Other❋ Atmospheric ν Experiments

Maury Goodman; Argonne

Neutrino 2002*, Munich*

May 26, 2002

❋ Other than Super-Kamiokande

OUTLINE

Talking about atmospheric neutrinos without talking about Super-Kamiokande

*is like*__________ [fill in the blank yourself]

What I will Talk About:

- Introduction
- Some Real ν History
- Some Gedanken ν History
- Some New Data from Soudan 2 & MACRO

The Atmosphere

where atmospheric ν's come from

- Cosmic Rays hit atmosphere's top
- Density $x = Xe^{-\rho gh/kT} = X\,e^{-h/H}$
  - H = 8.4 km at sea level (isothermal)
  - T,H depend on altitude , H 6.4km near tropopause
- 2% seasonal variations
- $\nu_\mu/\nu_e \sim 2$ BUT
  - K_{e3} and K^0_{e3} decays
  - Containment differences
  - ν and $\bar{\nu}$ differences due to cross section from $\mu^+/\mu^- \sim 1.2$
  - Some μ hit the earth before decaying increasing above 2 GeV

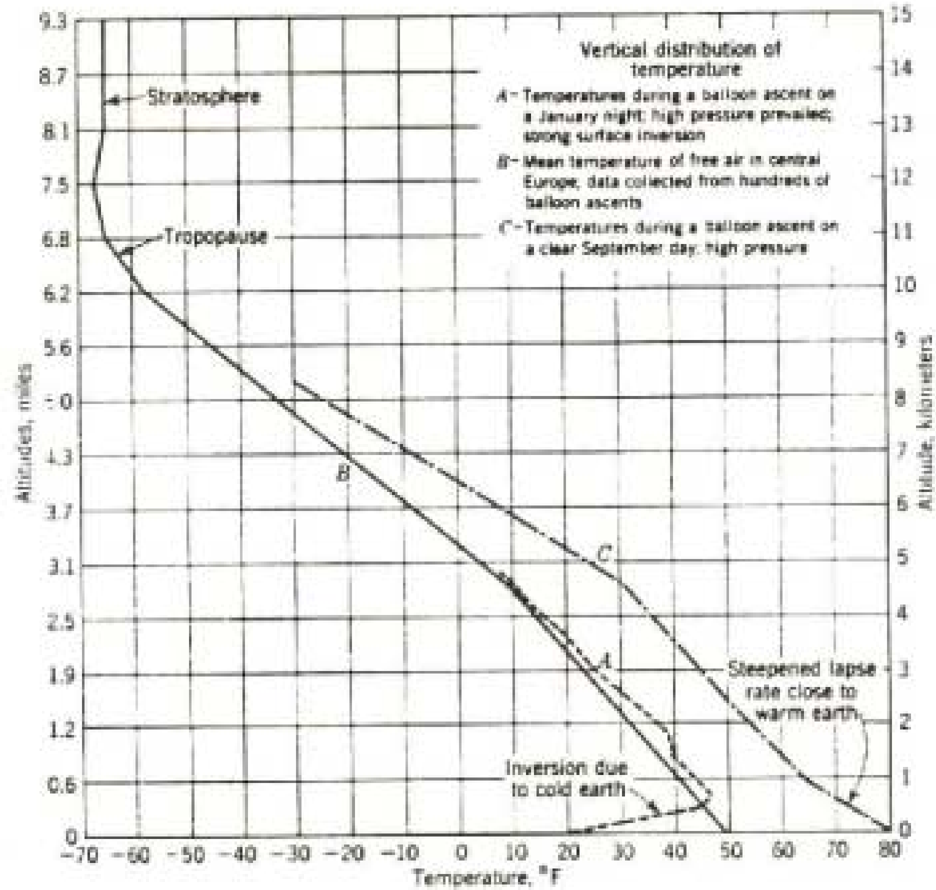
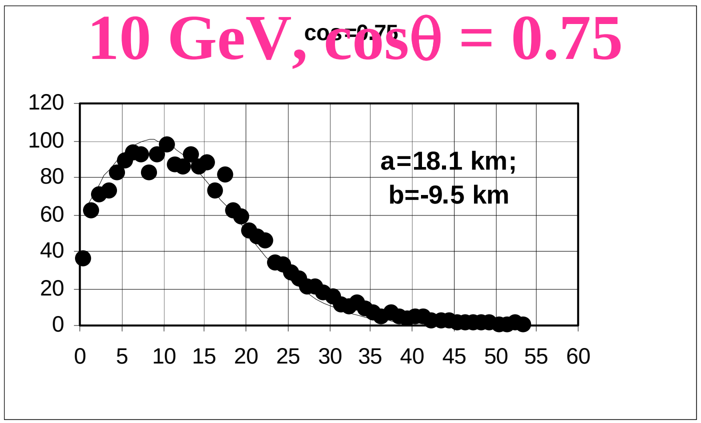
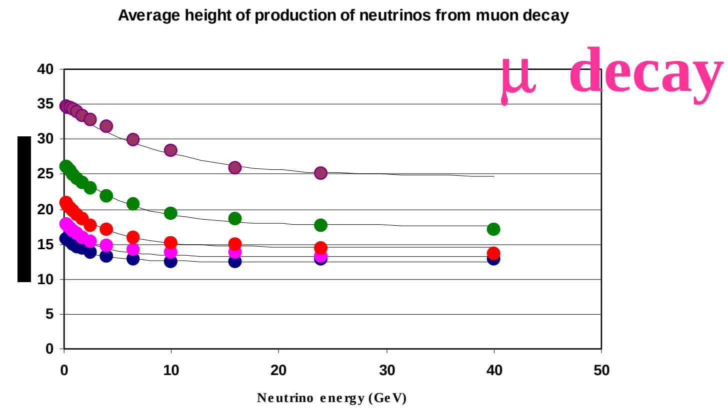
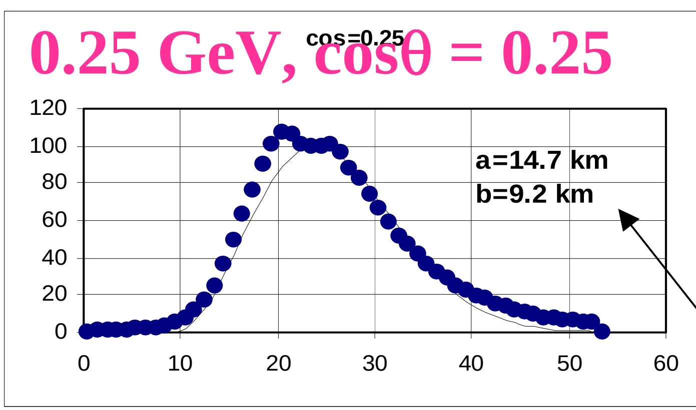


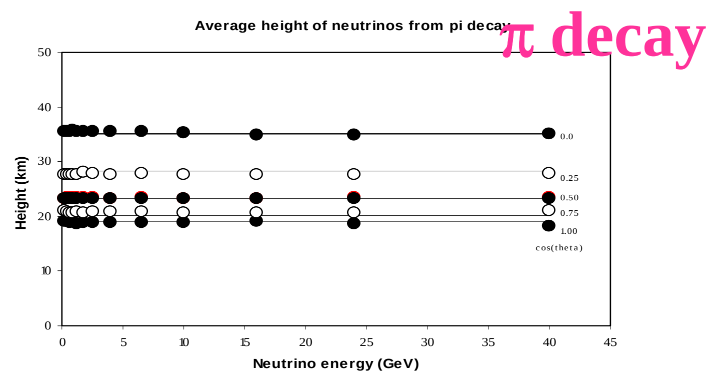
Figure 2.18 Contrasts in the vertical temperature distribution (lapse rates) A, on a winter night; C, on a summer day; and B, under average conditions. On the B lapse rate, plotting of temperature is continued up to 15 km (9+ miles) so that the tropopause and the stratosphere are represented.

ν Production Heights





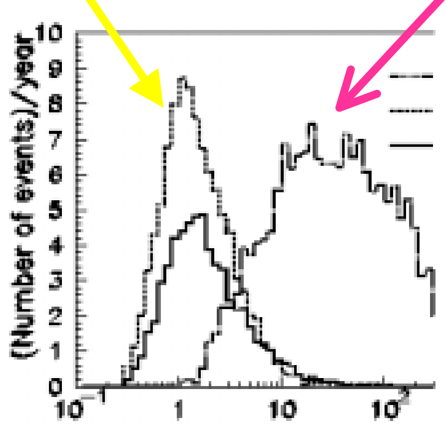




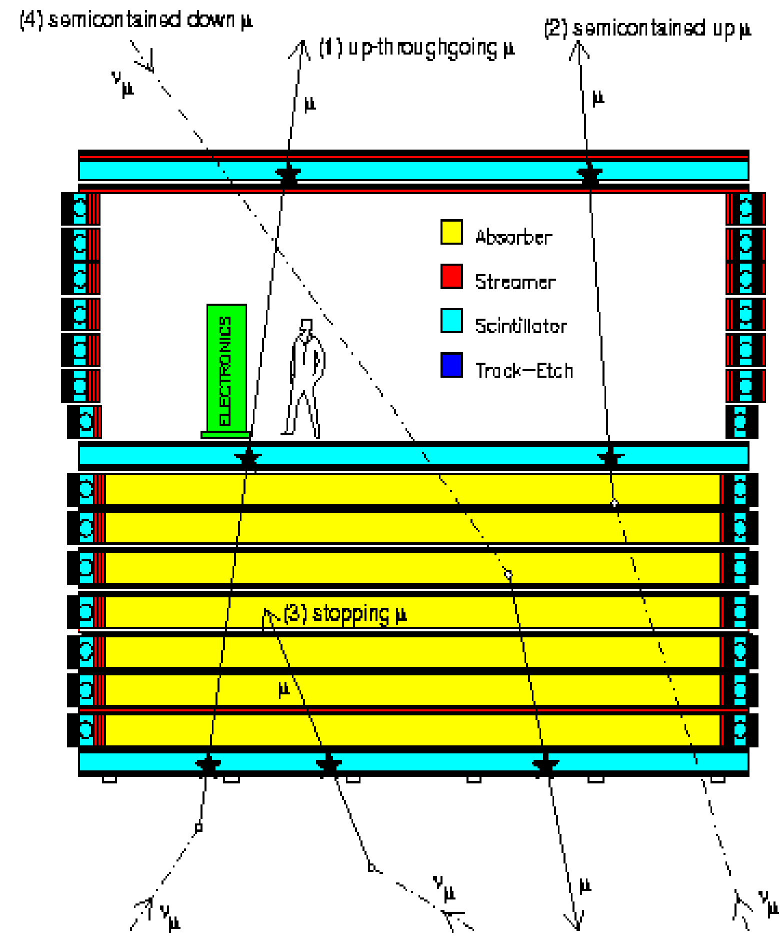
Keith Ruddick paramaterization

Detection of Atmospheric ν's

- Interaction in Detector
  - Fully Contained Events
  - Partially Contained Events
- Interaction Outside Detector
  - Throughgoing μ's
  - Up-stopping μ's



GeV



of “other” atmospheric ν’s

CWI/SAND	0 contained	121 ν induced μ
KGF	100	229
NUSEX	40	0
Soudan 1	1	0
Frejus	271	44
IMB	935	624
Kamioka	557	372
Soudan 2	561	85
LVD*	0	?+
BAKSAN*	0	801+
MACRO	285	940

$\Sigma = 6214\nu$

* Still running

+ <u>ν telescopes</u>

AMANDA* 204+(cut-L7)

Baikal* 44+

Talks Thursday

KGF– The 1st reported Atmospheric ν

Several detectors in KGF mine at various depths.

3 ν published 15 Aug 65

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

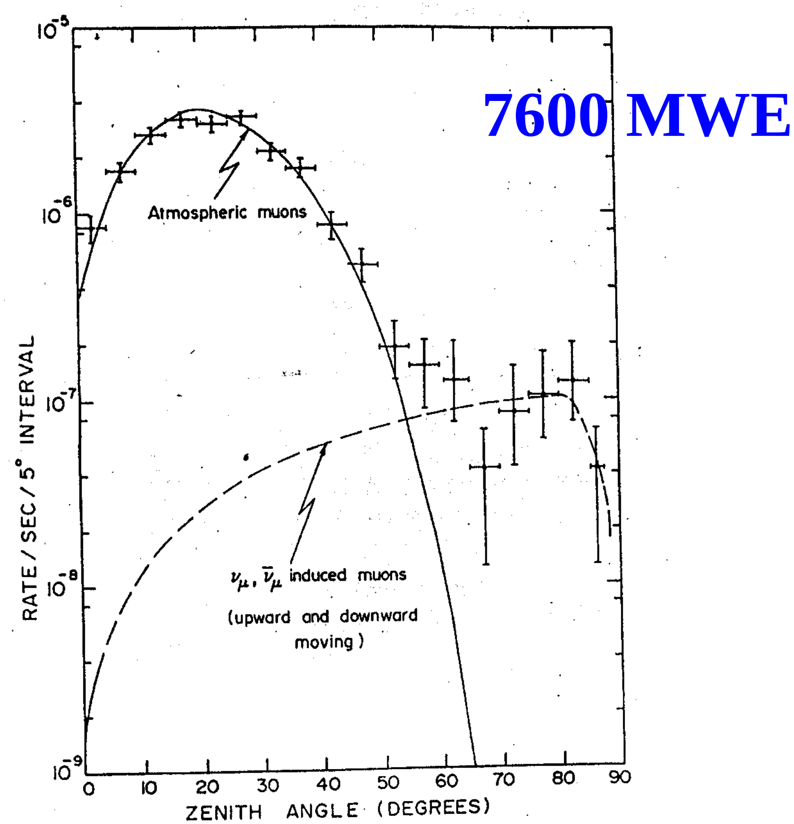
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

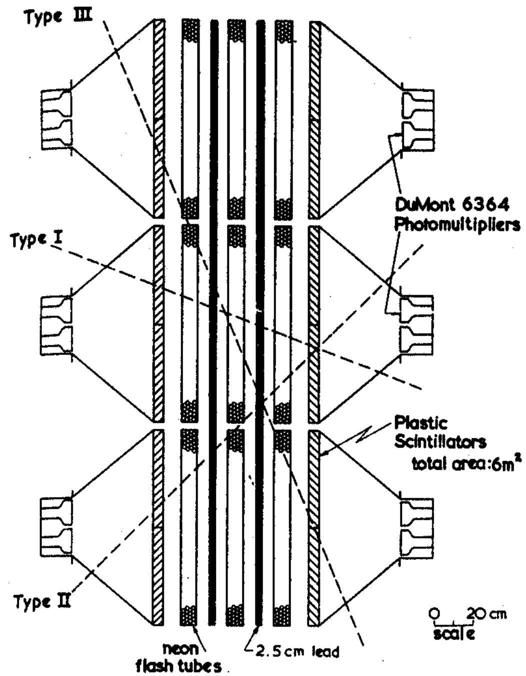
D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL.2 N_4+S_4	37°	30.3	20.04
2	TEL.1 N_1+S_1	48 ± 1°	27.4	18.26
3	TEL.2 N_6+S_6	75 ± 10°	25.5	20.03



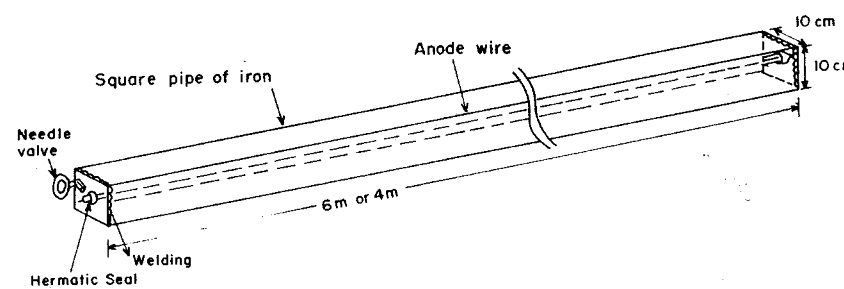
Detectors in KGF mine (1965-1991)



ν Telescope

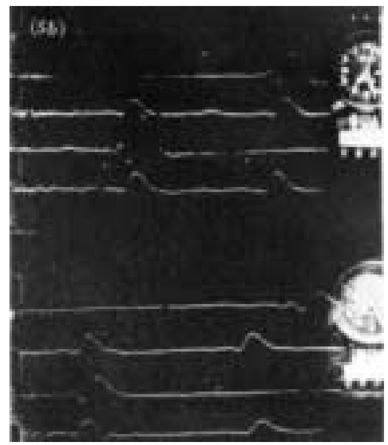
Iron, flash tubes & scintillator

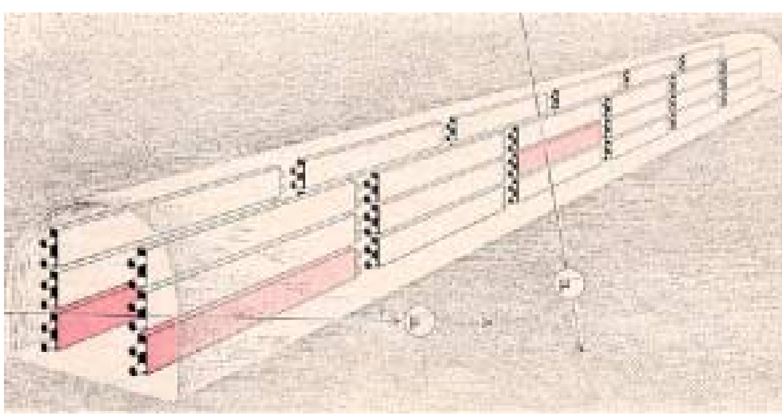
Proportional Tube element of proton decay detector and Monopole detector



CWI – The 1st recorded Atmospheric ν

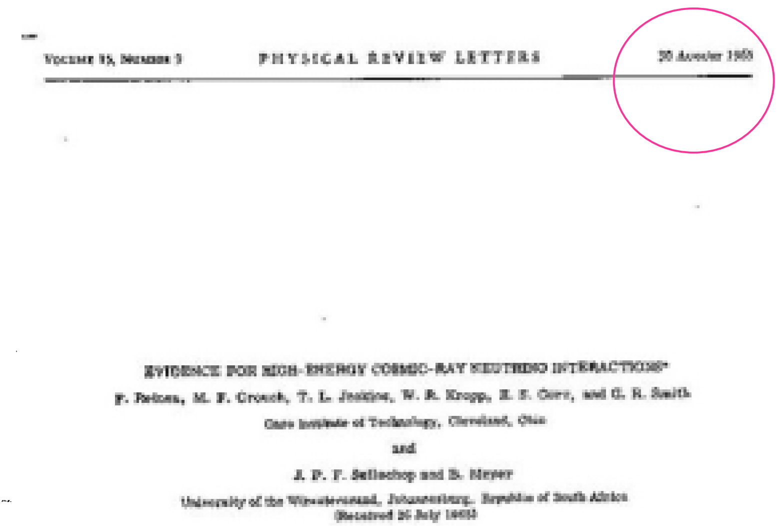
First ν
February 29, 1965
Recorded 100 (1/month)





CWI Data, neutrino induced μ's

- ~ 121 ν's
- 2 miles down!


Volume 15, Number 9 PHYSICAL REVIEW LETTERS 30 August 1965

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith

Case Institute of Technology, Cleveland, Ohio

and

J. P. F. Sellschop and B. Meyer

University of the Witwatersrand, Johannesburg, Republic of South Africa

(Received 26 July 1965)

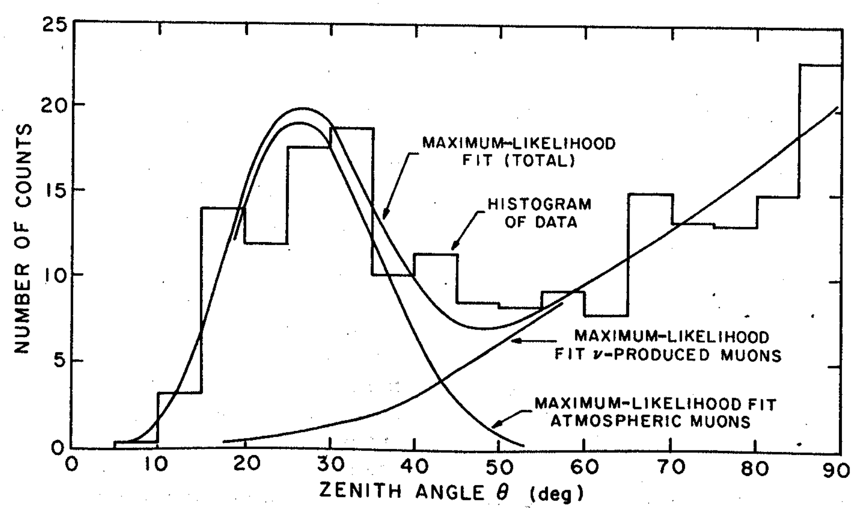


FIG. 8. Observed and expected numbers of counts vs zenith angle for events in which zenith angle is determined.

1986 - The beginning of the "Too few nu mu" problem

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS

well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

decay. Also, there
observed in any c
nucleon-decay sign
lifetime range from
der of 10^{32} years. V
is now limited by
mospheric ν flux a
tions. To reduce th
quire specific exper
understanding of lo
precise atmospheric

IMB-1

1986

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

University of California, Irvine, Irvine, California 92717
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University of Notre Dame, Notre Dame, Indiana 46556
University College, London WC1E 8BT, United Kingdom
Warsaw University, Warsaw PL-00-681, Poland

(Received 6 June 1986)

We have developed an extensive model of atmospheric ν interactions which provide the backgrounds to nucleon-decay experiments. We report results from a 417-live-day exposure of the Irvine-Michigan-Brookhaven detector. During this time 401 contained events were observed at a rate and with characteristics consistent with atmospheric ν interactions. We have calculated the expected backgrounds to a variety of two- and three-body decay modes and have set lower limits on many nucleon partial lifetimes.

PACS numbers: 13.30.Ce, 96.40.Qr

$\nu_\mu n \to \mu^- p$; $\nu_\mu p \to \mu^+ n$; $\mu \to e\nu\nu$ decay

$\nu_e n \to \mu^- p$; $\nu_e p \to e^+ n$; no decay

1988 – The ν_μ Deficit Gets Serious

New Directions in Neutrino Physics at Fermilab
September 14-16, 1988 — Fermi National Accelerator Laboratory

- 1988 Koshiba points out consistency decays/rings
- 1988-1995 Ratio-of-ratios

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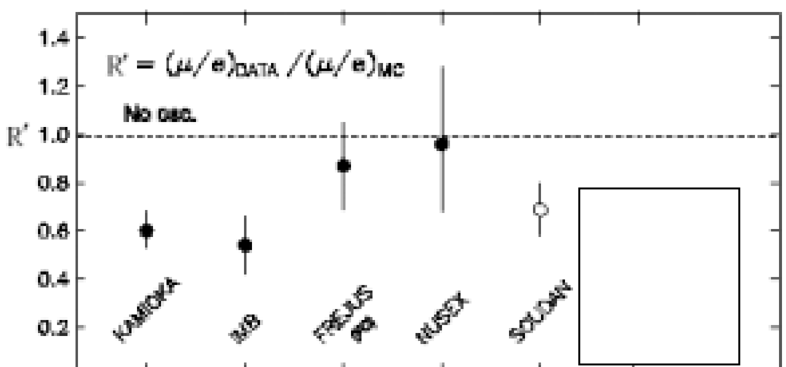



This is something new

Atmospheric ν's

Looking at the contained events in water Čerenkov detectors; the fraction of μ-e decay is considerably lower than expectation.

Data / M.C.

IMB (3.77 Kton·yr): (0.26±.03)/(0.34±.01) = 0.78±.09 — 2.6σ

KAM-II (2.87 Kton·yr): (0.61±.07)/(0.77±.01) = 0.80±.09 — 2.2σ

i) input νμ/νe ?
ii) μ-e decay electron detection efficiency ?
iii) as-yet-unaccounted-for physics ?

Now look at the μ/e separated events (single-ring events) (98% efficient) (0.2~2 GeV/c)

KAM-II data

(No. μ-events)^{Data}/(No. μ-events)^{MC} = 0.57 ± .06

(No. e-events)^{Data}/(No. e-events)^{MC} = 1.12 ± .18 — OK

In order to get rid of flux uncertainty:

(No. μ-events/No. e-events)^{Data}/(No. μ-events/No. e-events)^{MC} = 0.56 ± 0.09 — 5σ

This is to be compared to the calorimeter exp. Frejus

Frejus (1.0 Kton·yr)

$(\nu_\mu/\nu_e)^{Data}/(\nu_\mu/\nu_e)^{MC}$ = 0.75 ± .21 (0.2~20 GeV/c)

L. Moscoso stated consistent with 1.0

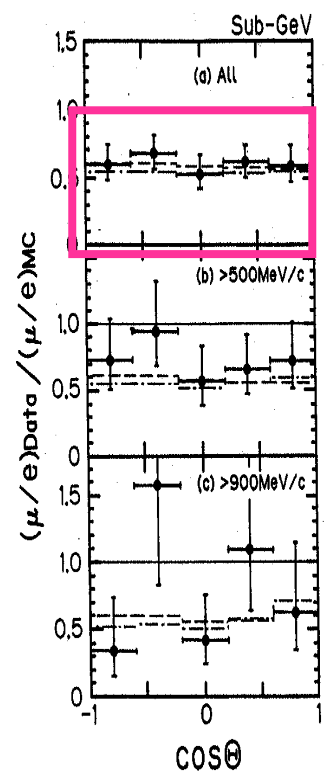
KAM-II result on this subject was sent, Jan '88, for publication to Phys. Lett. B B205 (1988) 416.

May 26, 2002

Maury Goodman, Neutrino 2(…)
“Other Atmospheric ν Experim(…)

1994 Kamioka's angular distribution

- Multi-Gev data
- Evidence for "oscillations"
- Gave higher Δm^2
- Note flat sub-Gev data
- Kamioka & initial Super-K fits differed, but data didn't differ noticeably
- Fits for Δm^2 not Gaussian!



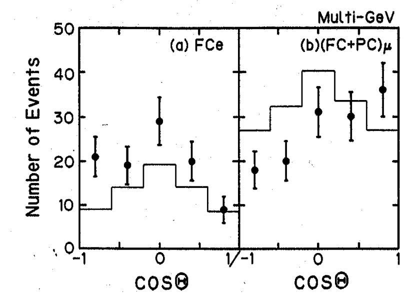


Fig. 3. Zenith-angle distributions for (a) the e-like events and (b) μ-like events (the fully-contained and partially-contained events are combined). The circles with error bars show the data and the histogram the MC (without neutrino oscillations). The downward direction is given by $\cos\Theta = 1$.

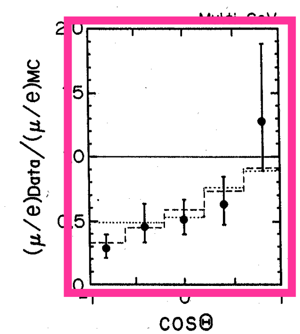


Fig. 4. Zenith-angle distribution of $(\mu/e)_{data}/(\mu/e)_{MC}$, where both the fully-contained and the partially-contained events are included. The circles with error bars show the data. Also shown are the expectations from the MC simulations with neutrino oscillations for parameter sets (Δm^2, $\sin^2 2\theta$) corresponding to the best-fit values to the multi-GeV data for $\nu_\mu \leftrightarrow \nu_e$ ((1.8×10^{-2} eV^2, 1.0), dashes) and $\nu_\mu \leftrightarrow \nu_\tau$ ((1.6×10^{-2} eV^2, 1.0), dots) oscillations.

Gedanken History #1 of atmospheric ν's

What if we had no GUTS?

- only CWI, Baksan & LVD?
- Inspiration for atmospheric neutrino experiments by now from solar neutrinos?
- Greater enthusiasm for LSND?
- Greater enthusiasm for BNL, CERN-JURA, COSMOS?
- No enthusiasm for LMA atmospheric projects until 2002?

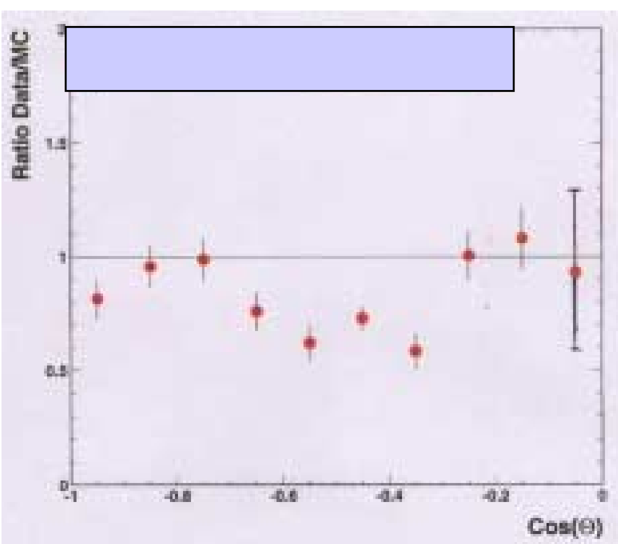
Gedanken History #2 of atmospheric ν's

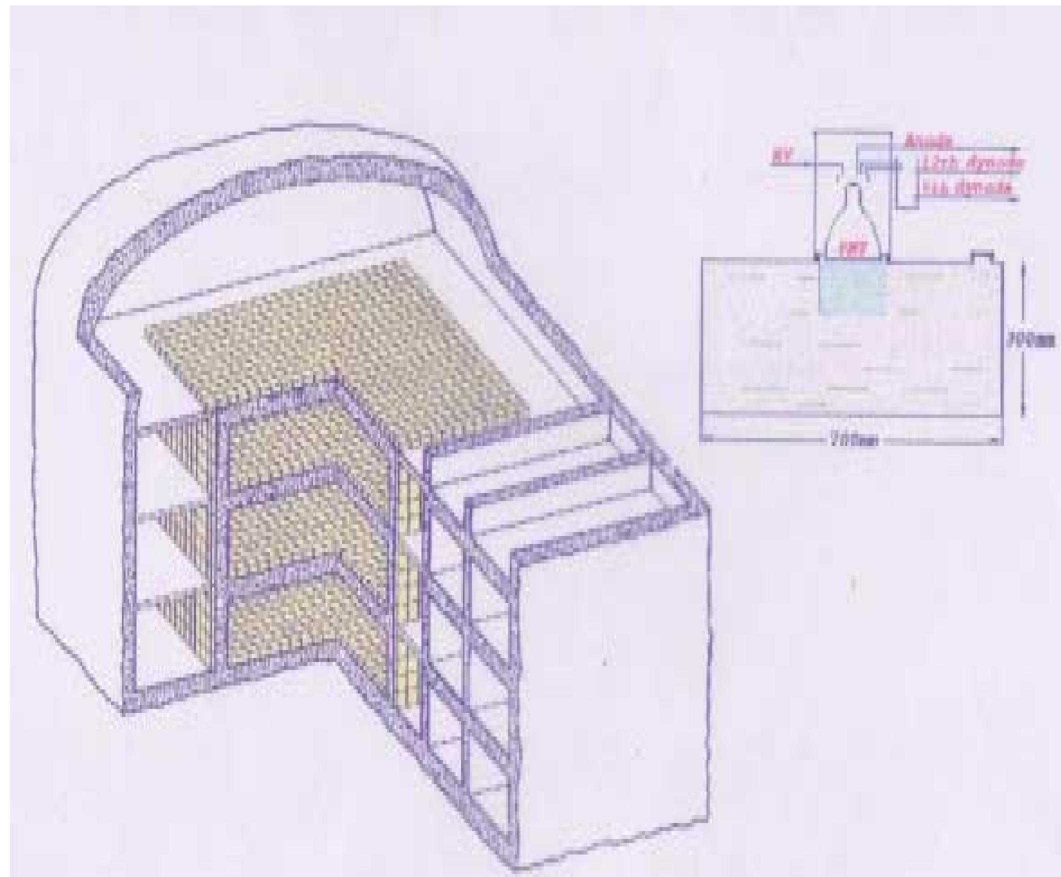
What if the Super-K accident happened on its first fill?

- Super-K might have been cancelled
- No K2K
- MINOS would be planning with the HE beam
- Oscillations of atmospheric ν wouldn't be universally accepted
- Δm_{23}^2 situation would be confused
- This talk would be more important

Baksan Underground Scintillator Telescope

- 801 upward μ's
- 941.6 expected
- + ~10% livetime





MACRO/Soudan Since Neutrino 2000

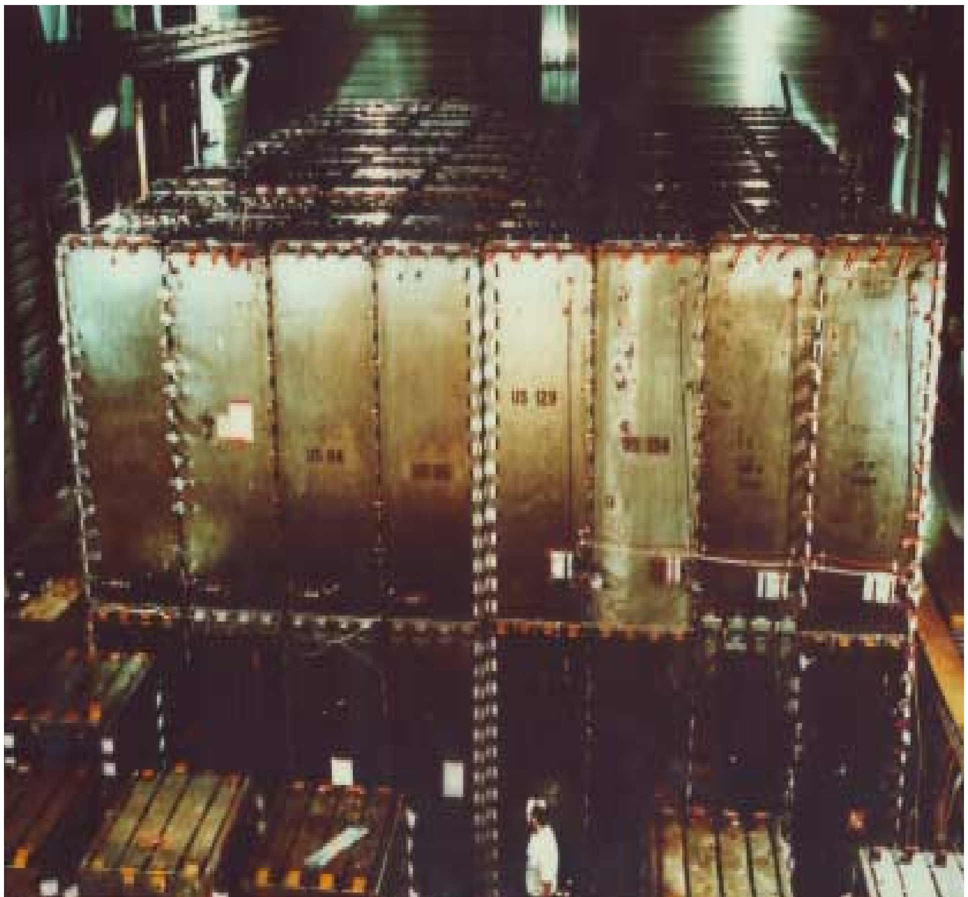
- ☹ MACRO stopped running
- ☺ More MACRO data (1087ν →1225 ν)
  - ☺ Details in Contributed Paper by M. Spurio

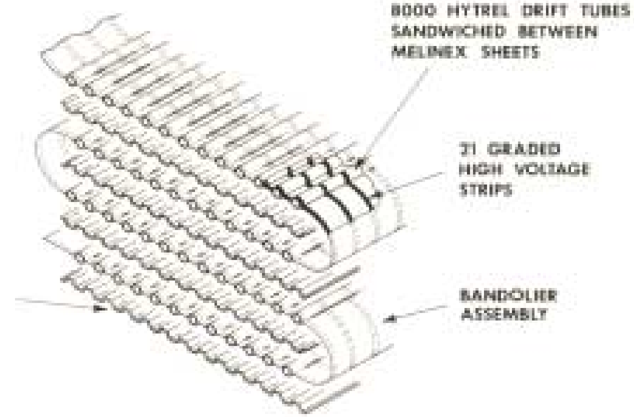
B2 "Measurement of the Atmospheric Muon Neutrino Flux: MACRO final Results"

- ☹ Soudan 2 stopped running
- ☺ More Soudan 2 data (~400 ν →661 ν)
  - ☺ Details in Contributed Paper by M.Sanchez

B1 "Recent Atmospheric Neutrino Results from Soudan 2"

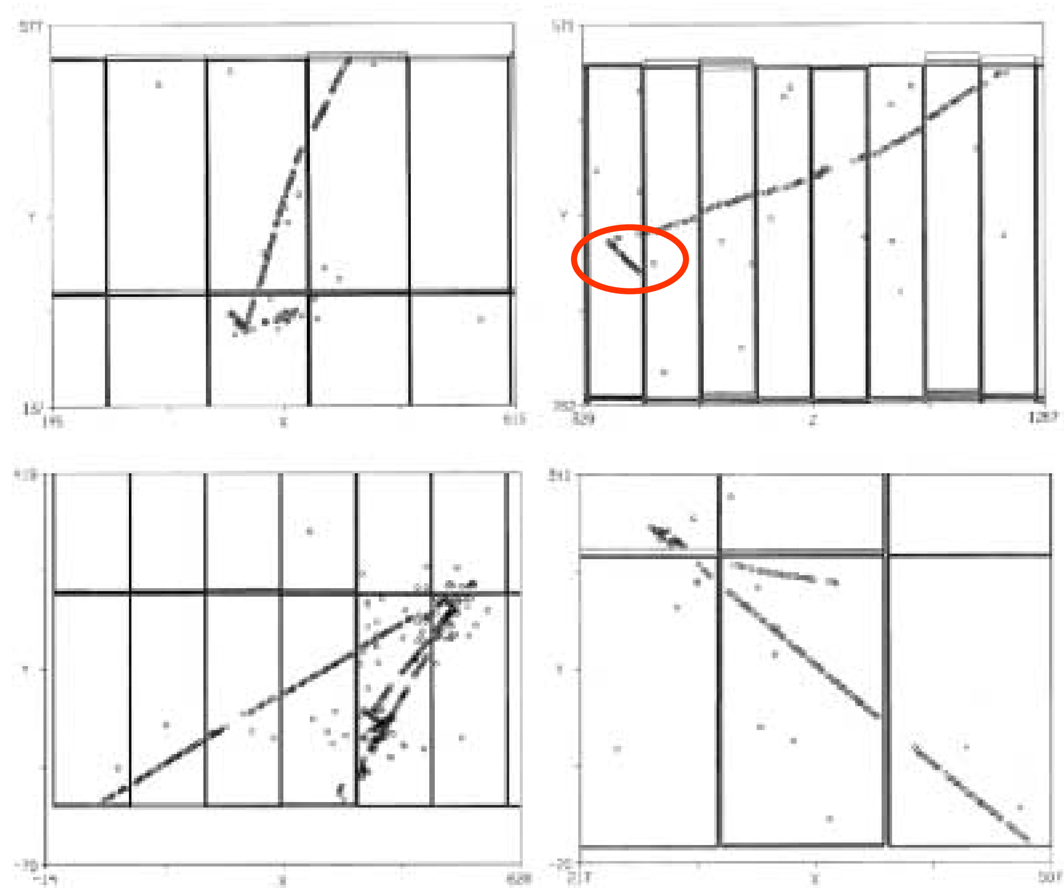
Soudan 2 1989-1991





Soudan 2

- Now includes Partially Contained Events
- 5.90 kt-years final exposure (fiducial)
- Problem with energy scale fixed
- Feldman-Cousins fitting for parameter space



- 4 different ν_μ events
- Note proton (short, straight heavily ionizing track)

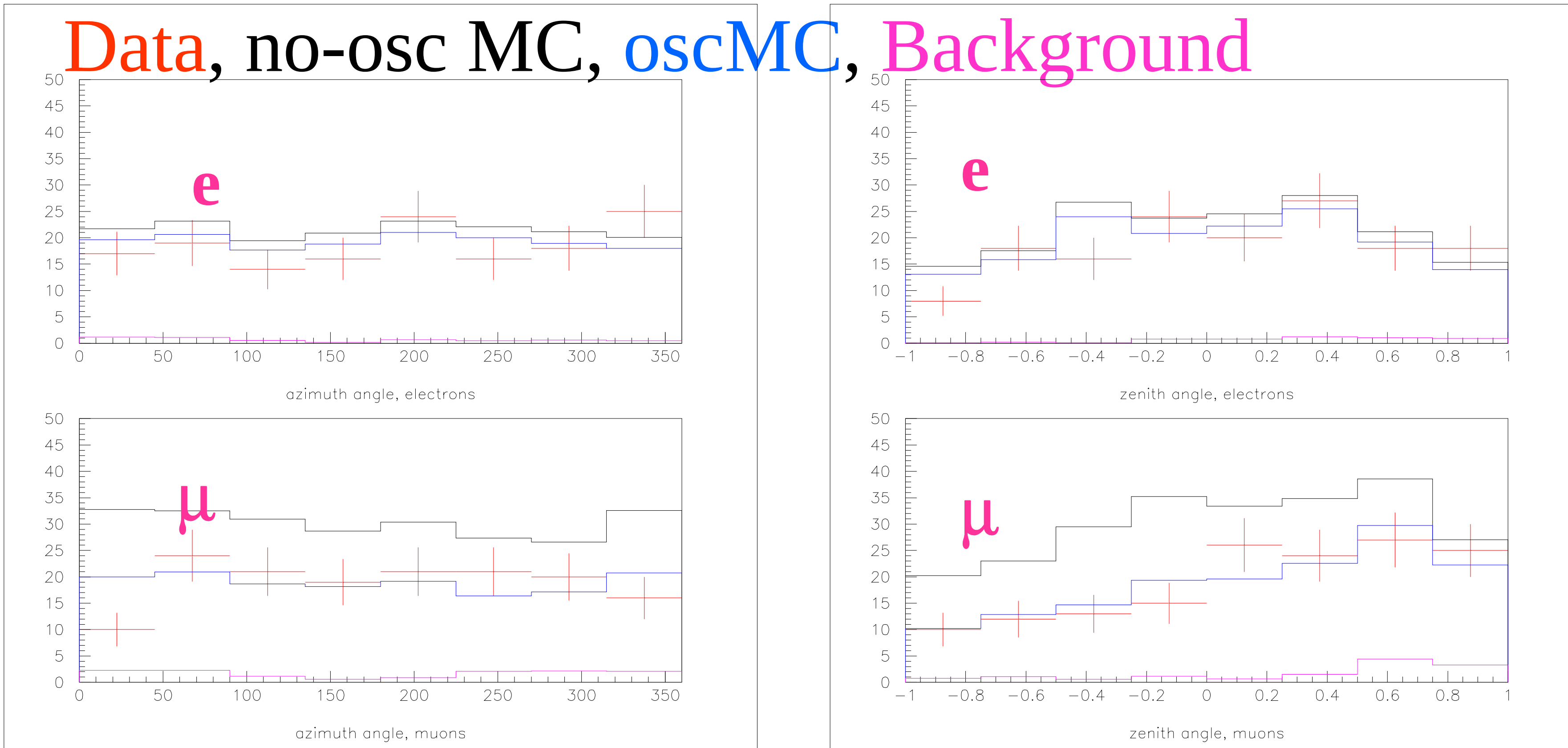
Soudan 2 L/E analysis

- E measured by full reconstruction of event, L measured by the event direction (zenith angle) ; protons and low energy pions are seen and included

Lepton energy (MeV)	0-200	200-400	400-600	>600
$\Delta\theta_z$ (ν-lepton) (degrees)	~90	75	49	28
$\Delta\theta_z$ (ν-(lepton+proton)) (degrees)	30	23	15	8

- define a "high resolution" sample:
  - high energy quasi-elastics,
  - low energy quasi-elastics with proton
  - high energy multiprongs

Soudan 2; Azimuth & Zenith plots



Soudan 2 Data sets, 5.90 kt years

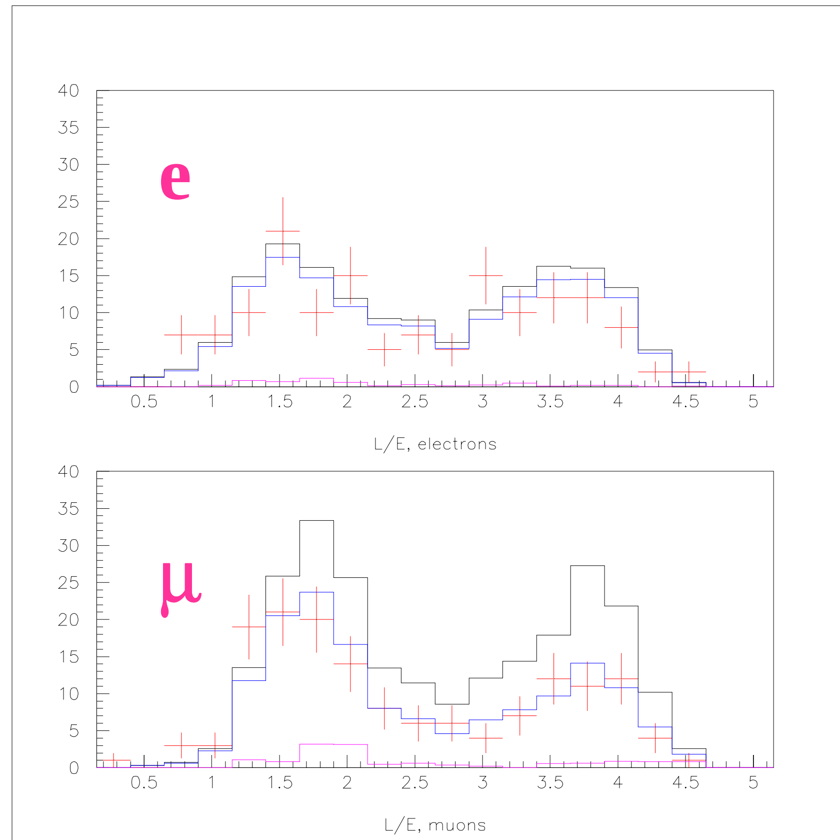
R values

no cut

- all 0.768 ± 0.098
- hires 0.681 ± 0.096
- lowres t/s 0.807 ± 0.278
- lowres m 0.826 ± 0.224

300 Mev cut

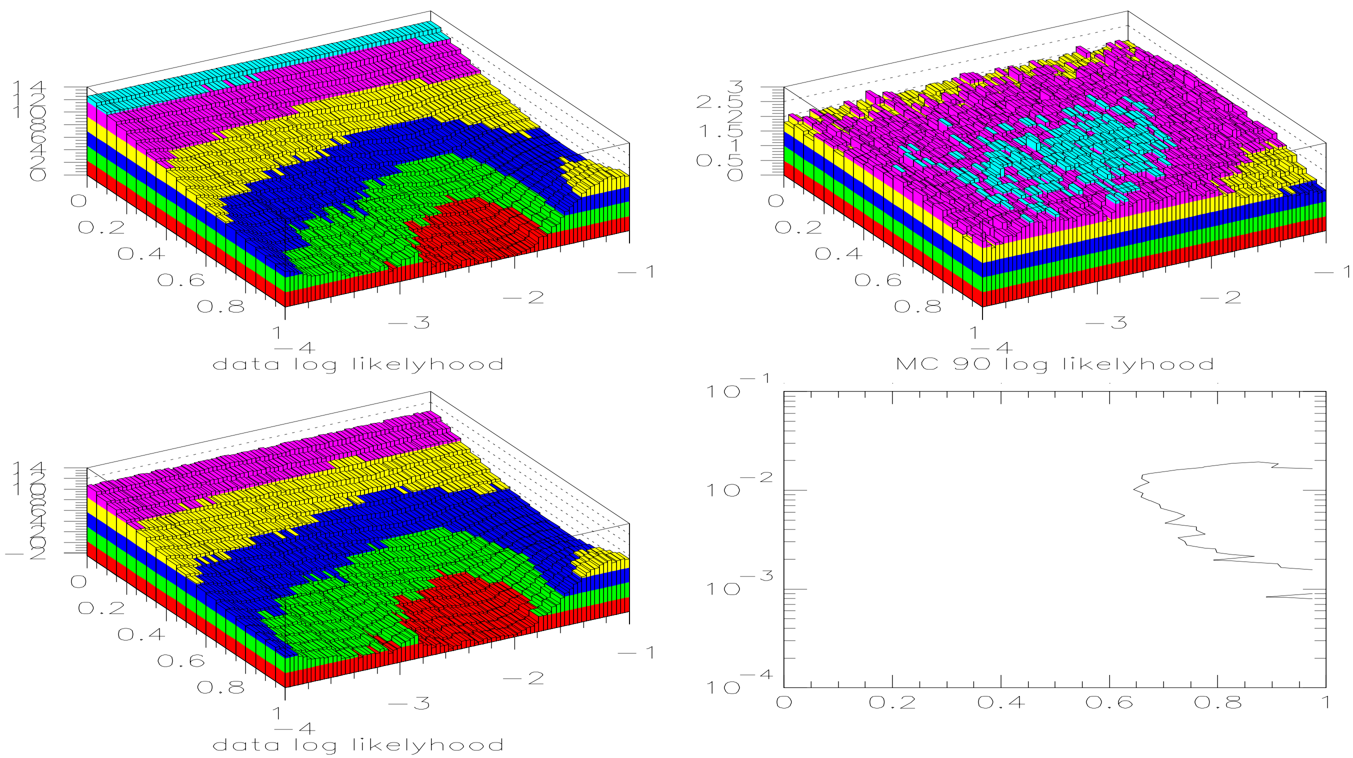
- all 0.708 ± 0.092
- hires 0.643 ± 0.105
- lowres t/s 0.641 ± 0.260
- lowres m 0.851 ± 0.167



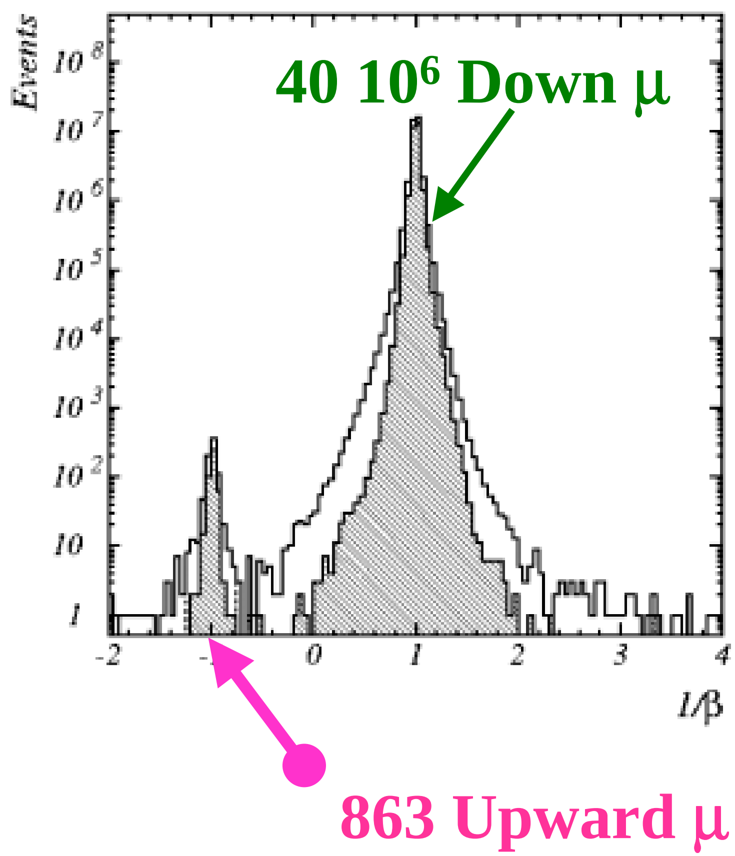
L/E

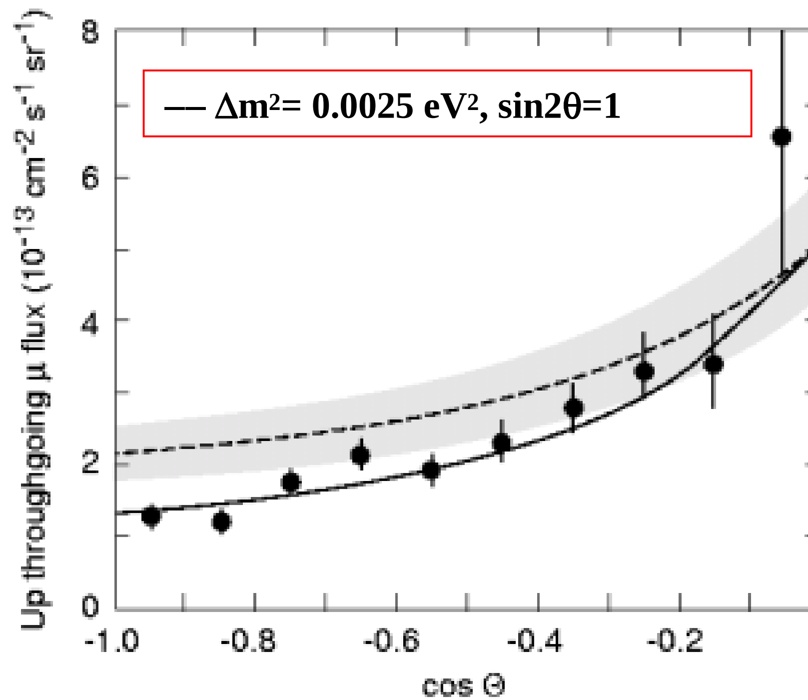
Soudan 2 parameter contours

Best Fit Δm^2=0.010 $\sin^2 2\theta$=0.975 f=0.150 (0.164)

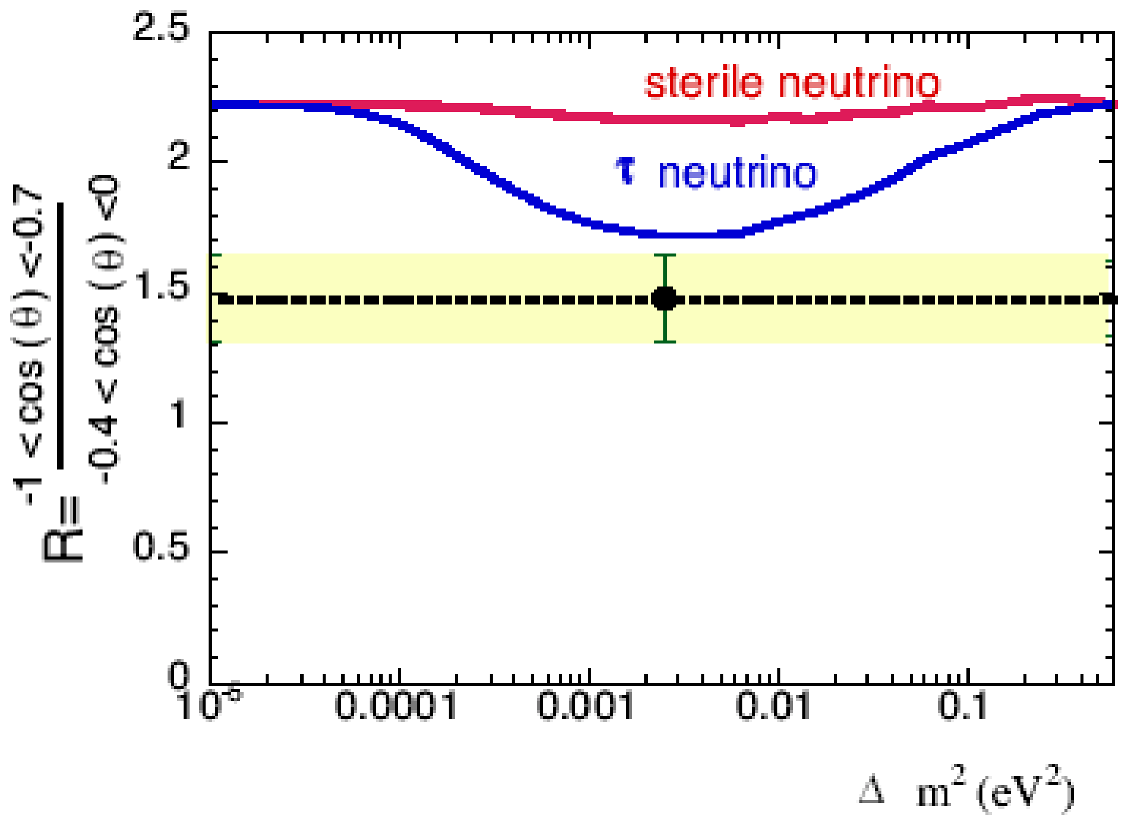


Macro High Energy Events

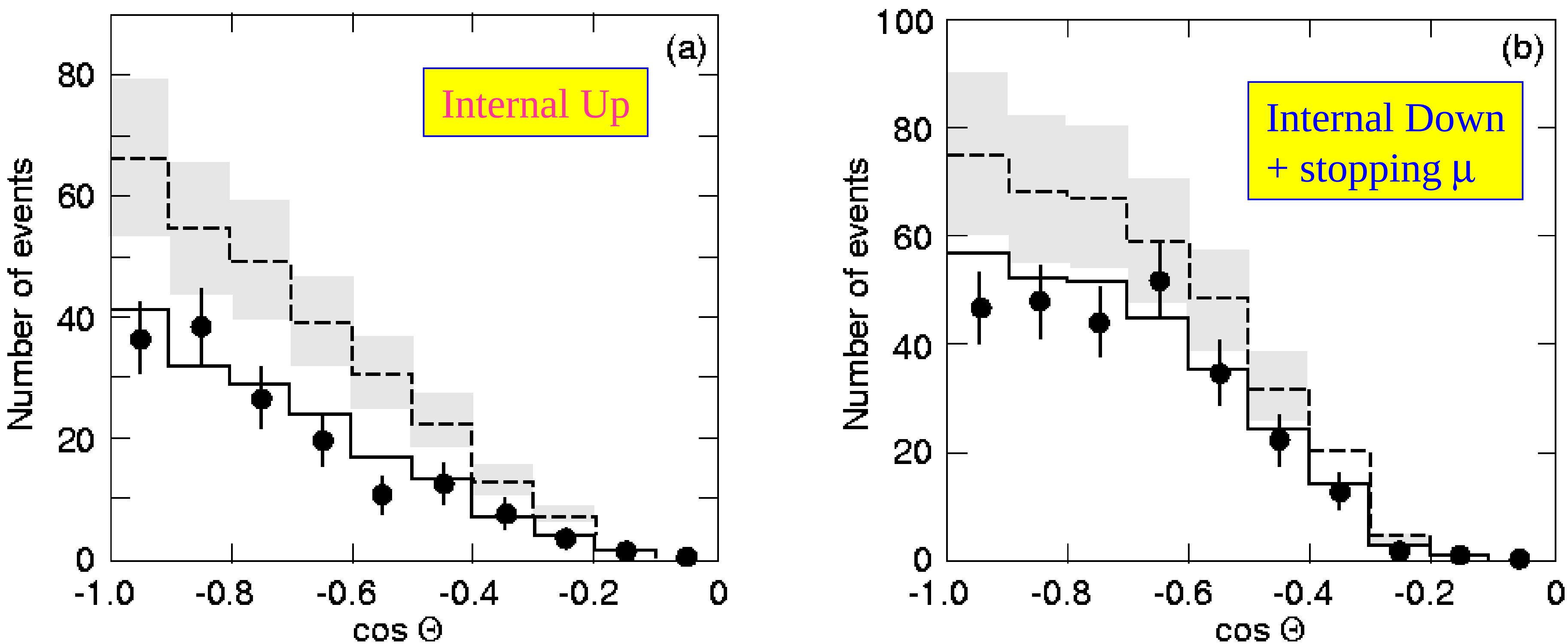




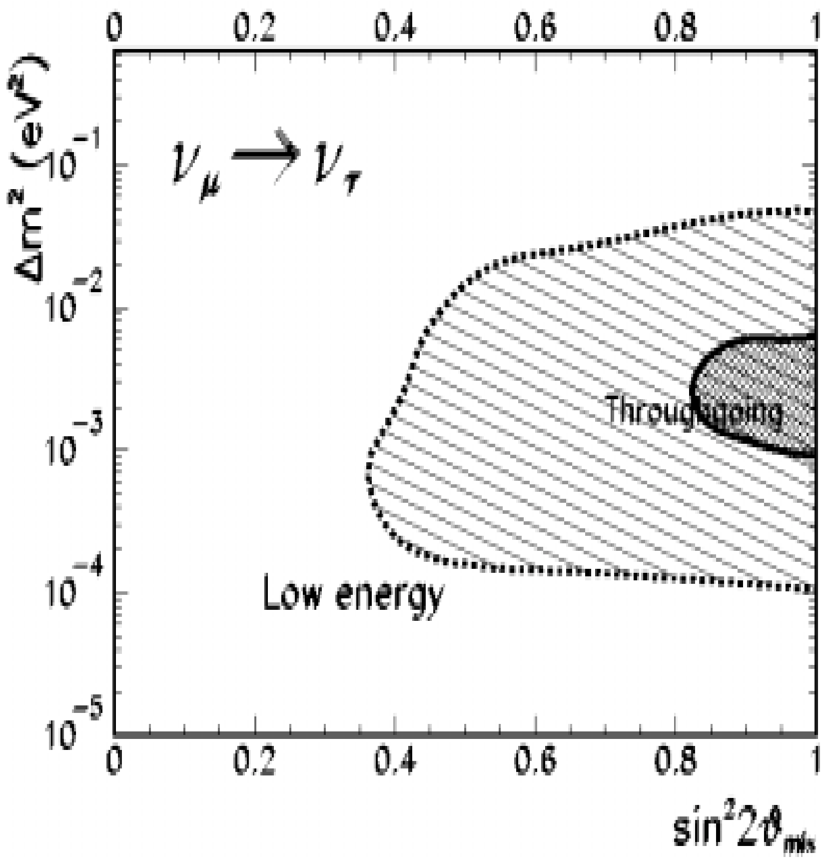
Macro sensitivity to Matter effects

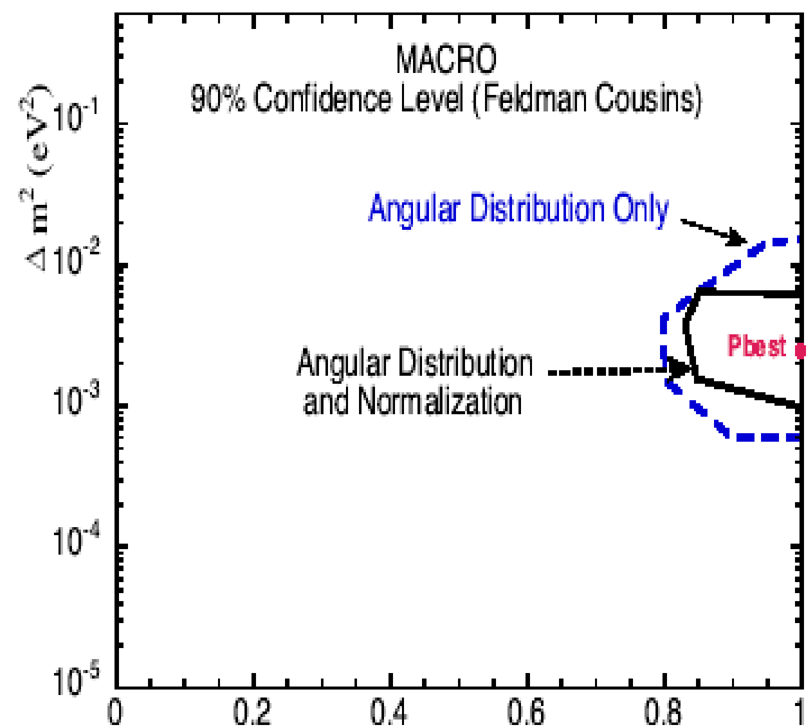


Macro Low Energy Events



Macro Oscillation Fit (High Energy)

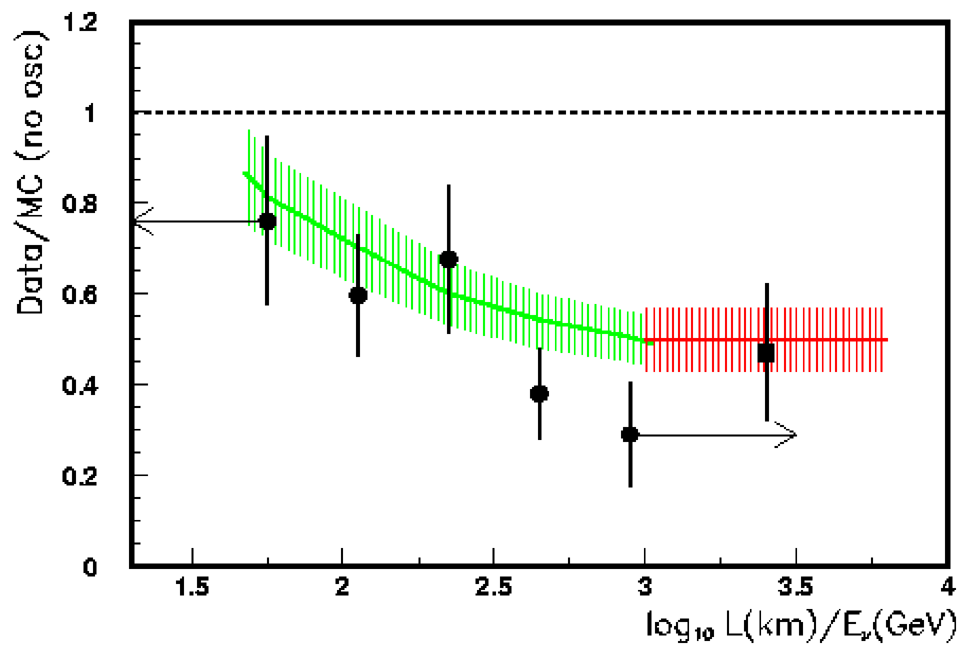




MACRO L/E using multiple scattering

$$\sigma_{MCS} \simeq \frac{X}{\sqrt{3}} \frac{13.6 \cdot 10^{-3} GeV}{p\beta c} \sqrt{X/X^0} \cdot (1 + 0.038 \ln(X/X^0))$$

- E estimate from Multiple Scattering
- 3 E bins (streamer tubes in digital mode)
- 4 E bins (streamer tubes in drift mode + Neural Net)



Δm^2 $\sin^2(2\theta)$ Comparison

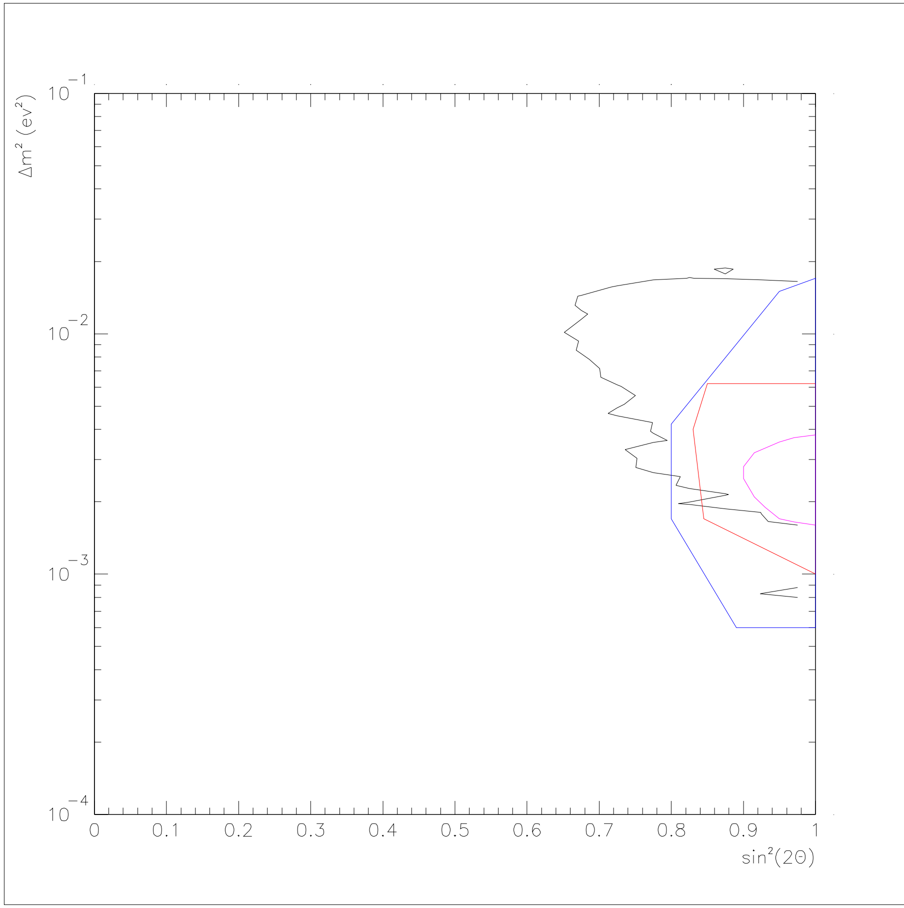
color code:

Soudan

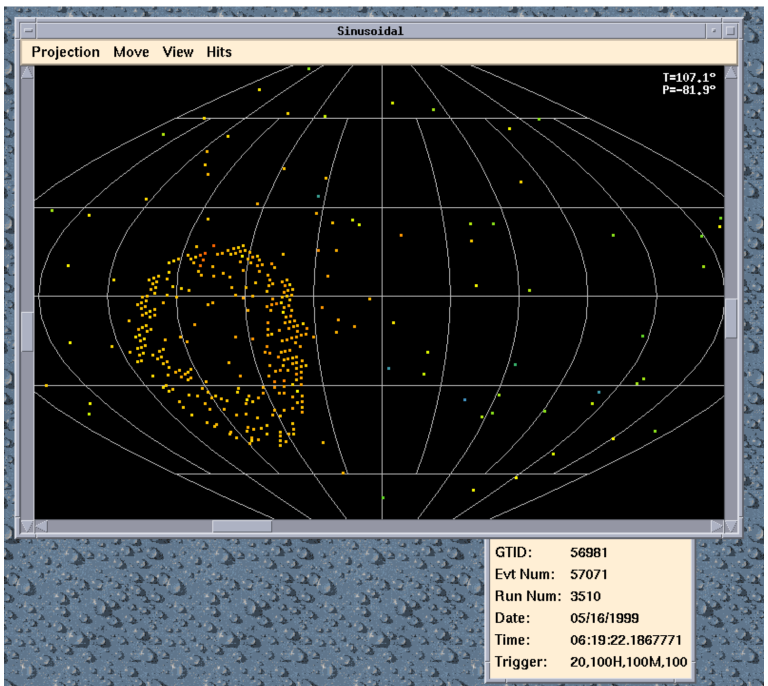
Macro HE

Macro LE

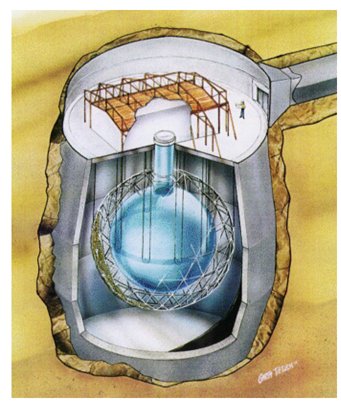
Super-Kamiokande



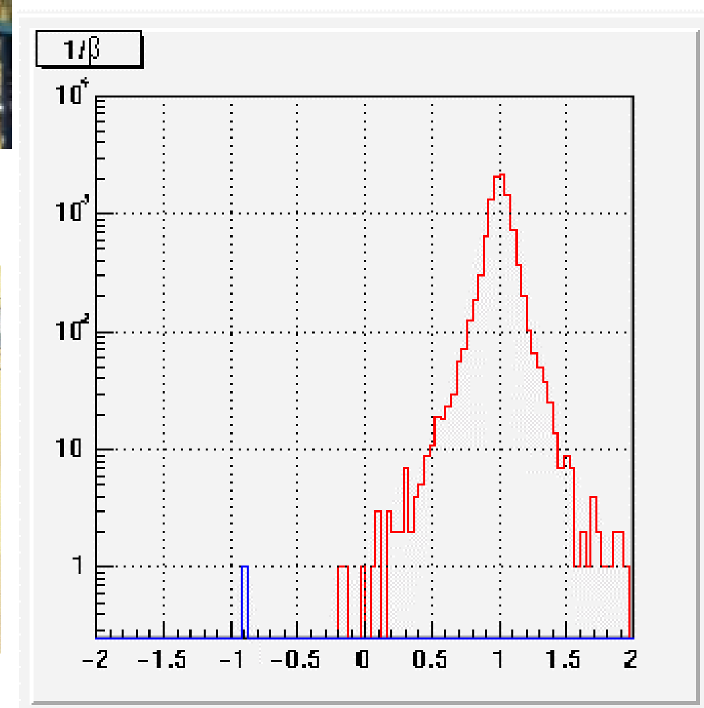
New data from SNO and MINOS



MINOS



SNO



Contained ν_μ Event in SNO

Upward Muon in MINOS

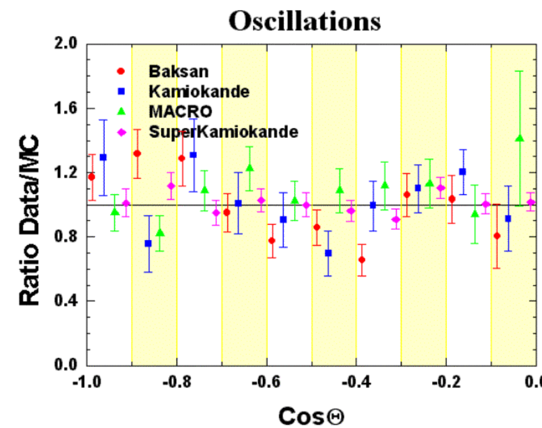
Summary – Contained ν's

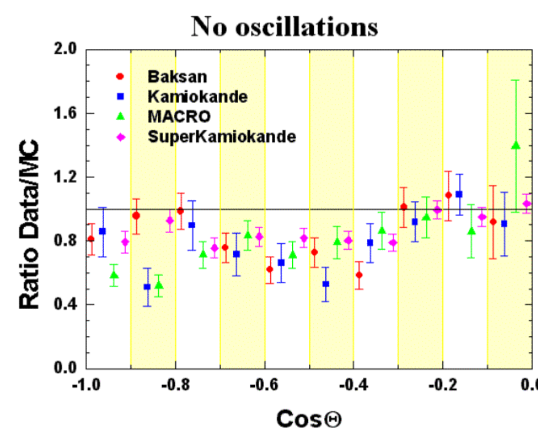
- IMB/Kamioka/Soudan 2/Frejus data taken as a whole agree with Super-Kamiokande's interpretation of neutrino oscillations
- Soudan 2 now has significant up/down difference
- MACRO using dE/dx to estimate L/E
- Soudan 2 has the resolution, but not the statistics, to see "reappearance"
- See posters: Spurio(MACRO) & Sanchez (Soudan 2)

Summary – ν induced μ

- Oscillations fit all data much better then null hypothesis.
- However P < 30% in all 4 experiments.
- ??

[plots courtesy S. Mikheyev]





A GUT Prediction

Another order of magnitude or two search for nucleon decay can take place in our lifetimes. This can be accompanied by precision atmospheric neutrino measurements.