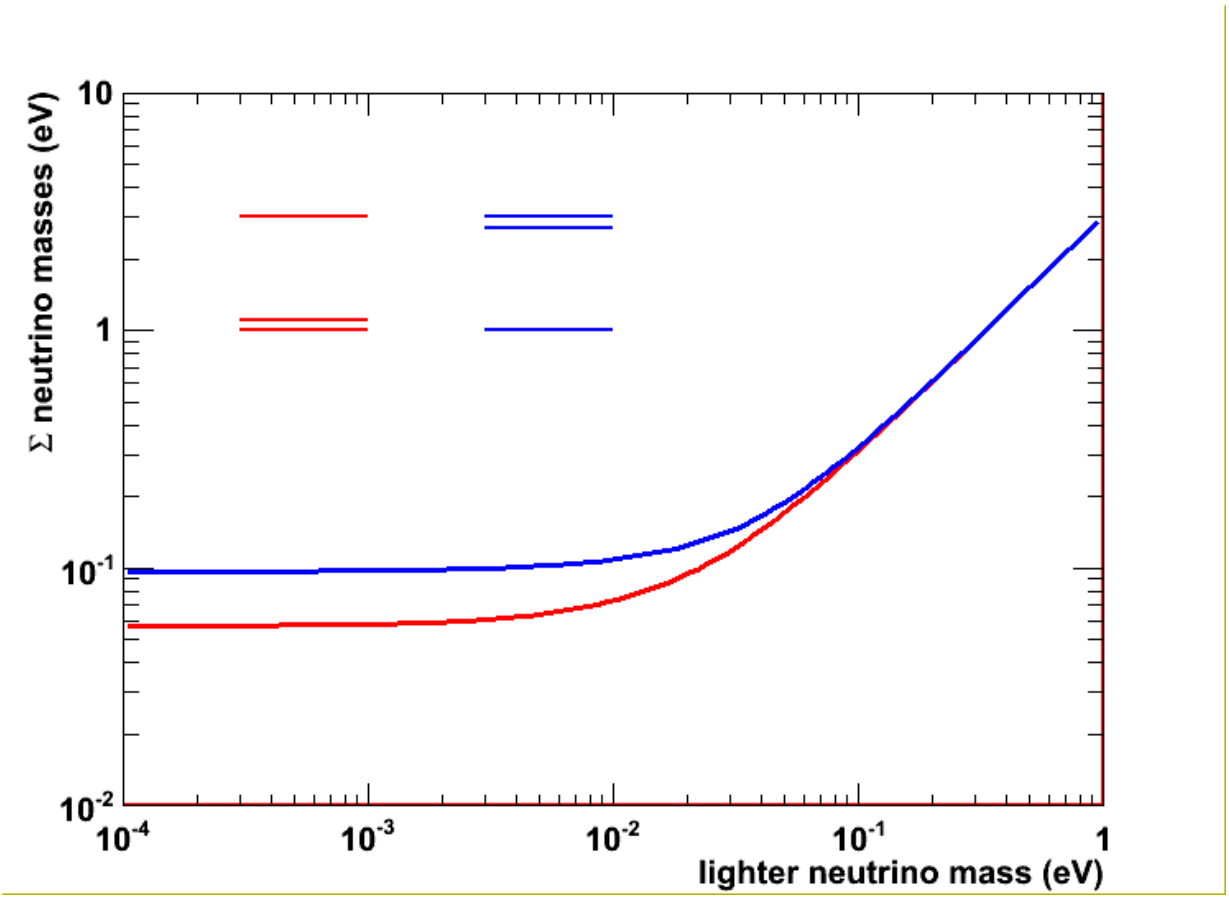


Data-set:
749.1 days
(Mar. 9, 2002
-Oct. 30, 2004)
Fiducial:
5 m radius

($E\nu = E_{prompt} + 0.8$MeV)




CDHSW
CHORUS
NOMAD
KARMEN2
NOMAD
NOMAD
CHORUS
MiniBooNE
Bugey
LSND 90/99%
K2K
SuperK 90/99%
CHOOZ
PaloVerde
MINOS
all solar 95%
Cl 95%
KamLAND
95%
SNO
95%
Super-K
95%
Ga 95%
$\nu_e \leftrightarrow \nu_X$
$\nu_\mu \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\tau$
$\nu_e \leftrightarrow \nu_\mu$
All limits are at 90%CL
unless otherwise noted
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
Δm^2 [eV^2]
10^{-4}
10^{-2}
10^0
10^2
$\tan^2\theta$



event	Δt (s)	E_e (MeV)	E_ν (MeV)
1	0.000	20.0	21.3
2	0.107	13.5	14.8
3	0.303	7.5	8.8
4	0.324	9.2	10.5
5	0.507	12.8	14.1
6	1.541	35.4	36.7
7	1.728	21.0	22.3
8	1.915	19.8	21.1