MACRO and neutrino oscillations
a quasi-historical reconstruction

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LNGS - June 28, 2025

OUTLINE

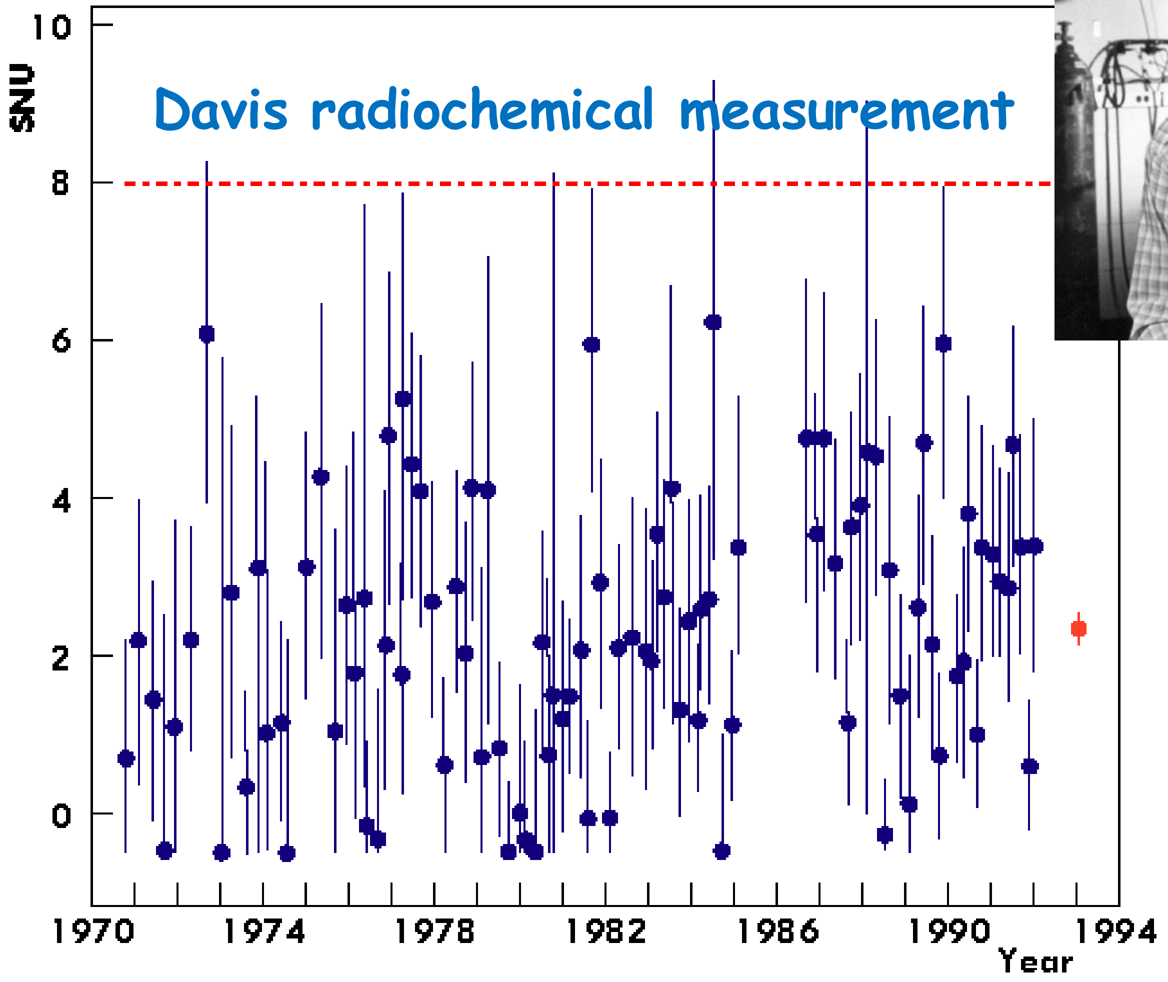
- Neutrino physics in the early '90s
- Neutrino events in MACRO
- First steps of up-μ analysis
- Attico construction and low-energy ν-events
- Pion back-scattering
- Many many checks
- 1998, Takayama
- Five papers on ν oscillation

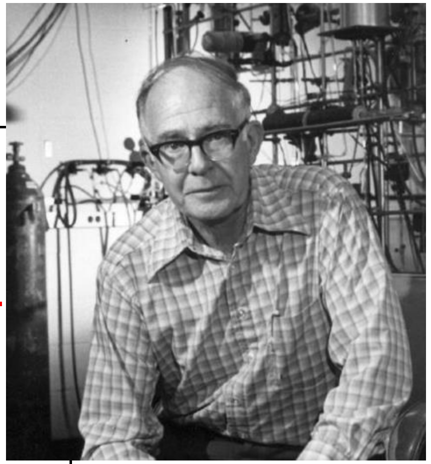
Based on my memories and on Ronga's historical reconstruction (www.lnf.infn.it/~ronga/nustor.pdf)

Sorry if I forget anything or anyone

Solar neutrino puzzle

In the early '90s



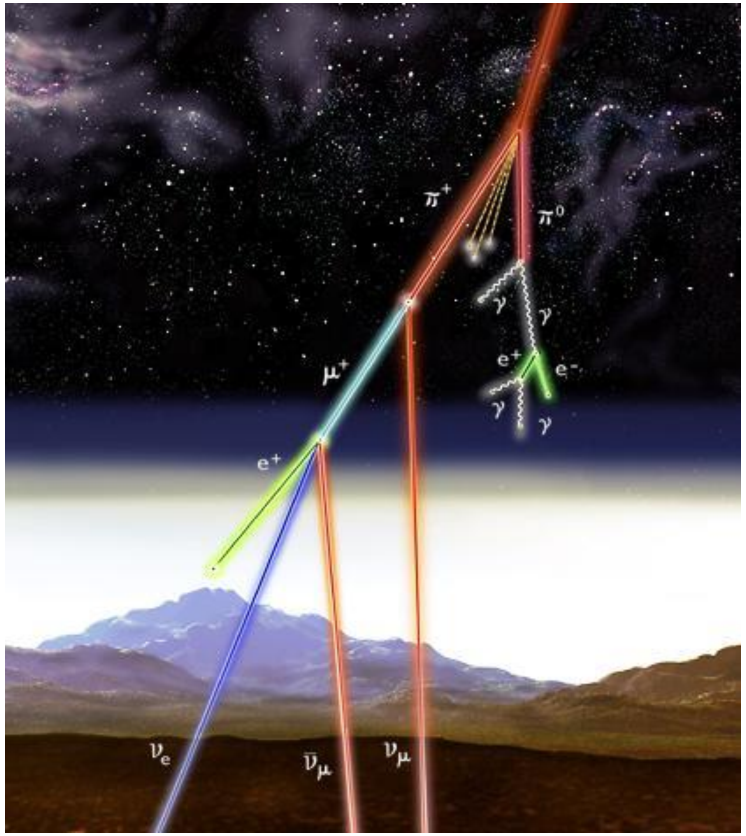


Neutrino oscillation ?

or

Wrong solar model ?

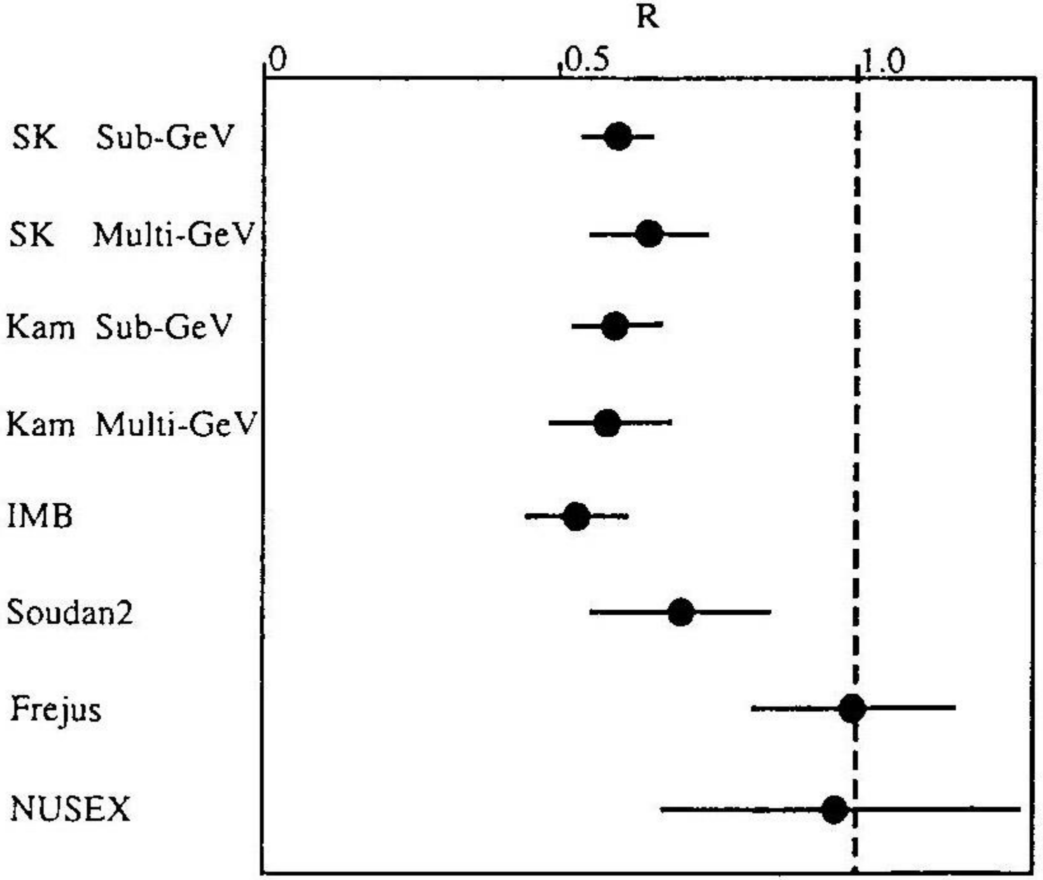
Atmospheric neutrino anomaly



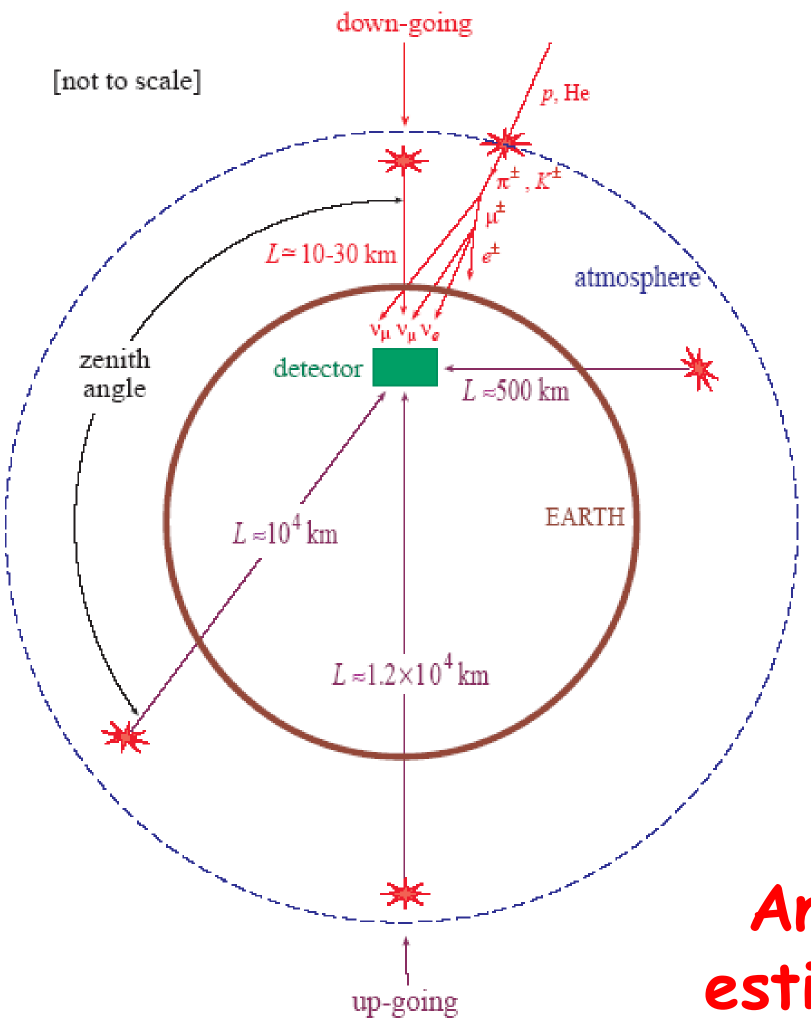
1 ν_e 2 ν_μ

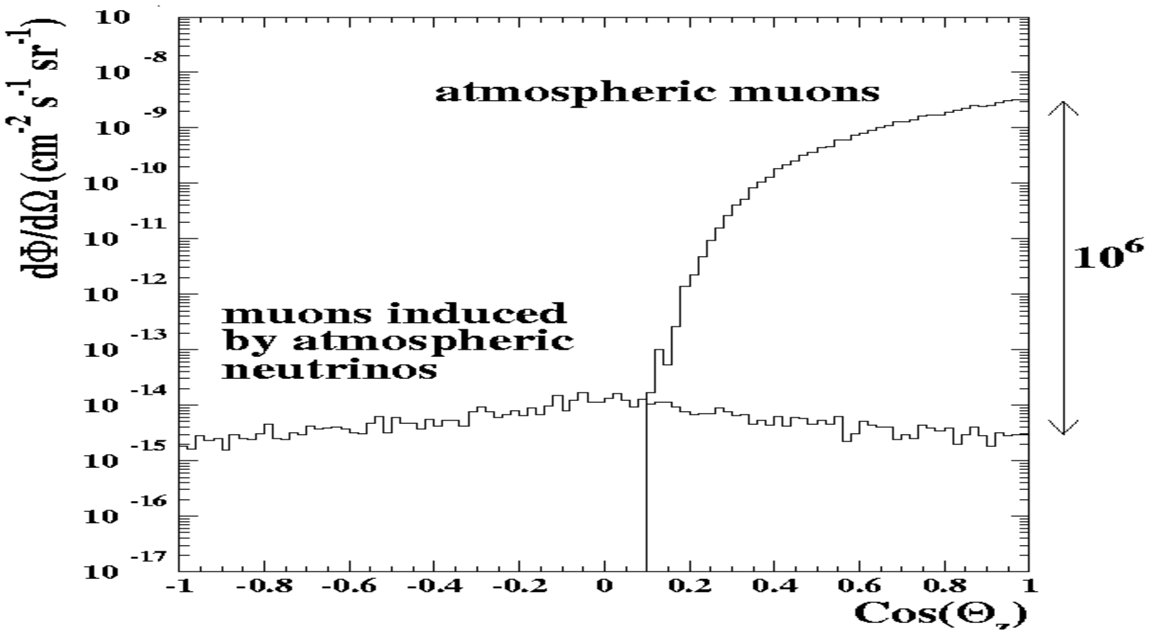
$$R = \frac{\left(\frac{\mu}{e}\right)_{DATA}}{\left(\frac{\mu}{e}\right)_{MC}}$$

In the early '90s



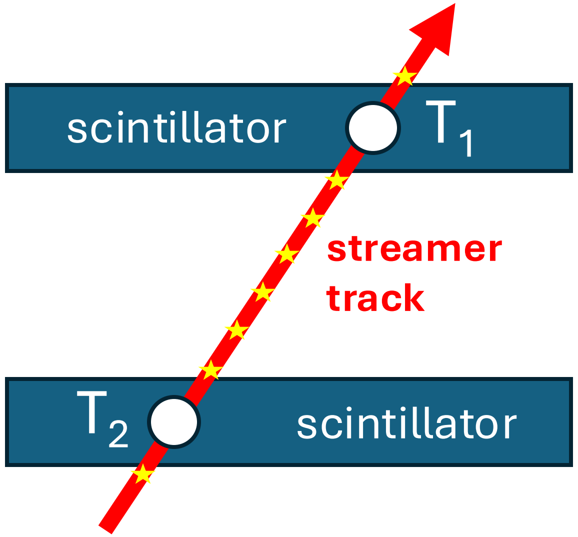
Upwardgoing muons in MACRO





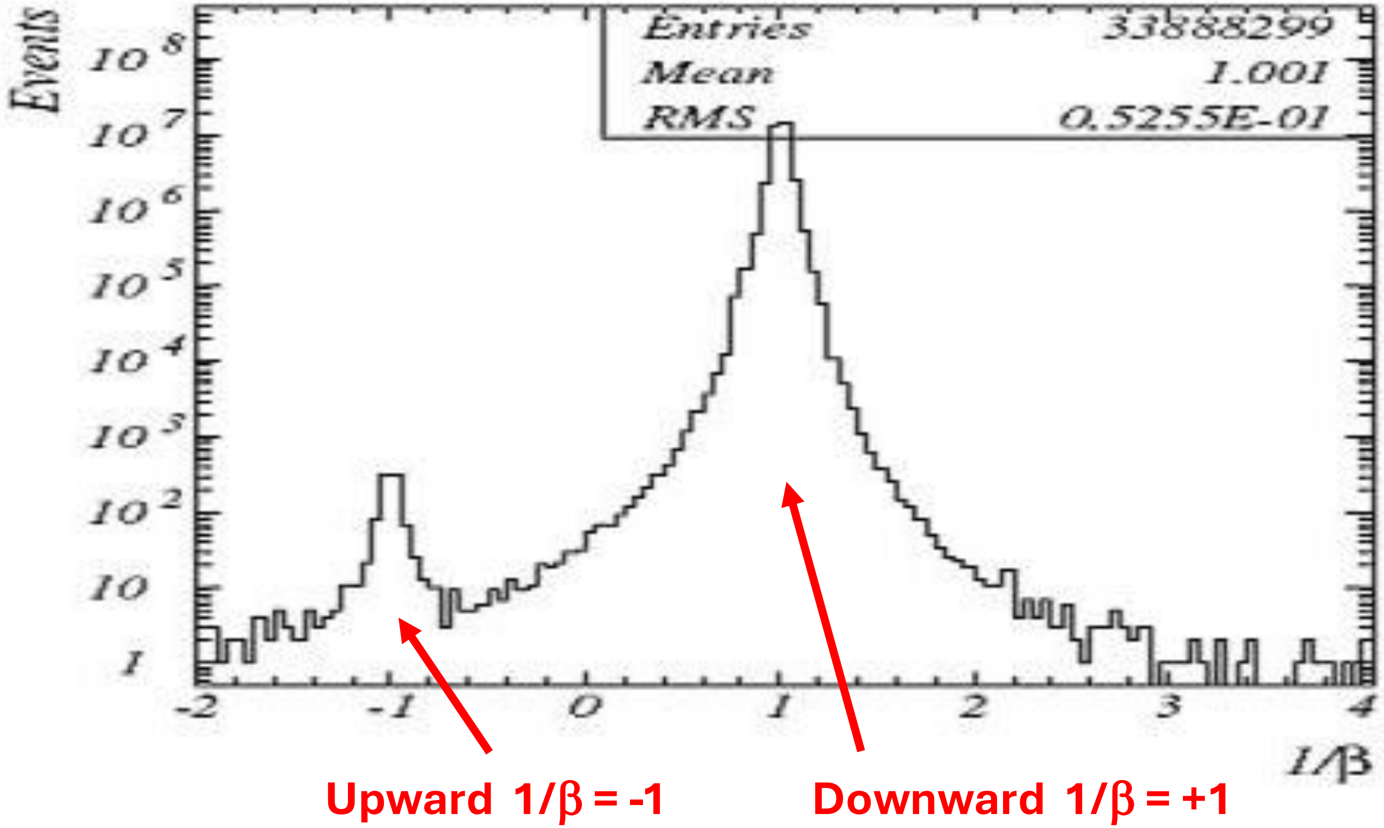
Angular measurement to estimate neutrino path (L_ν)

Time-of-Flight Method



$$\frac{1}{\beta} = (T_2 - T_1) \times \frac{c}{L}$$

$$L = track\ length$$



November 1984 – MACRO proposal

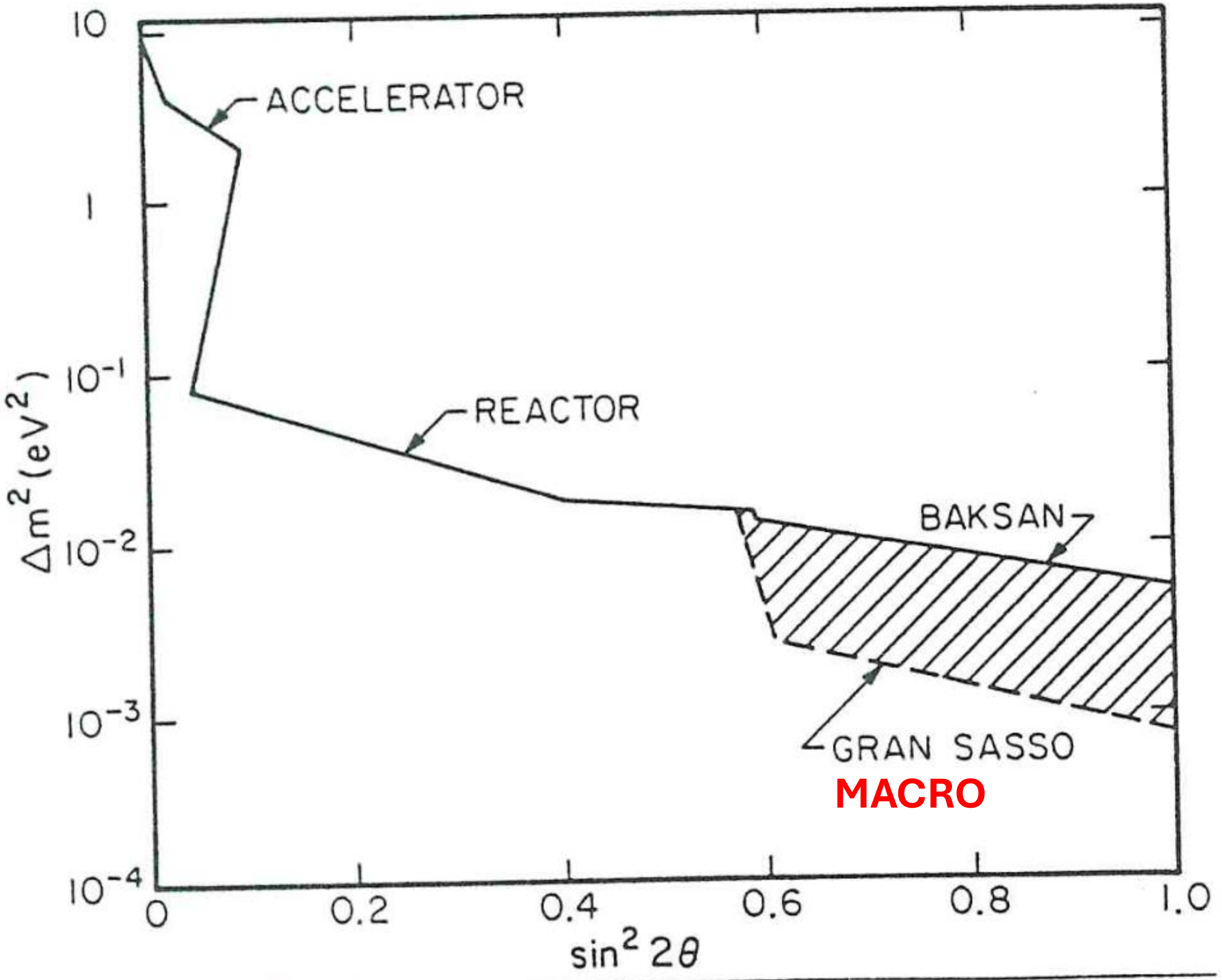


Fig. (2)13 Present best limits on Δm^2 vs. $\sin^2 2\theta$. The shaded region represents the improvement obtainable with our experiment.

IMB collaboration
PRL 69 (1992) 1010

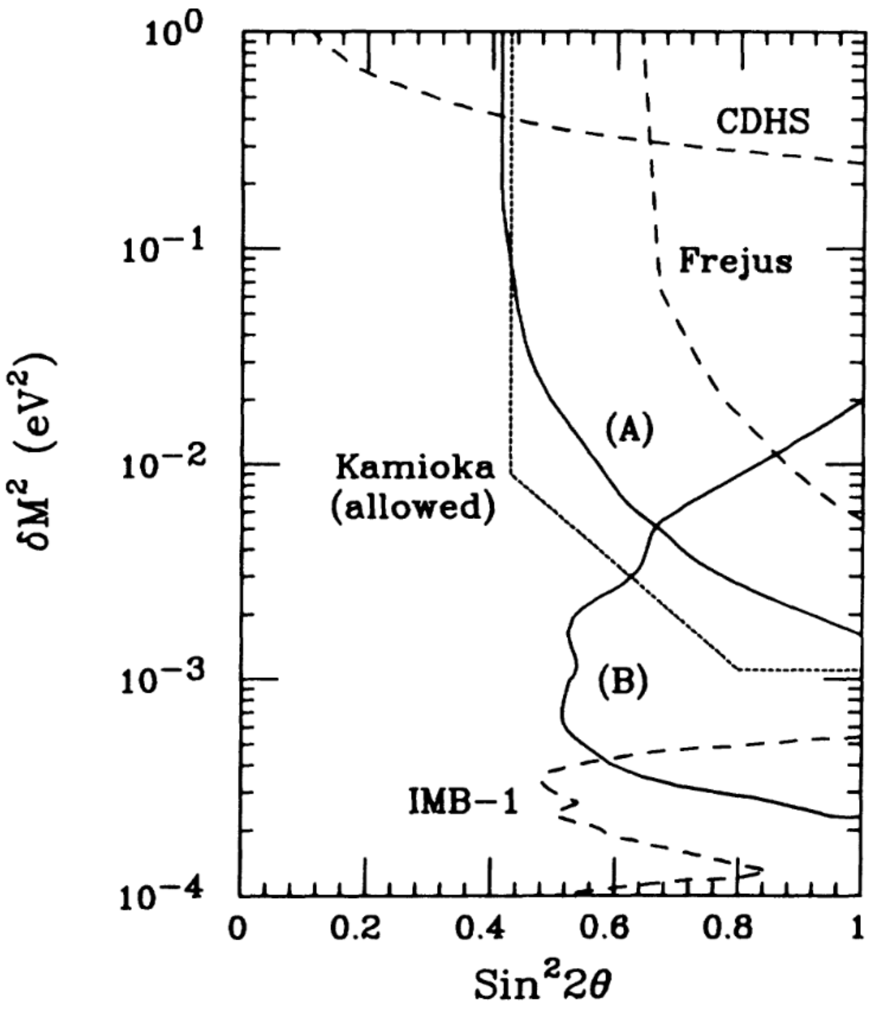
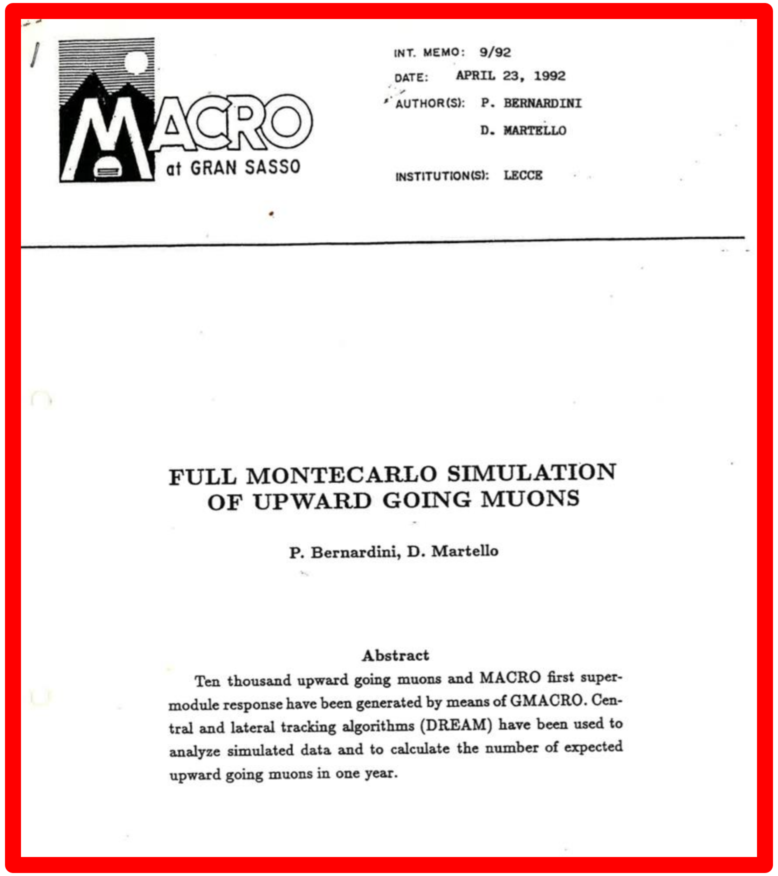


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (A) and stopping fraction (B). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

These limits rule out much (but not all) of the "allowed" region of parameter space if the muon neutrino deficit measured by IMB and Kamiokande at low energies is due to ν_μ oscillations to ν_τ. In addition, the high mixing angle region from 5×10^{-4} to 5×10^{-3} eV^2 is newly excluded.

MACRO: a hopeless search ?

Cesena meeting, 1991 => Memo, April 1992


INT. MEMO: 9/92
DATE: APRIL 23, 1992
AUTHOR(S): P. BERNARDINI
D. MARTELLO
INSTITUTION(S): LECCE

FULL MONTECARLO SIMULATION OF UPWARD GOING MUONS

P. Bernardini, D. Martello

Abstract

Ten thousand upward going muons and MACRO first supermodule response have been generated by means of GMACRO. Central and lateral tracking algorithms (DREAM) have been used to analyze simulated data and to calculate the number of expected upward going muons in one year.

P. Lipari inserted the Bartol atmospheric ν flux in the GMACRO code

In the following the muon flux was simulated by S. Mikheyev and C. Okada

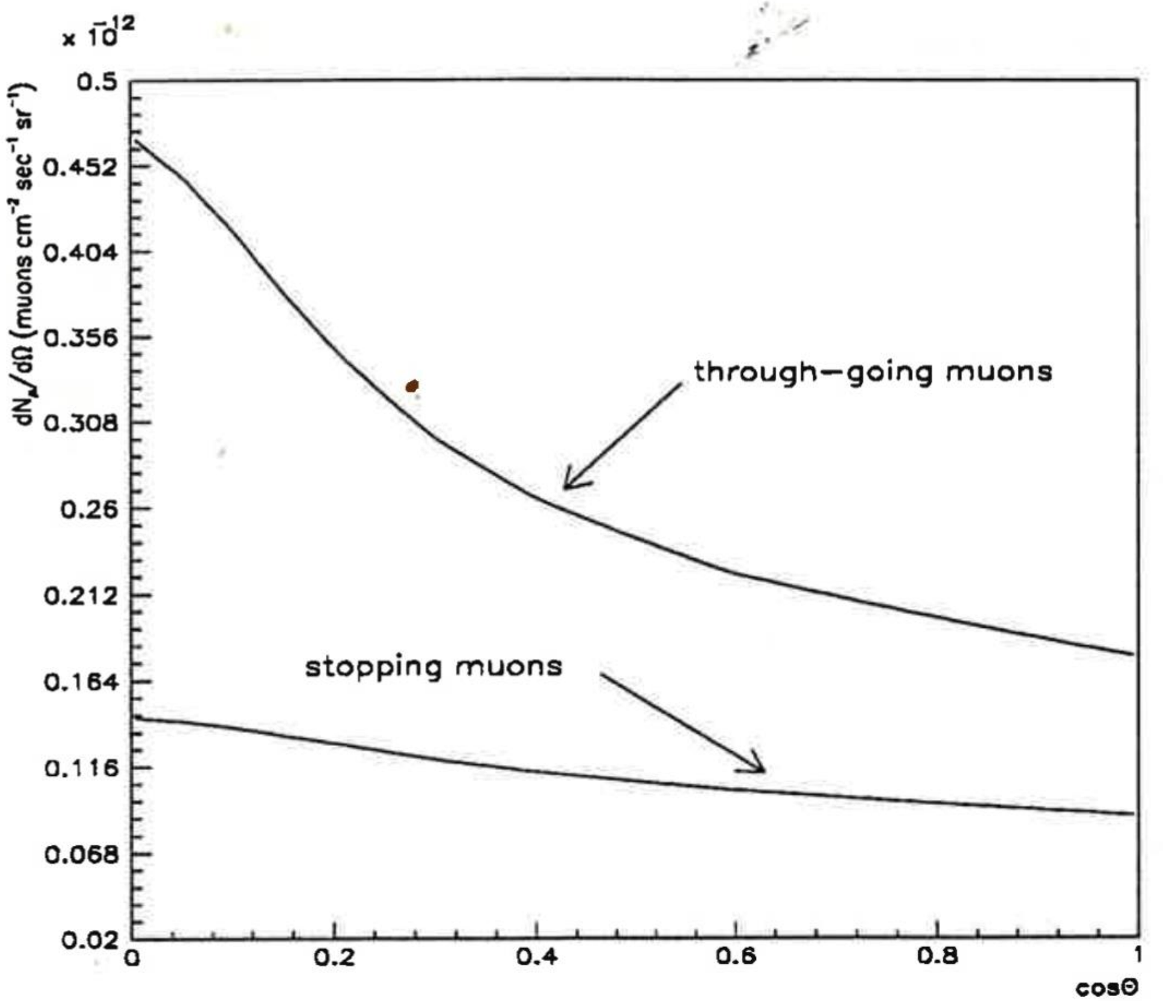


Figure 1.2: Stopping muons ($0.2 \leq E_\mu \leq 1.5$ GeV) and through-going muons ($E_\mu \geq 1.5$ GeV) flux as a function of $\cos\theta$.

Neutrino Working Group

&

6-Month Data

Status of Upgoing Muon Analysis for 6 Month Run

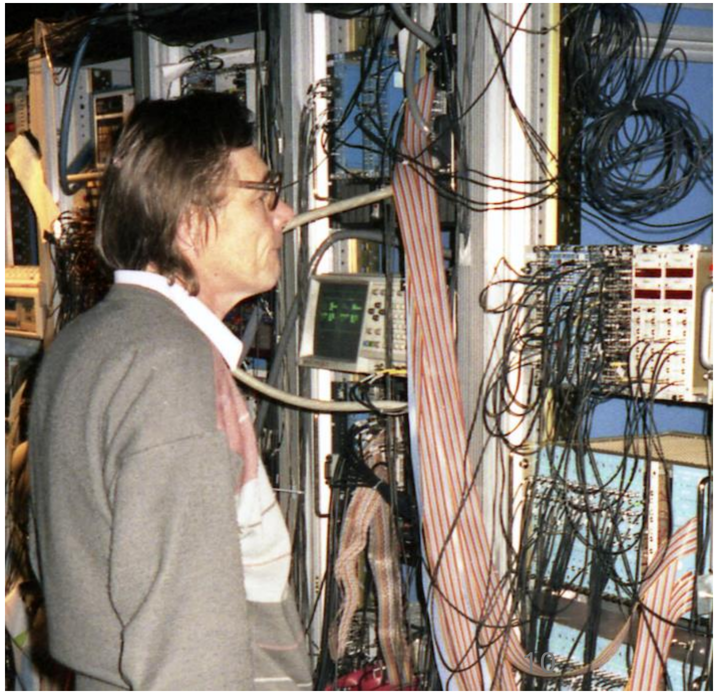
D. Michael
Caltech

reporting on work from E. Diehl. A. Hawthorne. D. Michael. S. Mikheyev. T. Montaruli. J. Musser. C. Okada. B. Pavesi. N Pignatano. F. Ronga

Sep. 7. 1993

Abstract

This is a summary of the work which has been done on analysis and simulation of upgoing muons for the 6-month run. The purpose of this document is to provide background information for a possible presentation of upgoing muon results at TAUP in September. 1993. Four different analyses of upgoing events have been extensively compared in order to check efficiency and backgrounds. Two different Monte Carlo analyses have been performed and used for understanding detector acceptance and to predict the expected number of events for the 6-month run. In addition. the detector acceptance has been checked using the data for downward going muons and good agreement is found with expectations from MC simulations. Careful comparisons for larger zenith angles have not yet been made. An analysis which combines the strongest features of the separate analyses has been made. For zenith angles less than about 50°. it is shown that the acceptance for the detector and this analysis for upgoing muons are known to at least 5% (the best estimate of the systematic uncertainty in the acceptance in this region is in fact 2%). For this analysis. it is estimated that

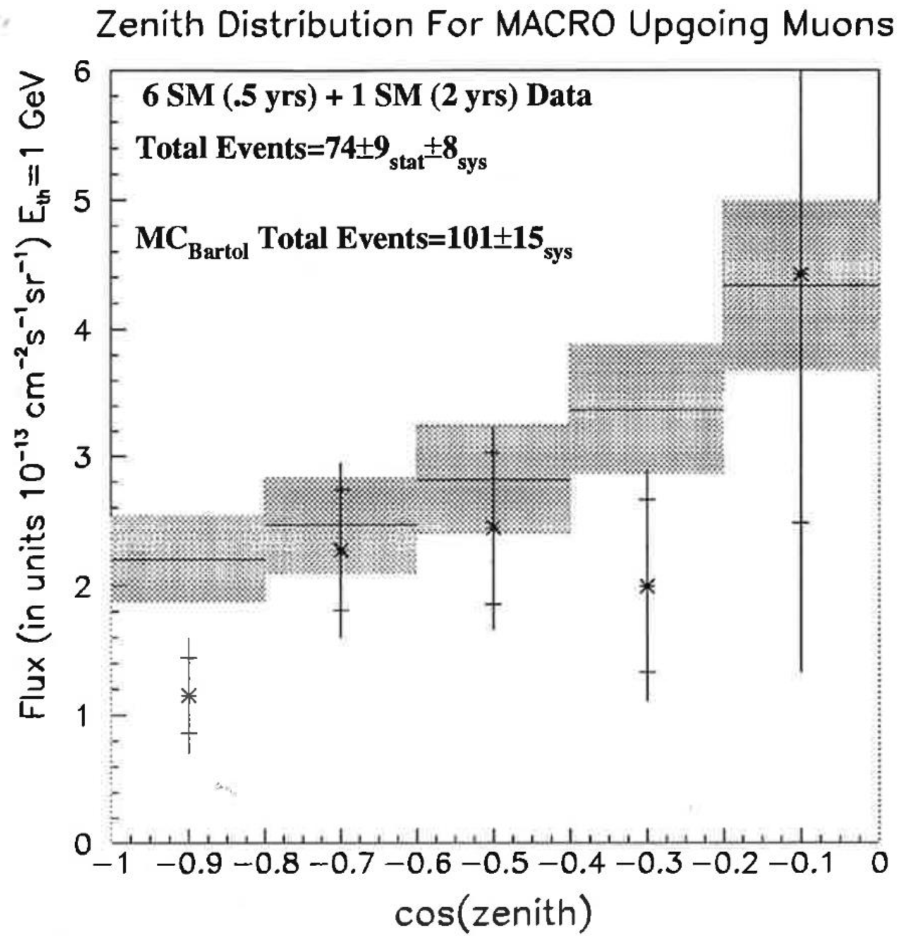


September 1994 WG memo => 1995 paper

Neutrino Telescope, Venice 1993
F. Ronga

Upgoing muons

- 45 detected
- 57 expected



Although this deficit gives good consistency with neutrino oscillation hypotheses suggested by contained-event analyses, it is also consistent with a no-oscillation hypothesis at the 90% confidence level.

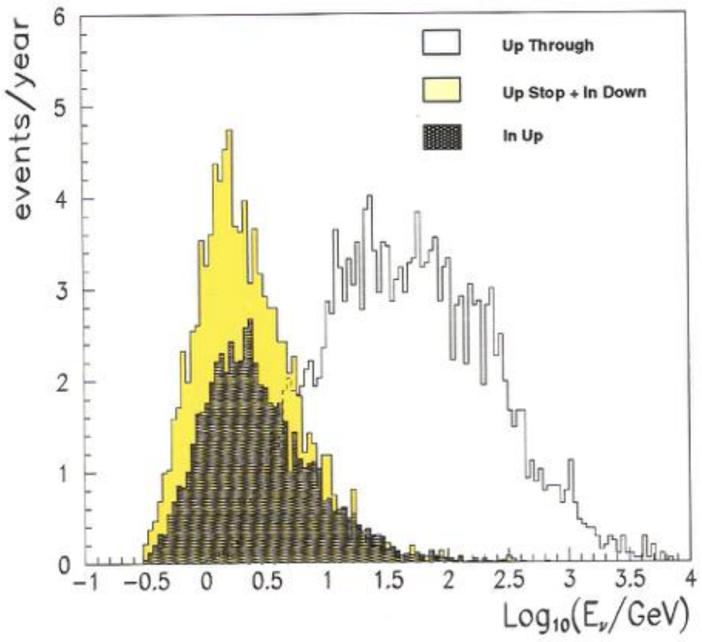
1994, ATTICO

Larger acceptance

Threefold ToF measurement

New topologies

Also lateral tracking



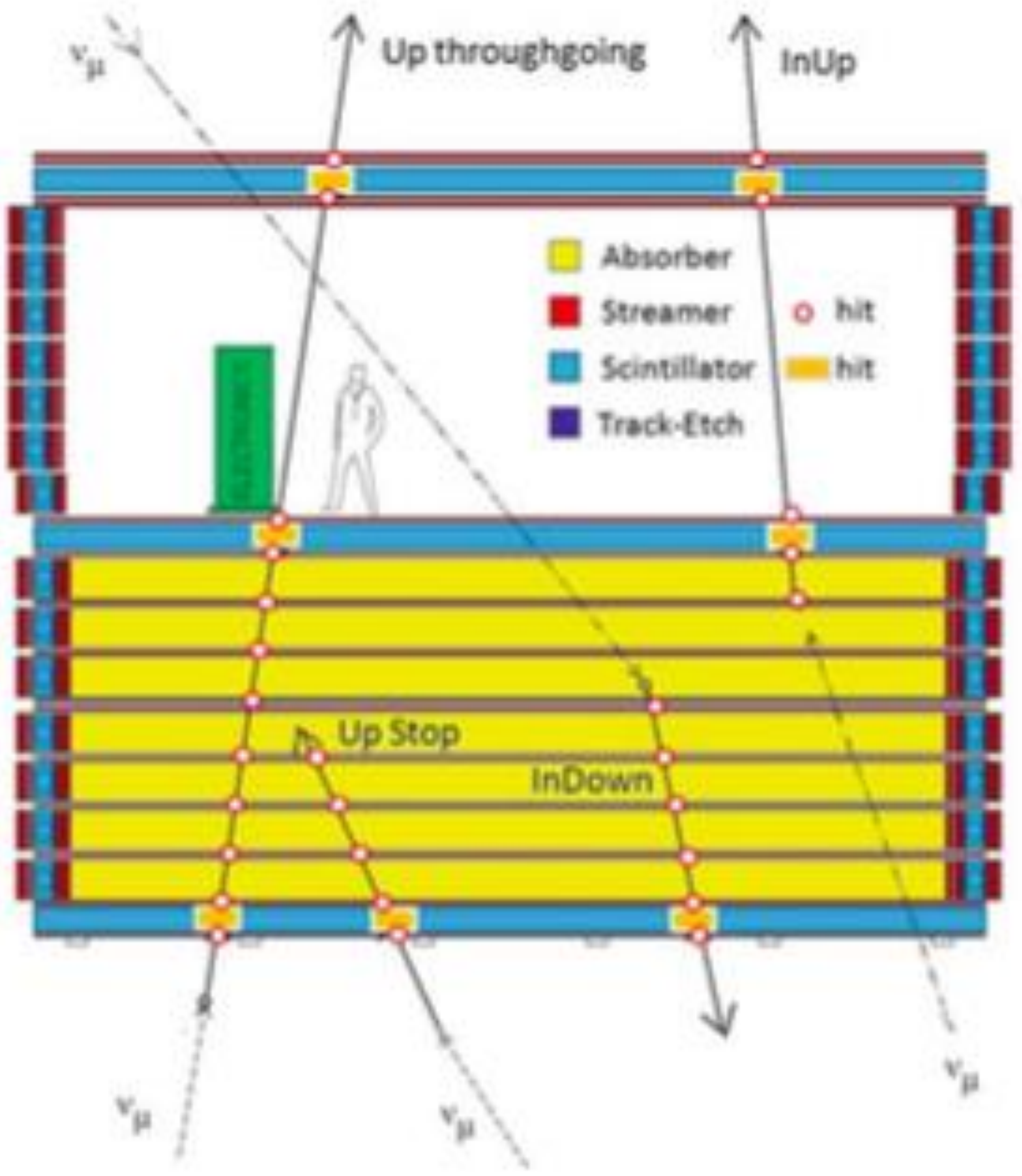


Fig. 11.16 Cross-sectional sketch of the Monopololes And Cosmic Ray Observatory (MACRO) detector and the different topologies of detected atmospheric neutrinos. At least two scintillator hits were needed to measure the ToF. The streamer hits allowed a precise track reconstruction

Some examples of strong data-analysis efforts

1996 – C. Okada

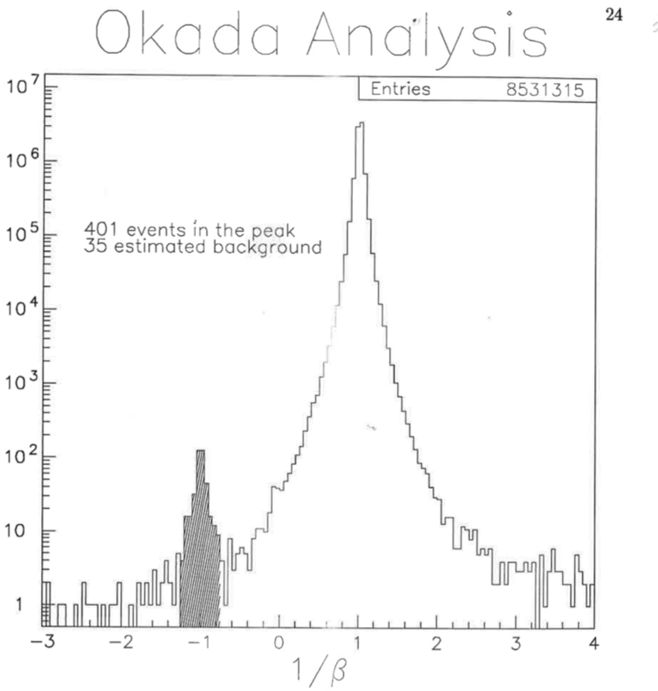


Figure 1.7: $1/\beta$ for the 'best' track in each event. The best track was selected by looking for 3 scintillator hit tracks, tracks which match the standard tracking well, or the track with the best χ^2.

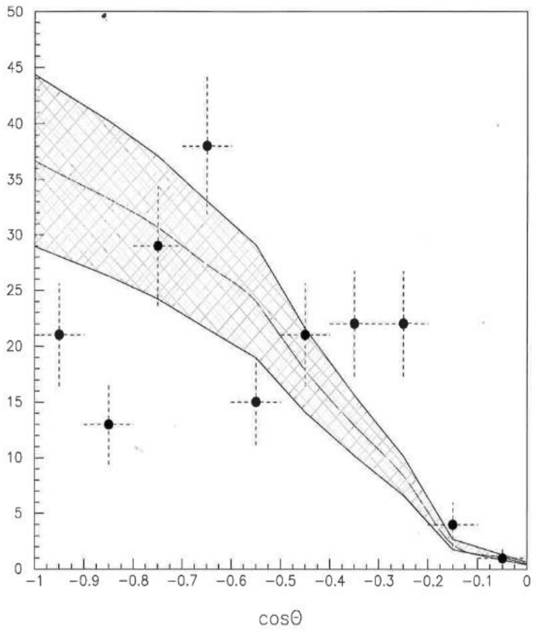


Figure 2: The zenith angle distribution for the data and Monte Carlo. Vertical muons are in the bins to the left of the plot while horizontal muons are to the right. The background has not been subtracted from the data. The shaded area for the Monte Carlo corresponds to a 21% systematic uncertainty.

1996 – A.P. Sanzgiri

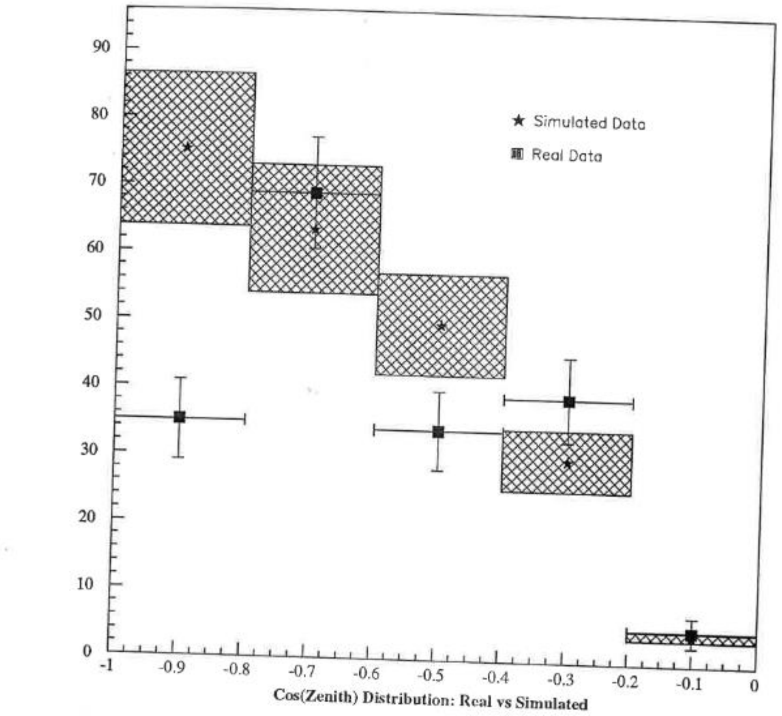
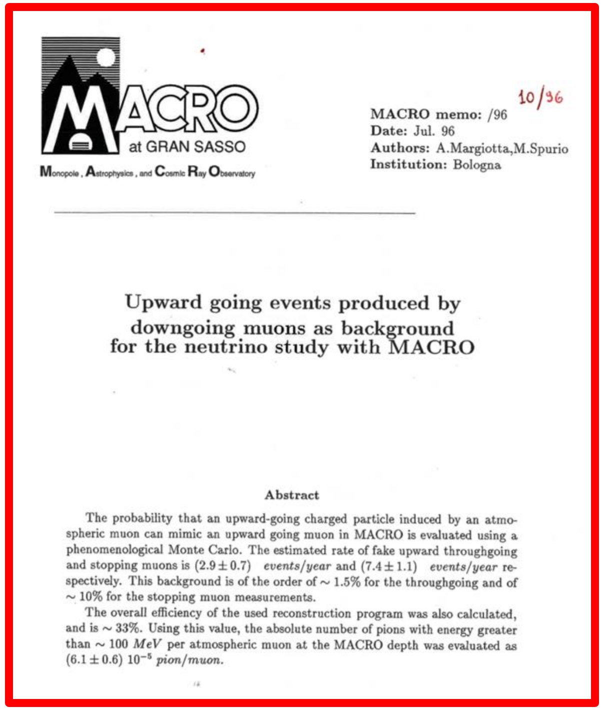


Figure 24: The zenith angle distribution of upgoing events in the real data as compared with the simulation. The real data is shown with statistical errors and the simulated data reflects the 15% uncertainty in the simulation.

July 1996, memo => Astrop. Physics 9 (1998) 1051117


MACRO at GRAN SASSO

Monopole, Astrophysics, and Cosmic Ray Observatory

10/96

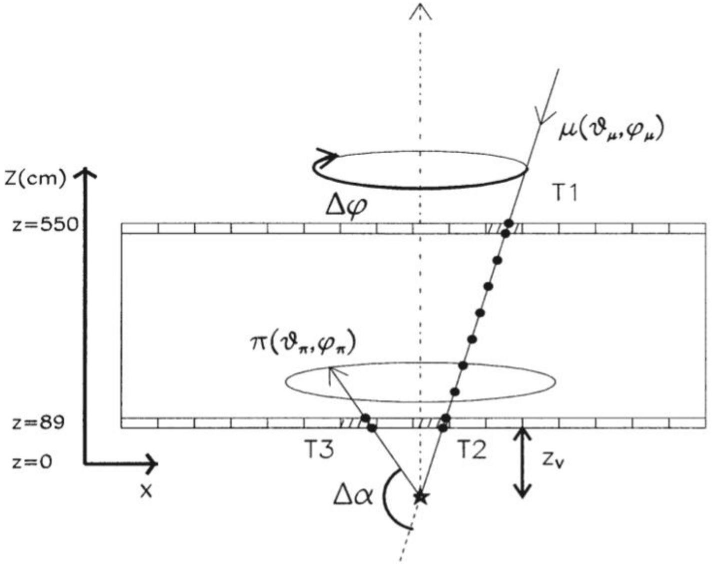
MACRO memo: /96
Date: Jul. 96
Authors: A.Margiotta,M.Spurio
Institution: Bologna

Upward going events produced by downgoing muons as background for the neutrino study with MACRO

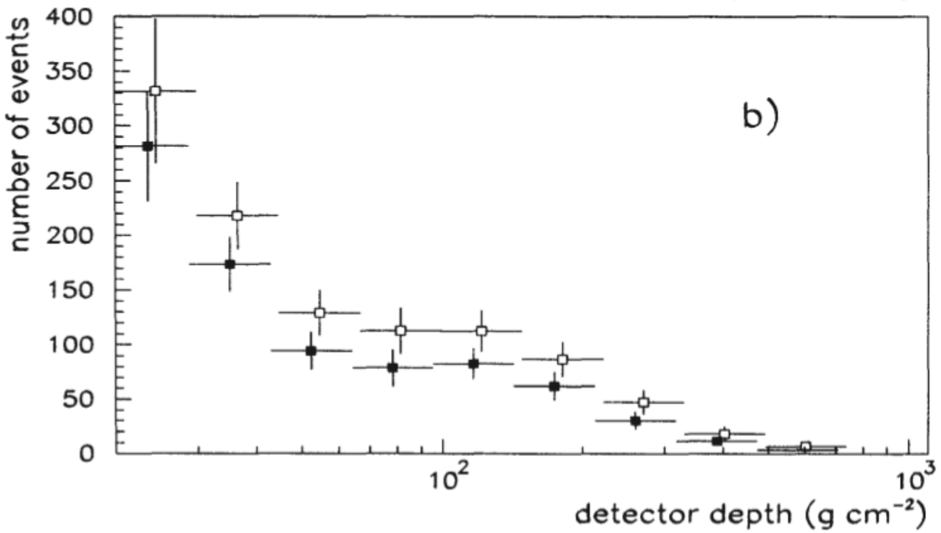
Abstract

The probability that an upward-going charged particle induced by an atmospheric muon can mimic an upward going muon in MACRO is evaluated using a phenomenological Monte Carlo. The estimated rate of fake upward throughgoing and stopping muons is (2.9 ± 0.7) *events/year* and (7.4 ± 1.1) *events/year* respectively. This background is of the order of ~ 1.5% for the throughgoing and of ~ 10% for the stopping muon measurements.

The overall efficiency of the used reconstruction program was also calculated, and is ~ 33%. Using this value, the absolute number of pions with energy greater than ~ 100 *MeV* per atmospheric muon at the MACRO depth was evaluated as $(6.1 \pm 0.6)\ 10^{-5}$ *pion/muon*.



To our knowledge, no experiment measuring the flux of atmospheric neutrinos using up-going muons (see references in [14]) has taken into account this background. In particular, shallower experiments for similar energy threshold should have a significant contamination from these events, because the average muon energy, $\overline{E}_\mu(h)$, and the corresponding pion yield, $Y_{\pi/\mu}$, decreases slowly with decreasing depth, while the total muon flux increases exponentially.



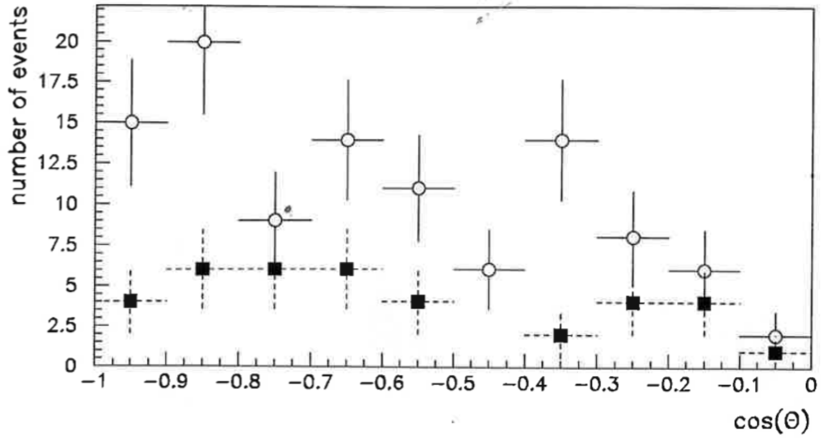


Figure 7: Zenith angle distribution for the fake throughgoing muons. Empty point:all the 105 events; full points: the 37 events with a crossed detector material depth greater than 200 $g\ cm^{-2}$.

Other examples of strong data-analysis efforts

1997, UpMu
Lecce group

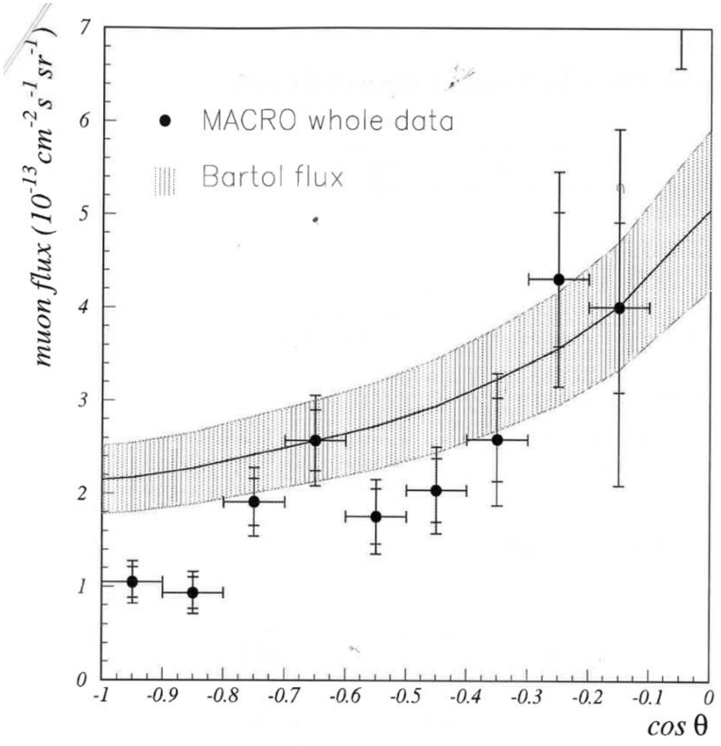


Figure 17: The expected Bartol flux is compared with the measured one for entire MACRO data sample (1 smod + 6 months + attico data). Statistical and systematical errors are reported for real data. The error for Bartol flux is 17 %. The sign of cos θ has been changed in order to get the flux standard plot.

1998, InUp
A. Surdo

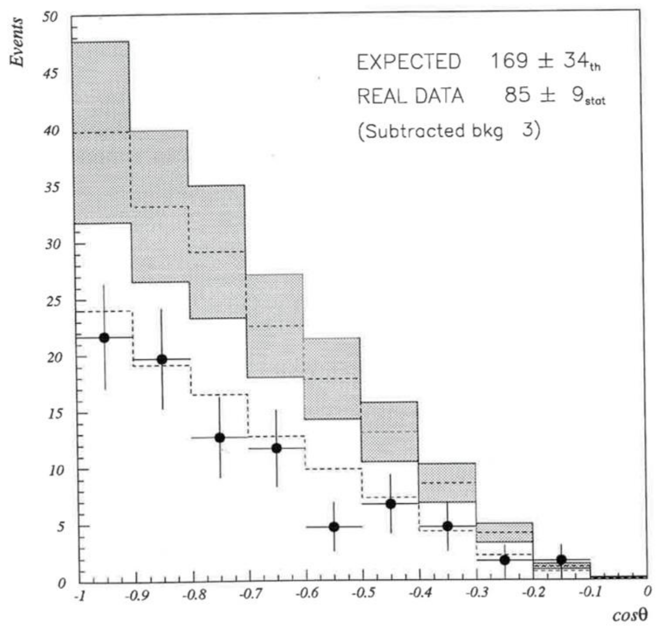


Figure 31: The $\cos\theta$ distribution expected on the basis of "configuration method" for the IUμ events with a reconstructed track is compared with the measured one. The dashed line refers to the Monte Carlo prediction assuming $\nu_\mu \to \nu_\tau$ oscillations with maximal mixing and $Deltam^2 = 5 \times 10^{-3}$ eV^2 Δm^2

1998, UpMu
F. Ronga, T. Montaruli

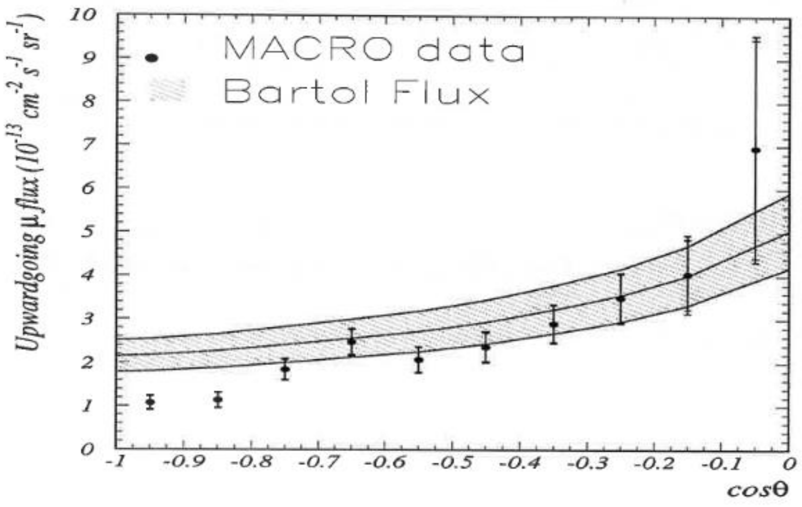


Figure 4: Angular distribution of the measured (circles) and expected (solid line) flux of upgoing muons with $E_\mu > 1$ GeV. Statistical error bars and the sum in quadrature of the statistical and systematic errors are shown.. Data until run 15499.

April 1998, memo

MACRO at GRAN SASSO

Monopole, Astrophysics, and Cosmic Ray Observatory

MACRO memo: 8/98
Date: Apr. 98
Authors: P.Cesaretti, M.Spurio
Institution: Bologna

Upward throughgoing muons with PHRASE

1 Introduction

This memo presents an analysis of upward throughgoing muons using only the PHRASE system. Data have been analyzed from 25/11/1994 to 3/11/1996 and from 31/7/1997 to 11/11/1997, corresponding to a total acquisition time of about 2.2 yr. In this period, $7.7 \cdot 10^6$ single muons crossing three scintillator layers were collected by the PHRASE system. This analysis is completely independent from the ones which have been executed so far (using ERP and the streamer tubes) because in this case only the PHRASE system of scintillators have been used. The aim was to check the standard analysis [1] which uses the ERP + streamer tube system, measuring also its efficiency. Moreover one can check possible and not understood systematic effects in the standard analysis which could alter the MACRO angular distribution of upgoing muons.

The main results of [1] are confirmed by this analysis. In particular, the measured number of events is smaller than the Monte Carlo prediction, and the distribution of the data as a function of zenith angle has the same unexpected shape reported by the standard analysis.

Energy Response Processor (ERP) was used for the ToF measurement (calibration by E. Diehl)

Same results using Pulse Height Recorder and Synchronous Encoder (PHRASE)

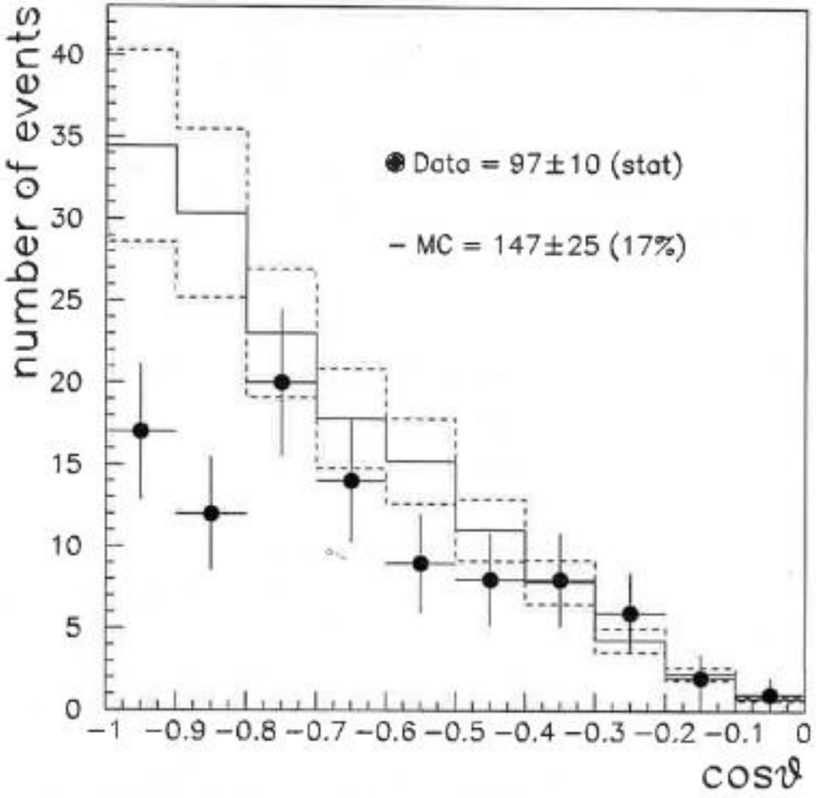


Figure 4: Angular distribution of the 97 PHRASE upgoing muons (circles). The solid line correspond to the Monte Carlo prediction; the dashed line indicates the quoted 17% theoretical error.

April 1998
Collaboration Meeting in Boston

There was much discussion about how to present the neutrino measurements in the summer conferences.

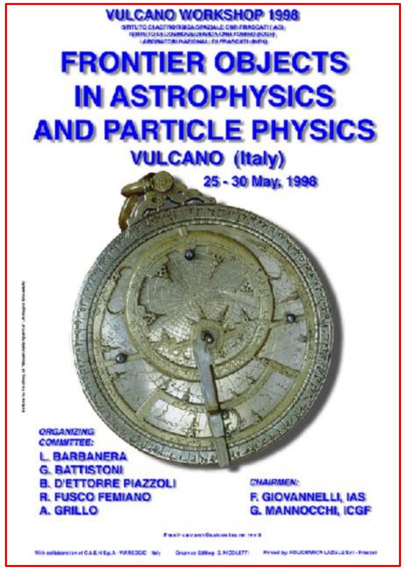
MACRO results were in disagreement with Kamiokande ones.

The reactor-based measurements (CHOOZ) cast doubt on electron-neutrino oscillation.

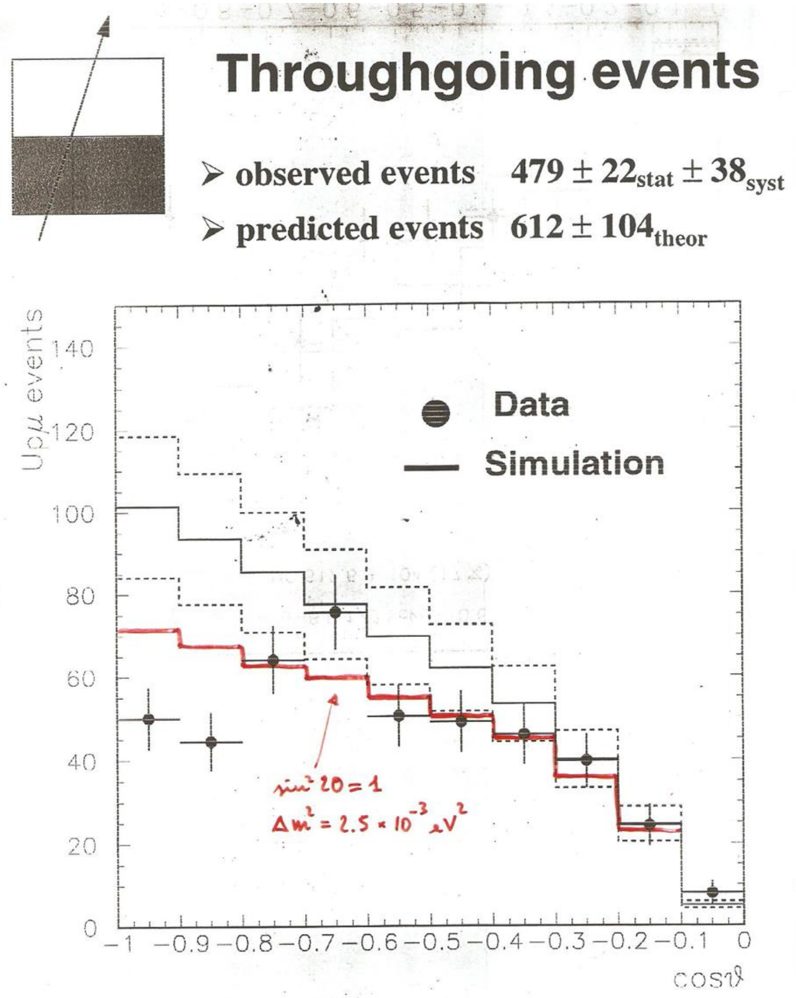
1998 – Boston Marathon

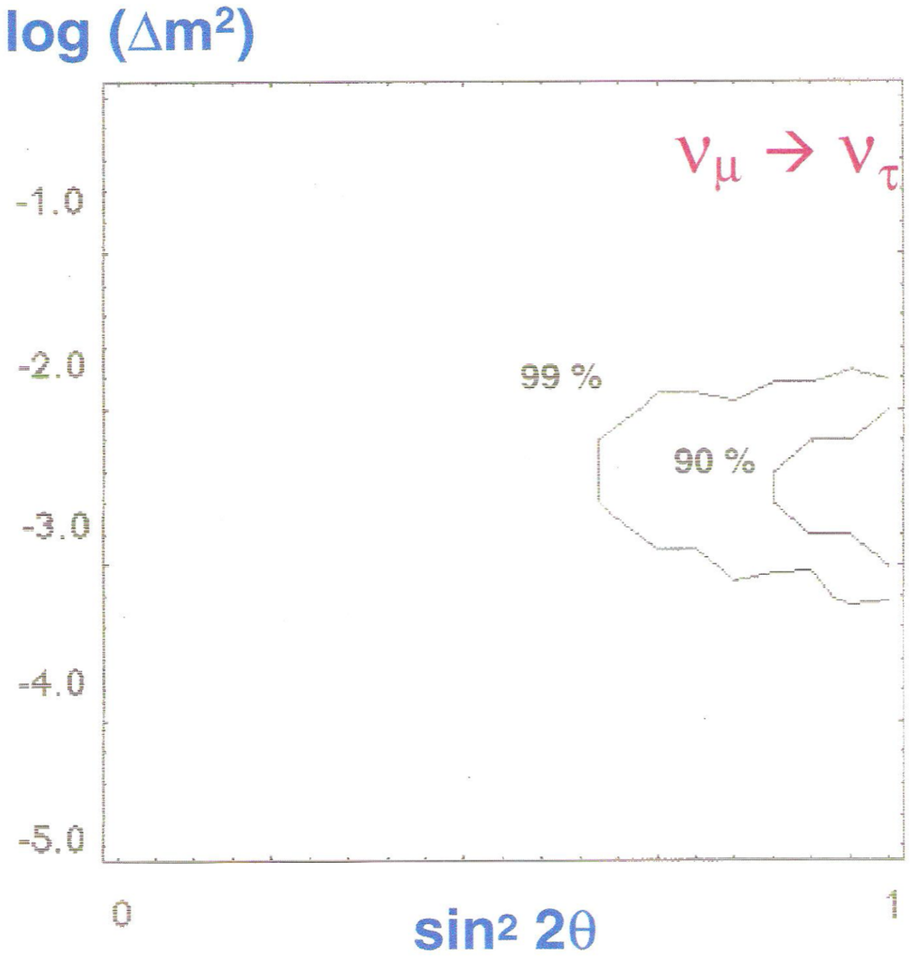
In the end, it was decided to show how the MACRO results were consistent with the oscillation hypothesis ($\nu_\mu \Rightarrow \nu_\tau$).

A week before Neutrino '98 at Takayama



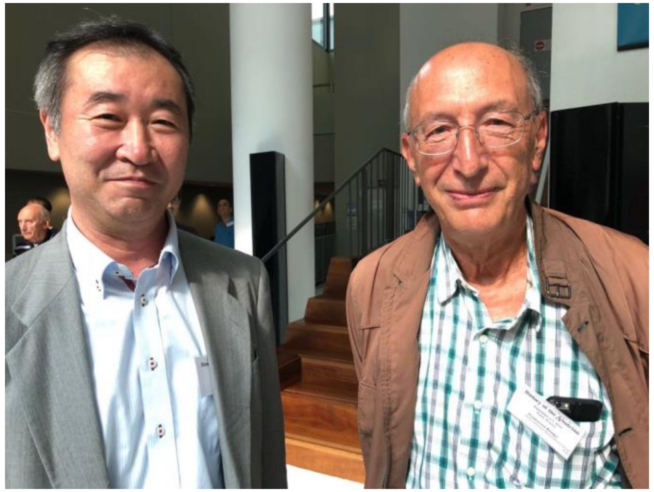
Measurement of Atmospheric Neutrino Induced Muon Flux with MACRO Detector

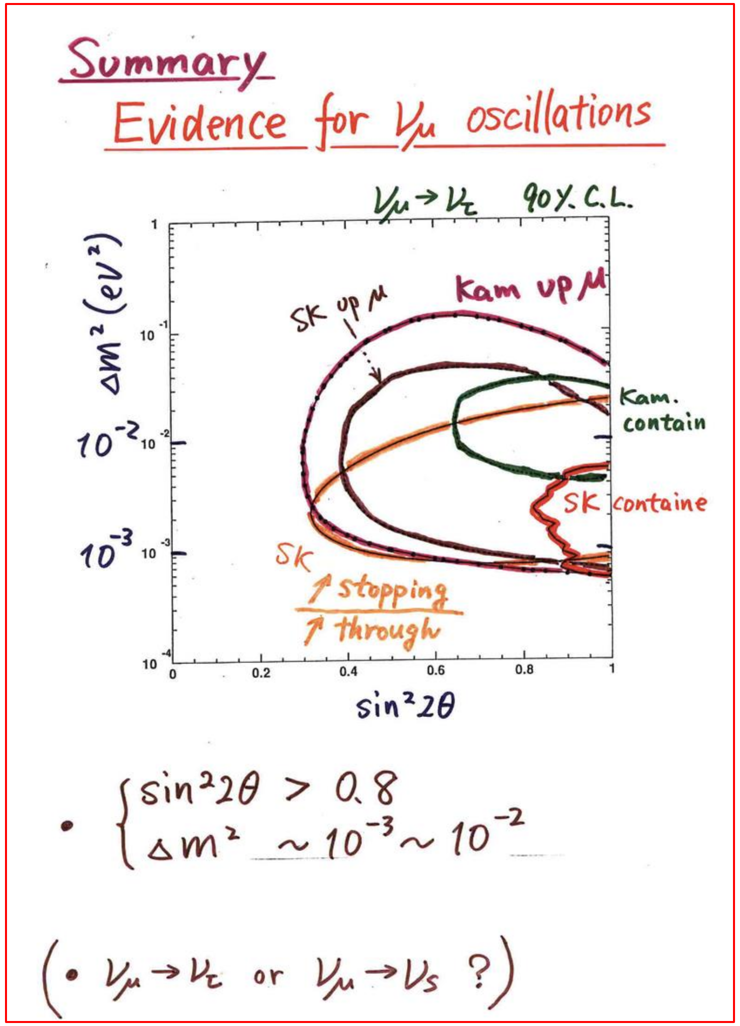


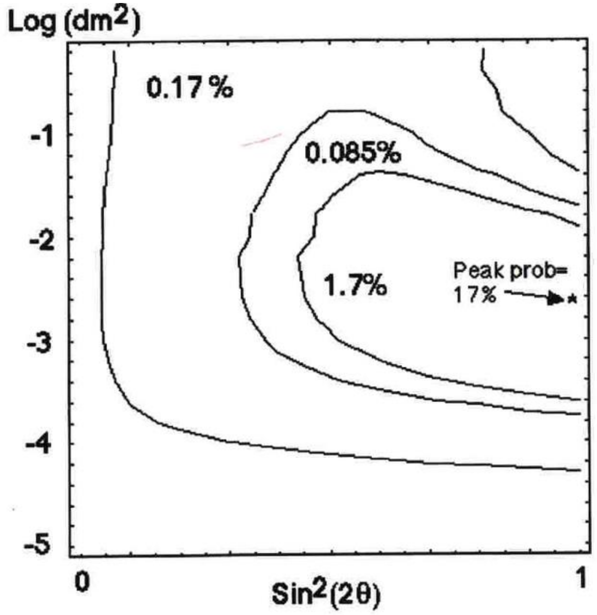


arxiv.org/abs/hep-ex/9809003

Takayama 1998

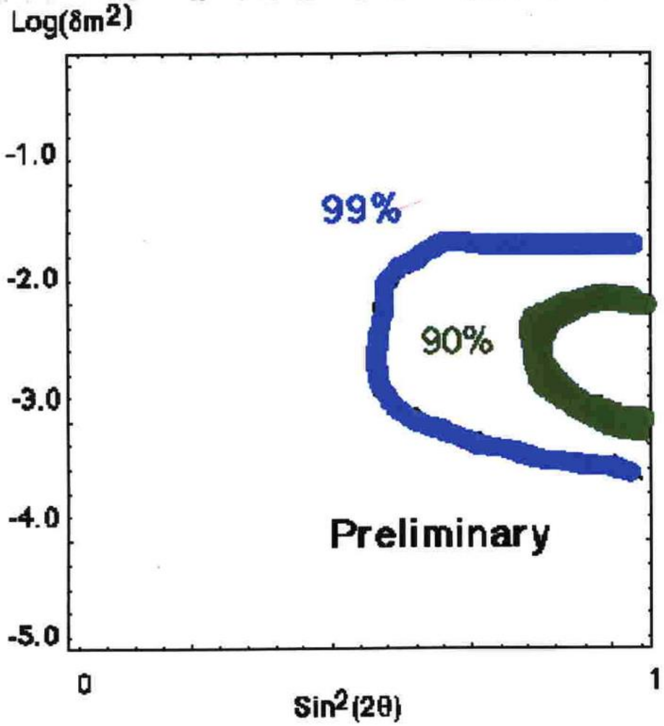






Equal-probability plot

SuperK claim confirmed by MACRO



Confidence regions

October 1998 - WG

MACRO Memo 14/98
(Updated version)
Measurement of the Atmospheric Neutrino-induced Muon Flux Using MACRO

P. Bernardini[1], T. Montaruli[2], F. Ronga[3], M. Spurio[4], A. Surdo[1]

1. Università and INFN, Lecce
2. INFN, Bari
3. INFN, Laboratori Nazionali di Frascati
4. Università and INFN, Bologna

October 20, 1998

Abstract

We present a measurement of the flux of atmospheric neutrino-induced muons using the MACRO detector. Three different event topologies are detected: externally produced upward-going (upgoing) muons coming from neutrinos of average peak energy of $\langle E_\nu \rangle \sim 100$ GeV; internally produced upgoing events ($\langle E_\nu \rangle \sim 4$ GeV); externally produced upgoing muons stopping in the detector or internally produced downgoing events ($\langle E_\nu \rangle \sim 4$ GeV).

For the first category of events the ratio of the number of observed to expected events integrated over nadir angles is $0.74 \pm 0.036_{stat} \pm 0.046_{syst} \pm 0.13_{theor}$. The shape of the observed zenith distribution does not fit well the expected one not considering ν oscillations, giving a maximum χ^2 probability of only 0.1%. The acceptance of the detector has been extensively studied using downgoing muons, independent analyses and Monte Carlo simulations. The systematic uncertainties cannot be the source of the discrepancies between the data and the expectation.

1

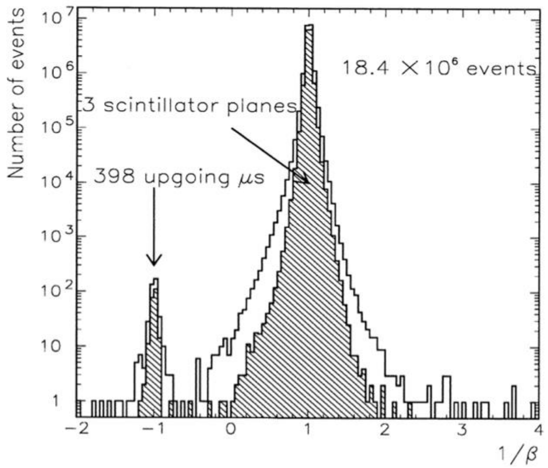


Fig. 1. Distribution of $1/\beta$ for all muons in the data set taken with the full detector apparatus. A clear peak of upgoing muons is evident centered on $1/\beta = -1$. The widths of the distributions for upgoing and downgoing muons are consistent. The shaded part of the distribution is for the subset of events where three scintillator layers were hit.

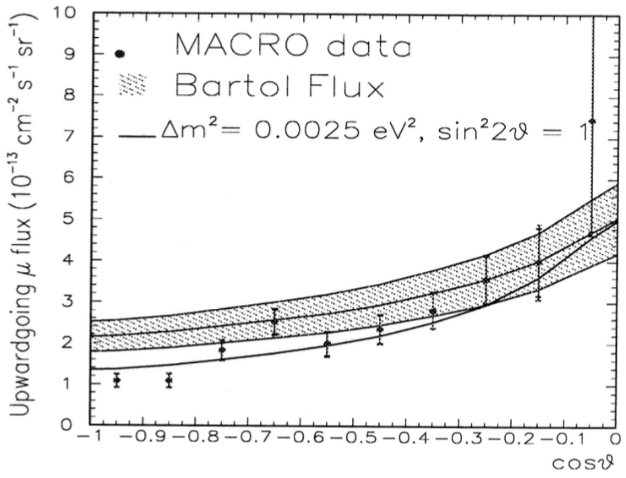


Fig. 2. Zenith distribution of flux of upgoing muons with energy greater than 1 GeV for data and Monte Carlo for the combined MACRO data. The solid curve shows the expectation for no oscillations and the shaded region shows the uncertainty in the expectation. The dashed line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

1998 paper

27 August 1998
PHYSICS LETTERS B
ELSEVIER
Physics Letters B 434 (1998) 451–457

Measurement of the atmospheric neutrino-induced upgoing muon flux using MACRO

MACRO collaboration

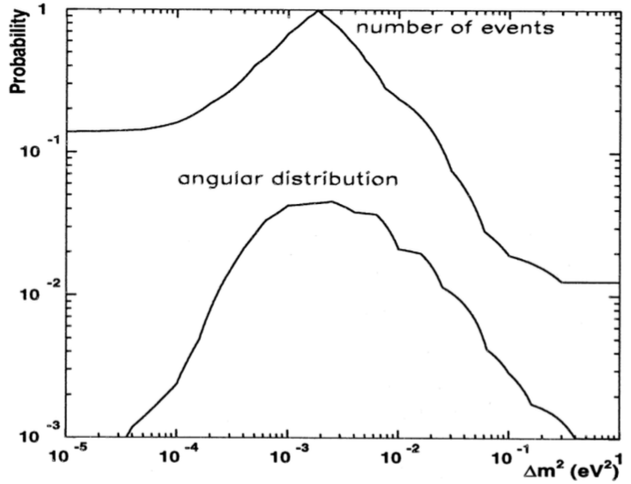


Fig. 3. Probabilities for obtaining the observed MACRO results on upgoing muons for $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2 2\theta = 1.0$ and for Δm^2 as shown. For the number of events, the curve shows the probability of observing a number of events which differs from the expectation by at least as much as the MACRO data for a given value of Δm^2. For the angular distribution, the curve shows the probability to observe a distribution which is at least as unlike the expectation based on a χ^2 comparison of the shape of the data as a function of zenith angle.

$$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$$

ELSEVIER
6 April 2000
PHYSICS LETTERS B
Physics Letters B 478 (2000) 5–13

Low energy atmospheric muon neutrinos in MACRO

MACRO Collaboration

2000 paper

Corresponding: M. Spurio

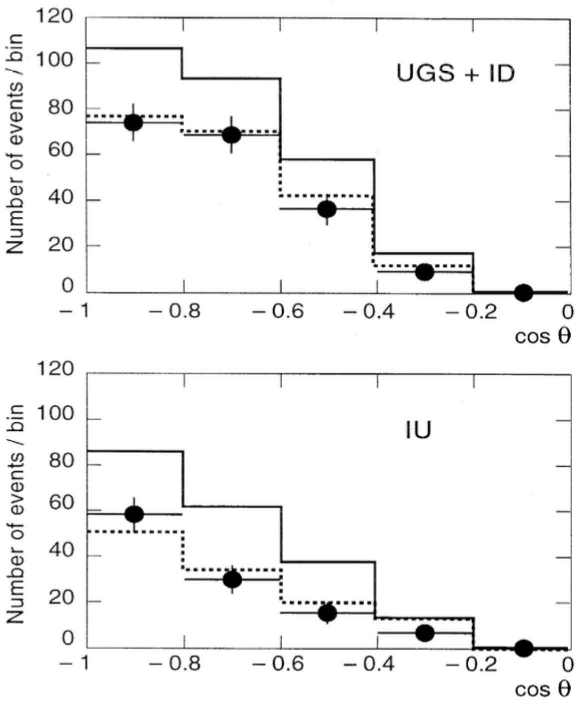


Fig. 4. Measured distributions in the cosine of the zenith angle Θ for the (a) ID+UGS and (b) IU events (black points with error bars). The solid lines are the Monte Carlo predictions assuming no oscillations. The dashed lines are the expectations for $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and maximal mixing.

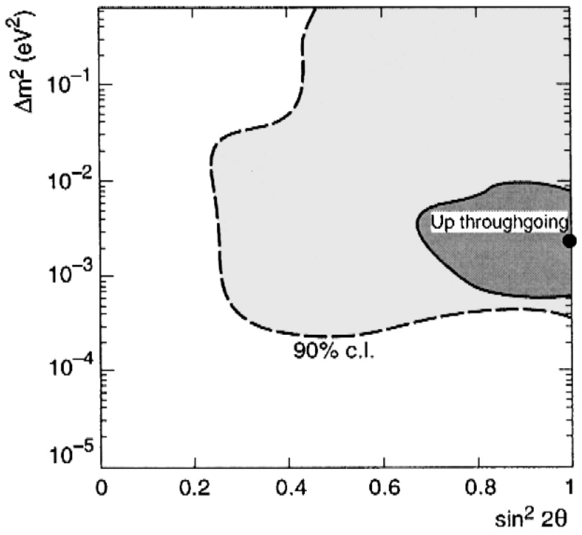


Fig. 6. Allowed contours at 90% C.L. for $\nu_\mu \to \nu_\tau$ oscillations obtained by combining the low energy neutrino events (IU and ID+UGS) using the prescription of [16]. The 90% C.L. contour and the best fit point from our high-energy analysis [5] is also shown as a solid line.

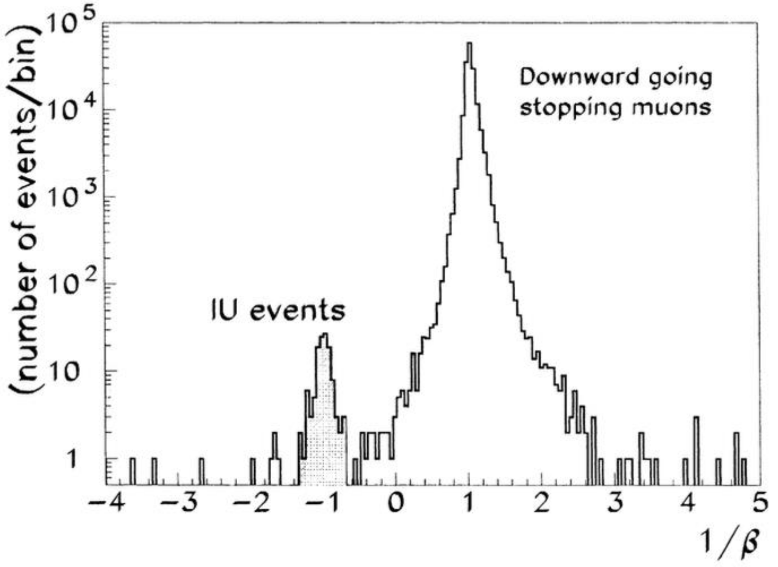


Fig. 3. The $1/\beta$ distribution of partially-contained events after all software cuts. 121 events are in the IU event signal region, $-1.3 < 1/\beta < -0.7$, with 5 estimated background events.

$$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$$

27 September 2001

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 517 (2001) 59–66

www.elsevier.com/locate/npe

Matter effects in upward-going muons and sterile neutrino oscillations

MACRO Collaboration

2001 paper

Corresponding: F. Ronga

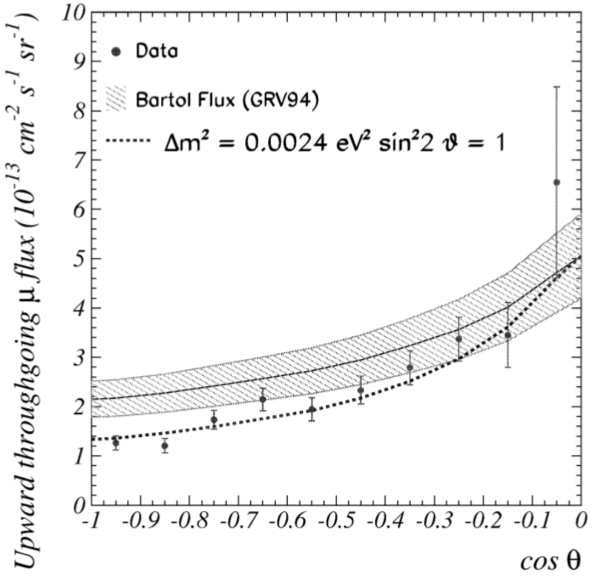


Fig. 1. Zenith distribution of the flux of up-going muons with energy greater than 1 GeV for the combined MACRO data. The shaded region shows the expectation for no oscillations with the 17% normalization uncertainty. The lower line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0024\ \text{eV}^2$.

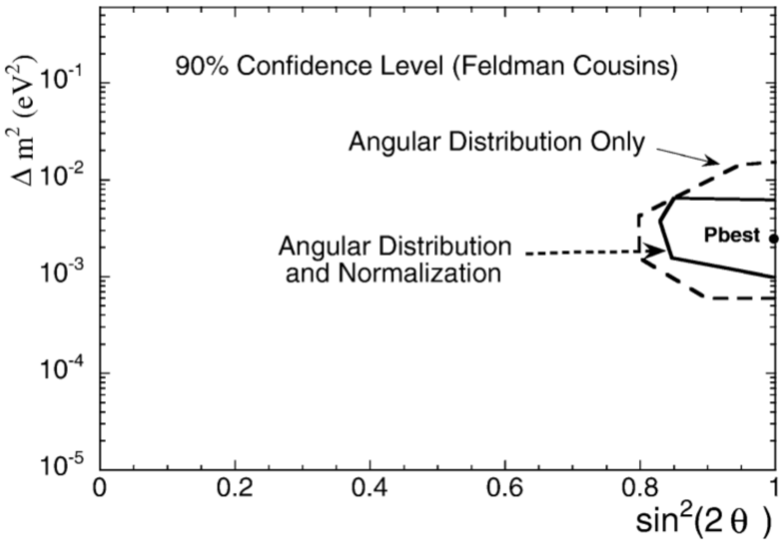


Fig. 2. The MACRO 90% confidence level regions computed using the angular distribution only (dashed line) and the angular distribution combined with the normalization (continuous line).

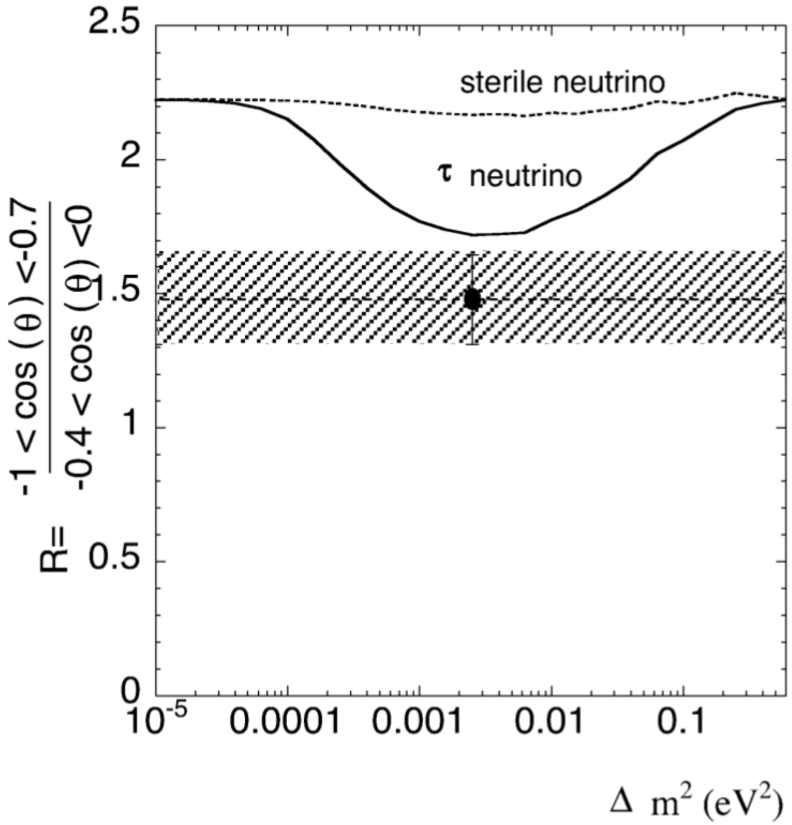


Fig. 4. The ratio between the data in two bins (dashed line) and the comparison with the ν_s and ν_τ oscillations with $\sin^2 2\theta = 1$. The error bar includes statistical and systematical error.

$$\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$$

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PHYSICS LETTERS B

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Atmospheric neutrino oscillations from upward throughgoing muon multiple scattering in MACRO

2003 paper

Corresponding: E. Scapparone, M. Sioli

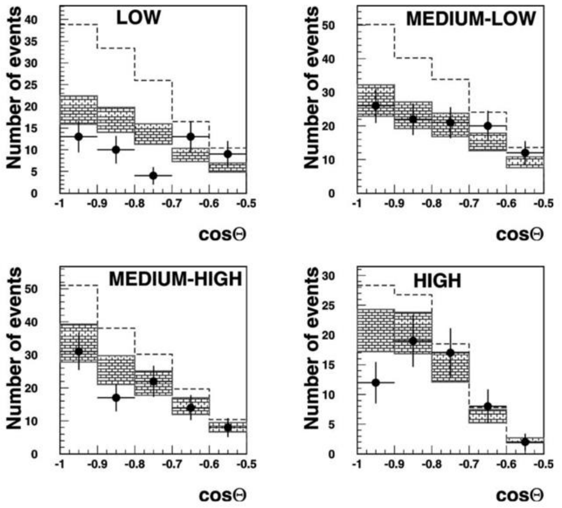


Fig. 4. Number of events versus the cosine of the zenith angle Θ for four energy ranges. Black points are the real data, dotted line is the Monte Carlo simulation, assuming no oscillation, and dotted boxes are the Monte Carlo expectation with $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$, including a 17% error.

$$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$$

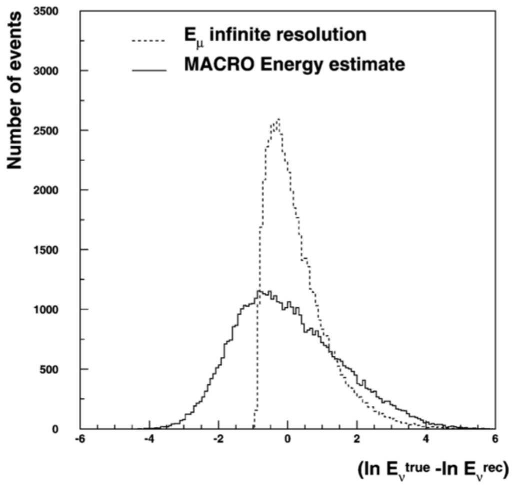


Fig. 3. Neutrino energy resolution that can be obtained with an ideal residual muon energy resolution (dotted line) and with the MACRO energy estimate (continuous line).

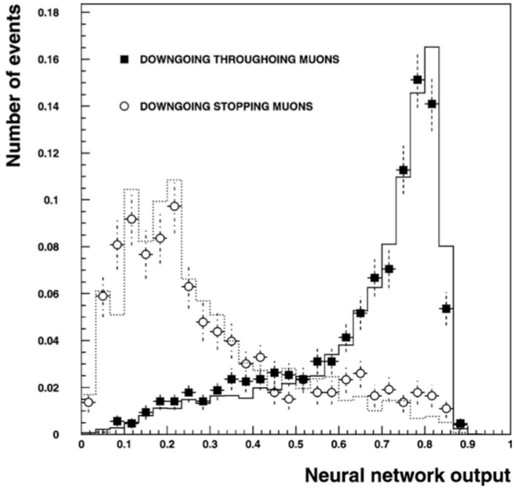


Fig. 2. Neural network (NN) output for down-throughgoing muons: real data (black squares) and Monte Carlo expectations (continuous line). NN output for downward going stopping muons: real data (empty circle) and Monte Carlo expectations (dotted line).

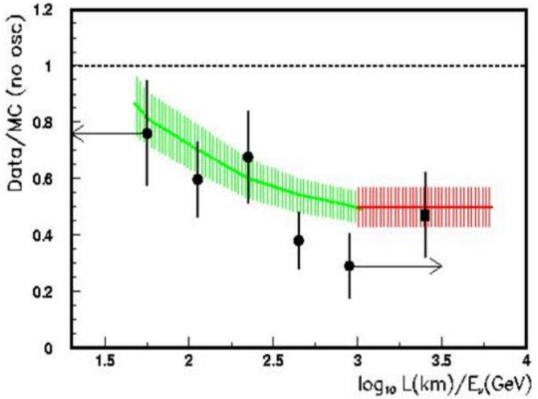


Fig. 5. Ratio (Data/MC) as a function of the estimated L_ν/E_ν for the MACRO upward throughgoing muon sample. The black circles are the real data over the MC (no oscillation), the solid line is the MC assuming $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and $\sin^2 2\theta = 1$ over the MC with no oscillation. The shaded region represents the MC uncertainties. The last point (empty circle) is obtained from semicontained upward going muons.

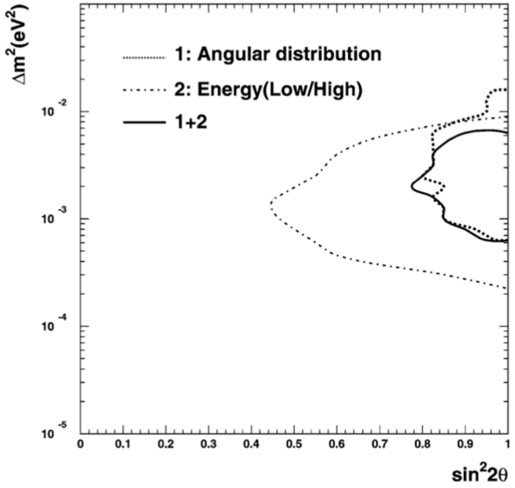


Fig. 7. 90% C.L. allowed region in the $(\Delta m^2, \sin^2 2\theta)$ plane for $\nu_\mu \to \nu_\tau$ oscillations, obtained with different data samples.

Eur. Phys. J. C 36, 323–339 (2004)
Digital Object Identifier (DOI) 10.1140/epjc/s2004-01951-9
THE EUROPEAN PHYSICAL JOURNAL C

Measurements of atmospheric muon neutrino oscillations, global analysis of the data collected with MACRO detector

The MACRO Collaboration

2004 paper

Corresponding: P. Bernardini, T. Montaruli

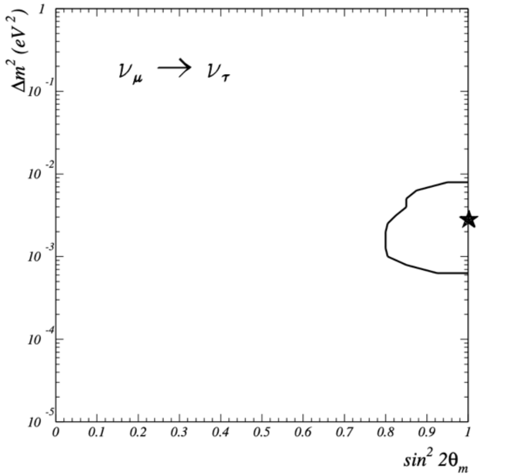


Fig. 12. The 90% c. l. region computed combining the angular distribution of *UpThrough* events, the low energy topologies and the high and low energy subsamples of *UpThrough* events. The star indicates the highest probability point in the physical region

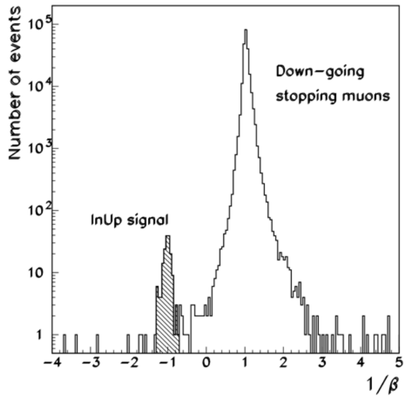
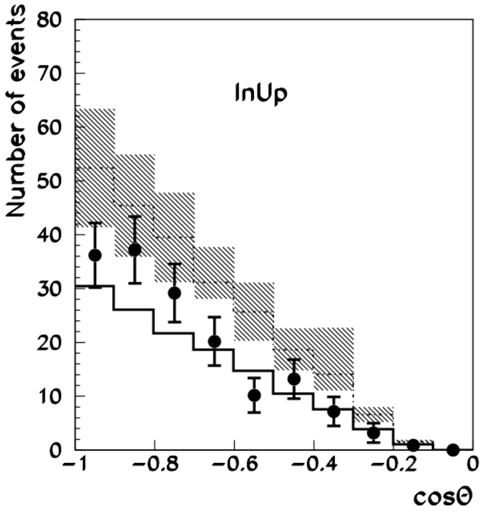
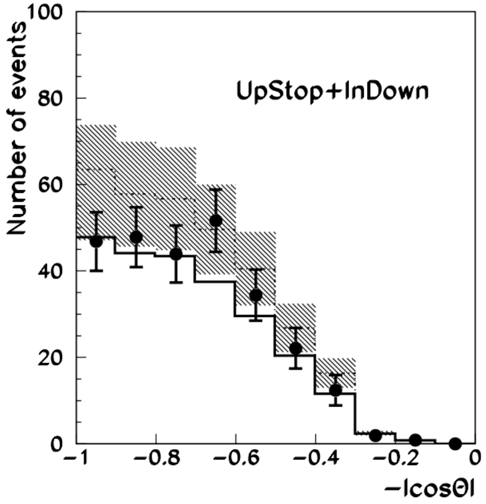


Fig. 9. The $1/\beta$ distribution of partially-contained events. The peak at $1/\beta \sim +1$ is due to downward-going muons stopping in the apparatus





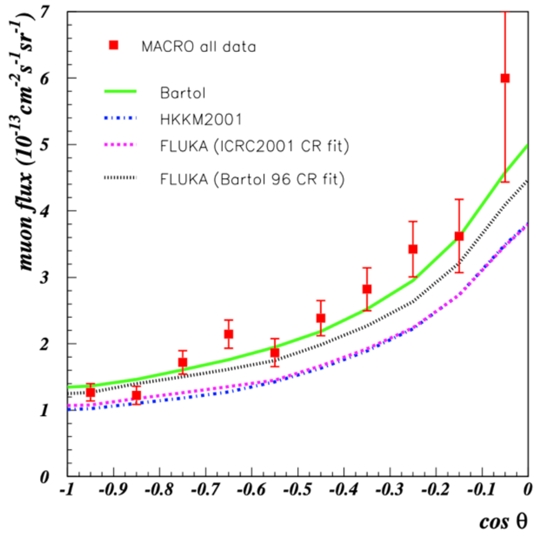
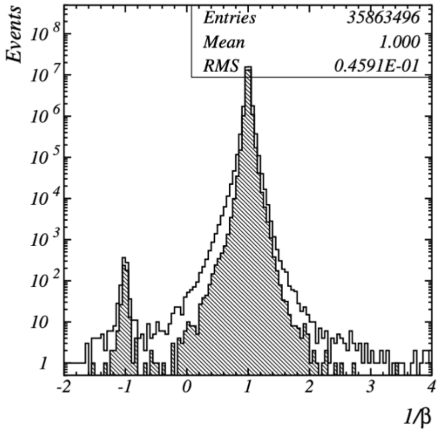
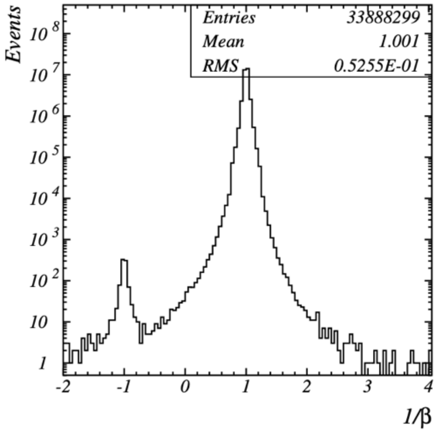


Fig. 4. Comparison between the measured angular distribution of the *UpThrough* muon flux and the MC predictions assuming ν-oscillations with the MACRO parameters. The solid curve indicates the Bartol flux [31], the dashed curve is for the FLUKA flux [34] fitted to the new CR measurements [37], the dotted curve is again the FLUKA flux with the fit in [31], and the dash-dotted line is for the HKKM-2001 flux [35]

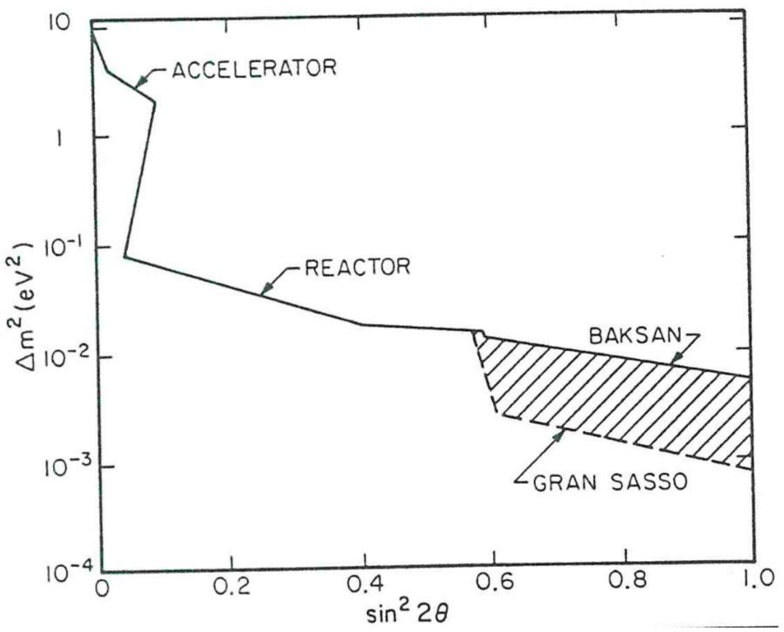




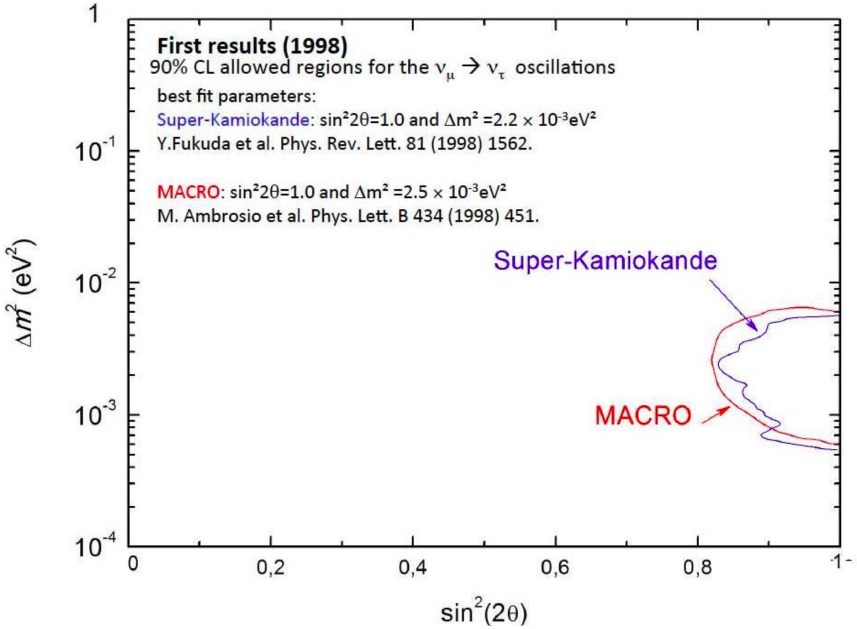
$$\Delta m^2 = 2.3 \times 10^{-3}\ eV^2$$

MACRO neutrino papers (not only oscillations)	Publication year	WOS references
Measurement of the atmospheric neutrino-induced upgoing muon flux using MACRO	1998	388
Matter effects in upward-going muons and sterile neutrino oscillations	2001	202
Limits on dark matter WIMPs using upward-going muons in the MACRO detector	1999	181
Measurements of atmospheric muon neutrino oscillations, global analysis of the data collected with MACRO detector	2004	137
Atmospheric neutrino oscillations from upward throughgoing muon multiple scattering in MACRO	2003	118
Atmospheric neutrino flux measurement using upgoing muons	1995	101
Low energy atmospheric muon neutrinos in MACRO	2000	98
Neutrino astronomy with the MACRO detector	2001	75
The observation of up-going charged particles produced by high energy muons in underground detectors	1998	45
Search for diffuse neutrino flux from astrophysical sources with MACRO	2003	36

1984 MACRO proposal



1998 SK/MACRO papers



2004 MACRO paper

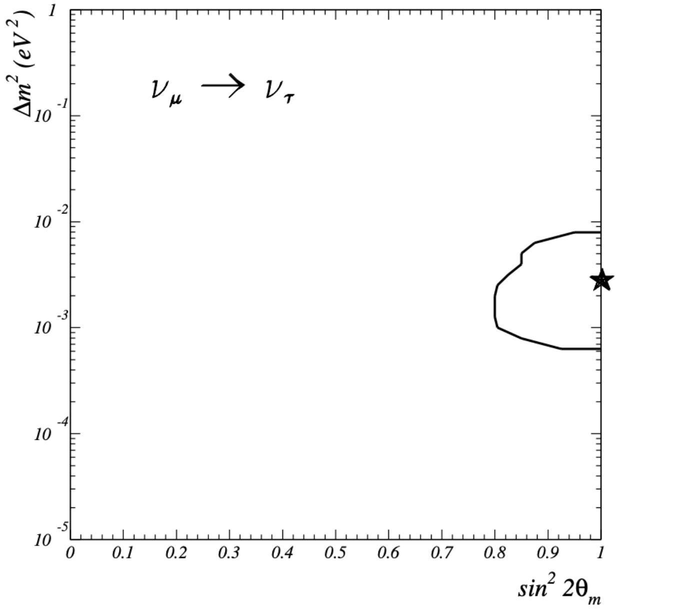
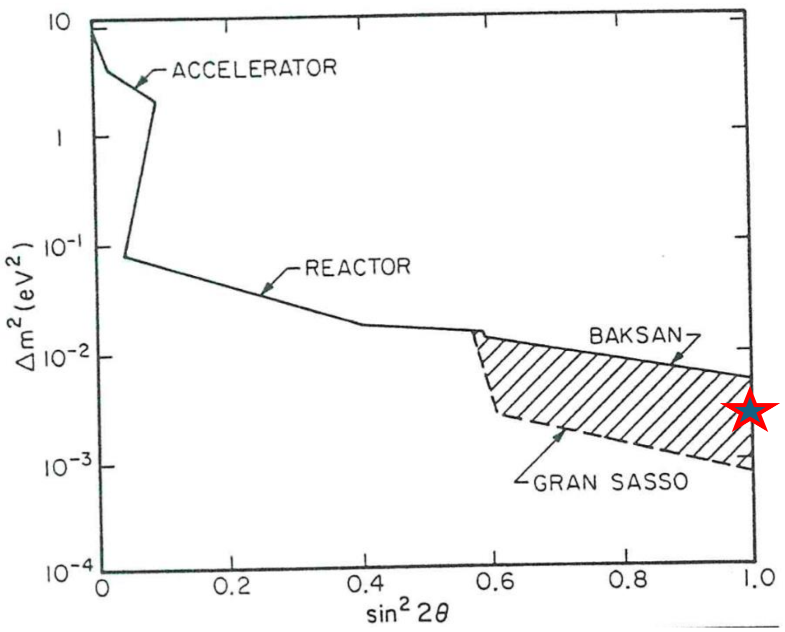


Fig. 12. The 90% c. l. region computed combining the angular distribution of *UpThrough* events, the low energy topologies and the high and low energy subsamples of *UpThrough* events. The star indicates the highest probability point in the physical region

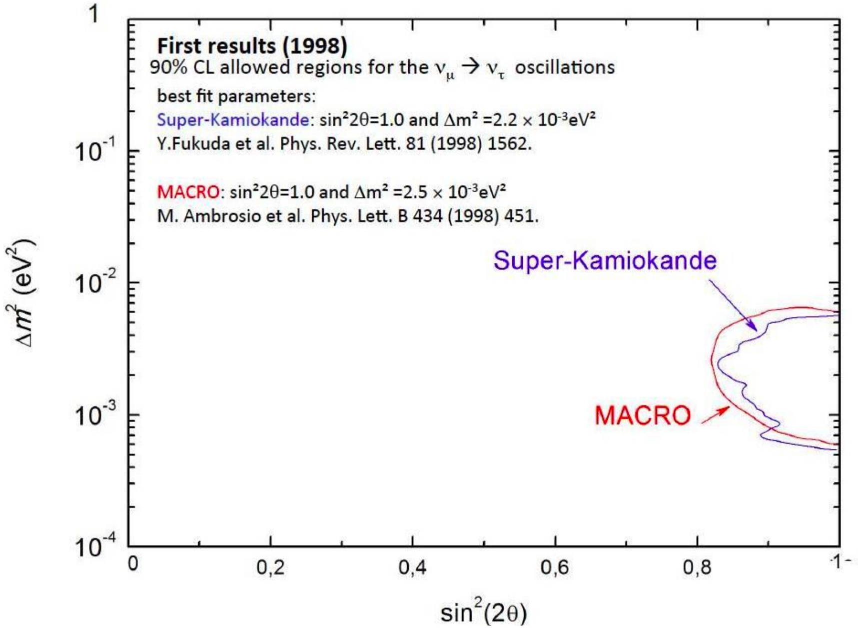
PDG 2024 – Δm^2_{32}

VALUE (10^{-3} eV^2)	
−2.529±0.029 OUR FIT	Assuming inverted ordering
2.455±0.028 OUR FIT	Assuming normal ordering

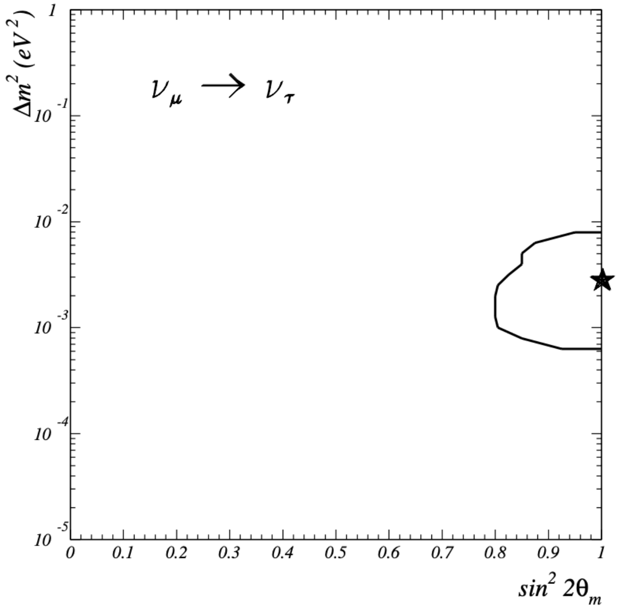
1984 MACRO proposal



1998 SK/MACRO papers



2004 MACRO paper



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PDG 2024 – Δm^2_{32}

VALUE (10^{-3} eV^2)	
−2.529±0.029 OUR FIT	Assuming inverted ordering
2.455±0.028 OUR FIT	Assuming normal ordering

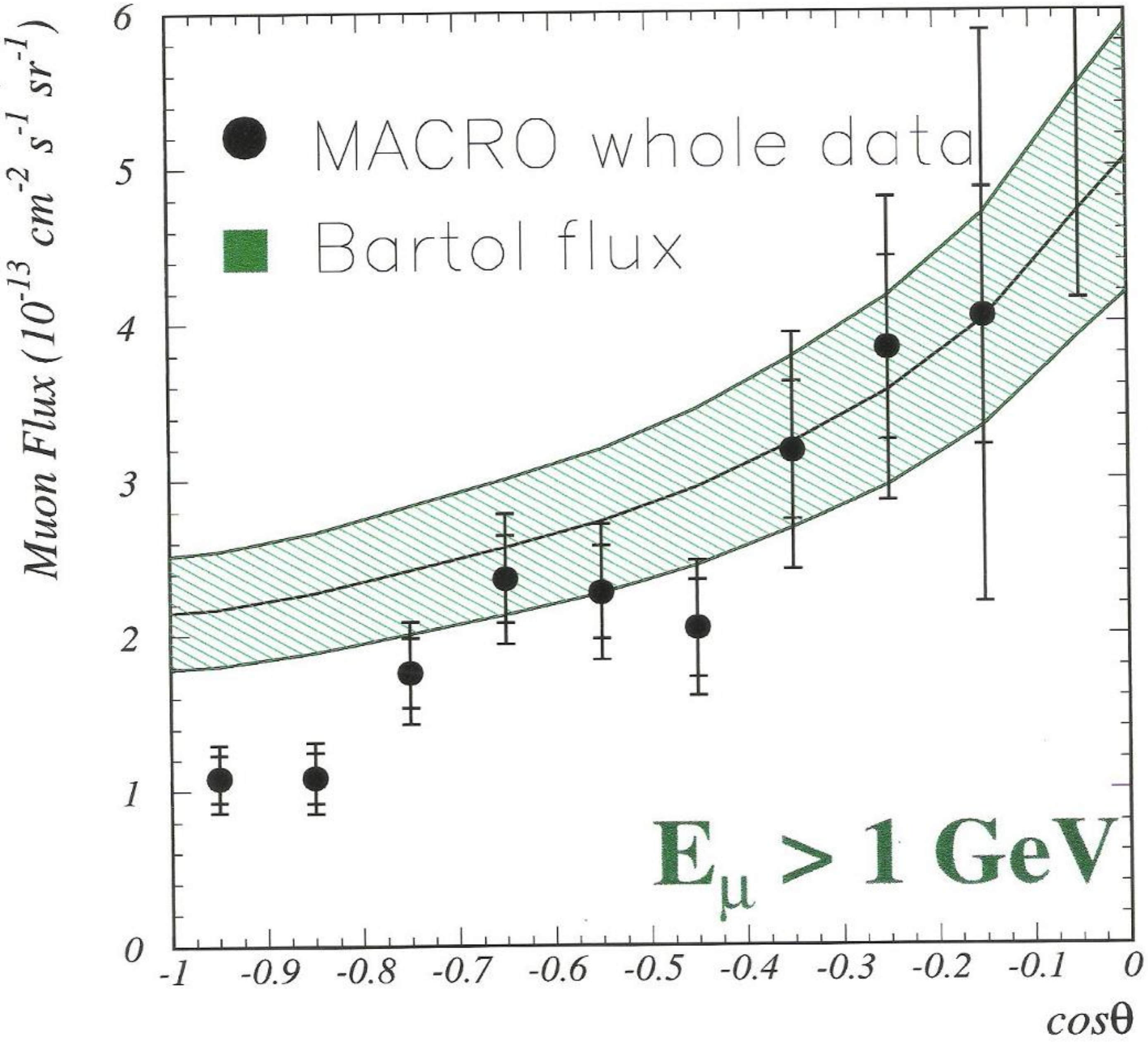
BACKUP

Takaaki Kajita
Nobel Prize lecture, 2015

MACRO was a large underground detector which was able to measure upward-going muons as well as partially contained neutrino events. This experiment also observed a zenith angle dependent deficit of both upward-going muons [15] and partially-contained ν_μ events [16]. The results from these experiments were completely consistent with those from Super-Kamiokande and consequently, neutrino oscillations were quickly accepted by the neutrino physics community.

15. M. Ambrosio, *et al.* (MACRO collaboration), *Phys. Lett.* B **434** (1998) 451–457.
16. M. Ambrosio, *et al.* (MACRO collaboration), *Phys. Lett.* B **478** (2000) 5–13.

Vulcano, 1998



ATMOSPHERIC NEUTRINO OSCILLATIONS IN MACRO

GIORGIO GIACOMELLI and MIRIAM GIORGINI
Dept. of Physics, University of Bologna, V.le C. Berti Pichat 6/2
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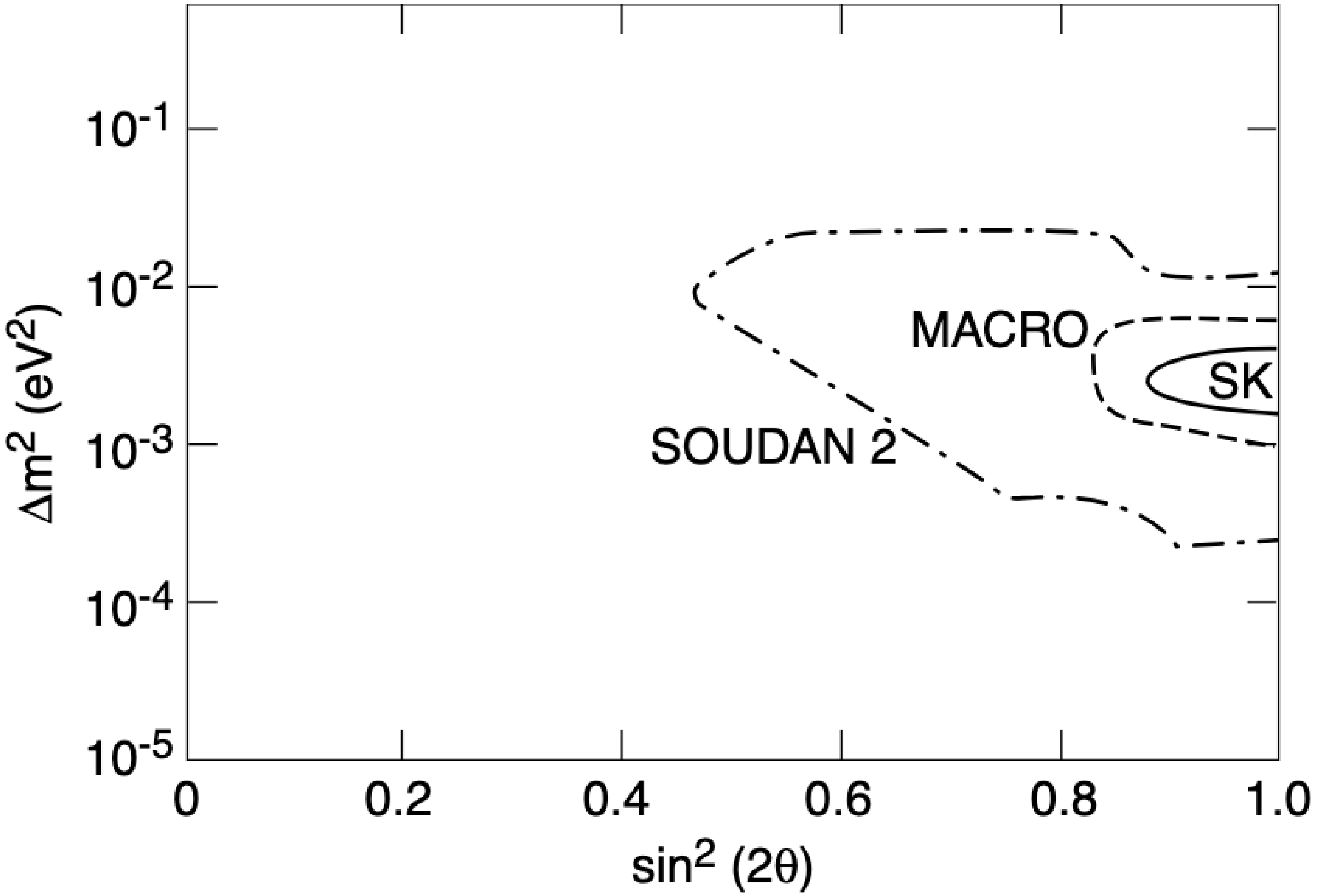
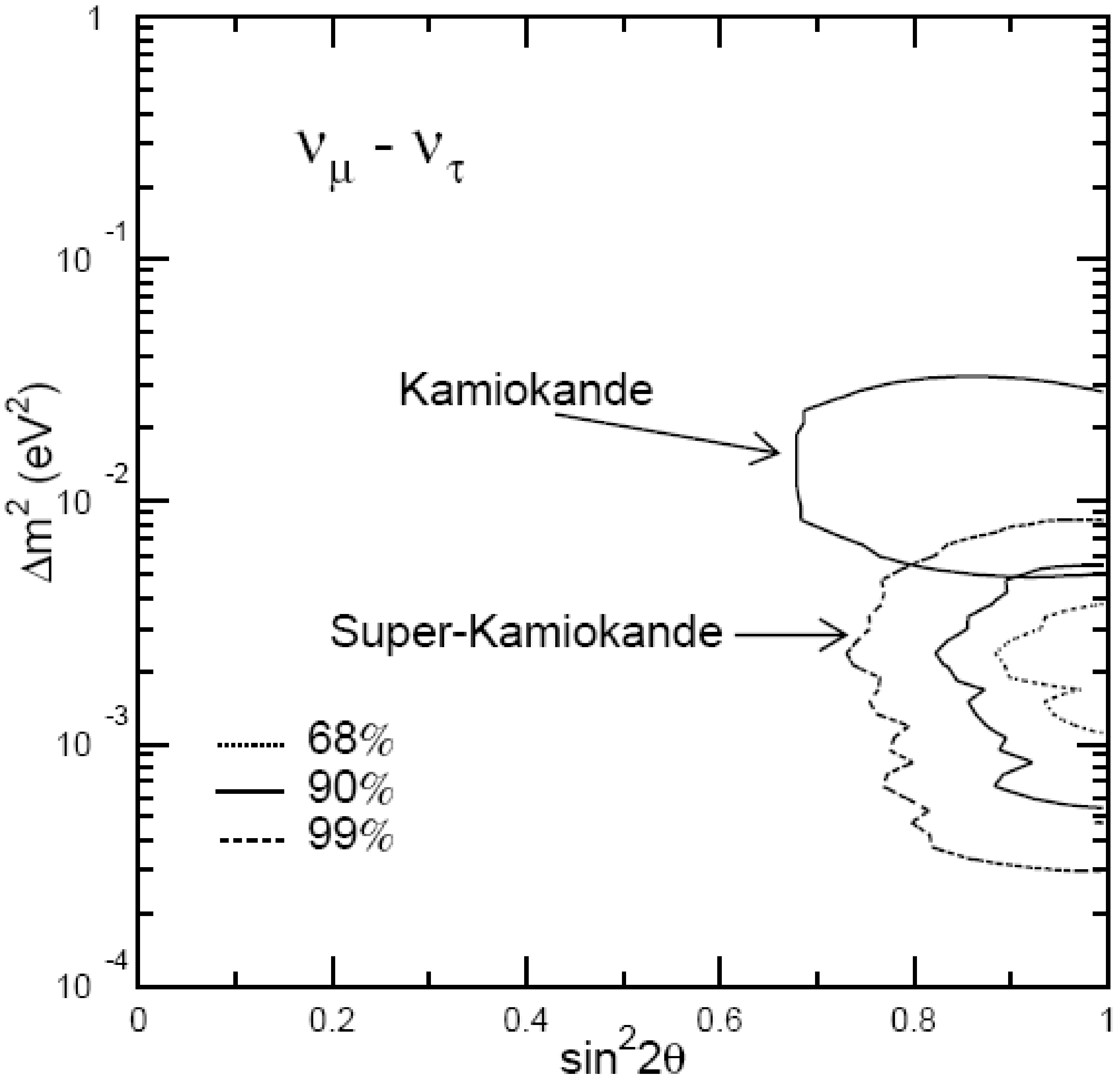
Invited paper at NO-VE, Int. Workshop on Neutrino Oscillations in Venice,
Venice, Italy, 24-26 July 2001.





1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Δm^2 (eV^2)
ν_μ - ν_τ
Kamiokande
Super-Kamiokande
68%
90%
99%
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$