Atmospheric Neutrinos:

from the Pioneering Experiments to Kamiokande

Paolo Lipari
INFN Roma "Sapienza"

History of the Neutrino

Paris: September 5th , 2018

First Detection

Proton Decay Experiments

“Anomaly”

“Hint for New Physics”

“Evidence for Neutrino Oscillations”

Established results
in physics textbooks.

At this conference:

John Learned
“The Saga of atmospheric neutrinos”.
September 5, 15:05

Takaaki Kajita
“Atmospheric neutrinos: the anomaly becomes the discovery”
September 6, 16:40

Christian Spiering
“High energy neutrinos and neutrino telescopes”
September 7, 14:45

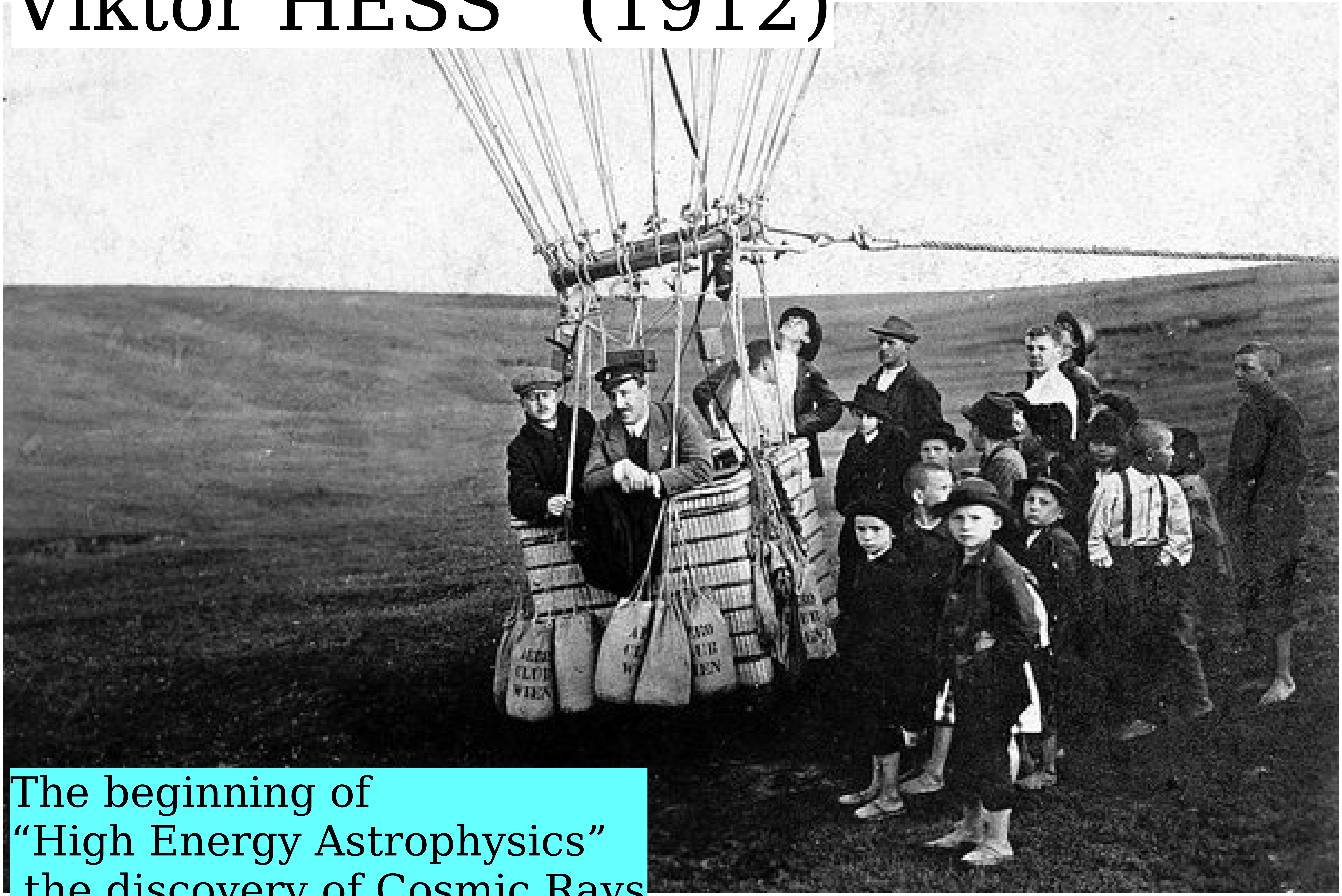
Posters:

John LoSecco: *“Discovery of the atmospheric neutrino anomaly*"

Francesco Ronga: *“Neutrino Oscillations: personal recollections*
Focused before the Kajita's talk 1998”

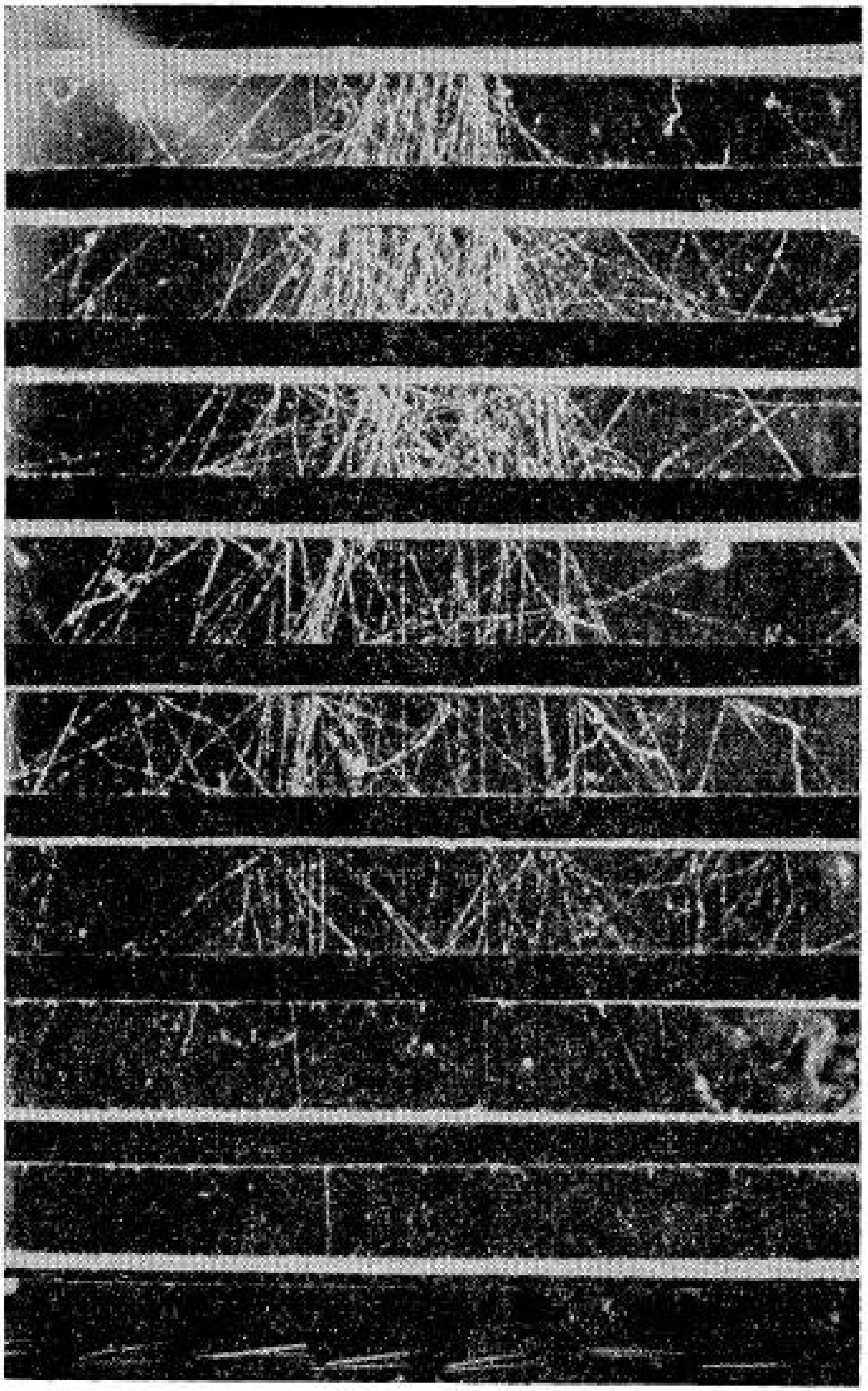
Igor Zheleznyk: *“The Soviet DUMAND program and the development*
of alternative large scale neutrino telescopes”

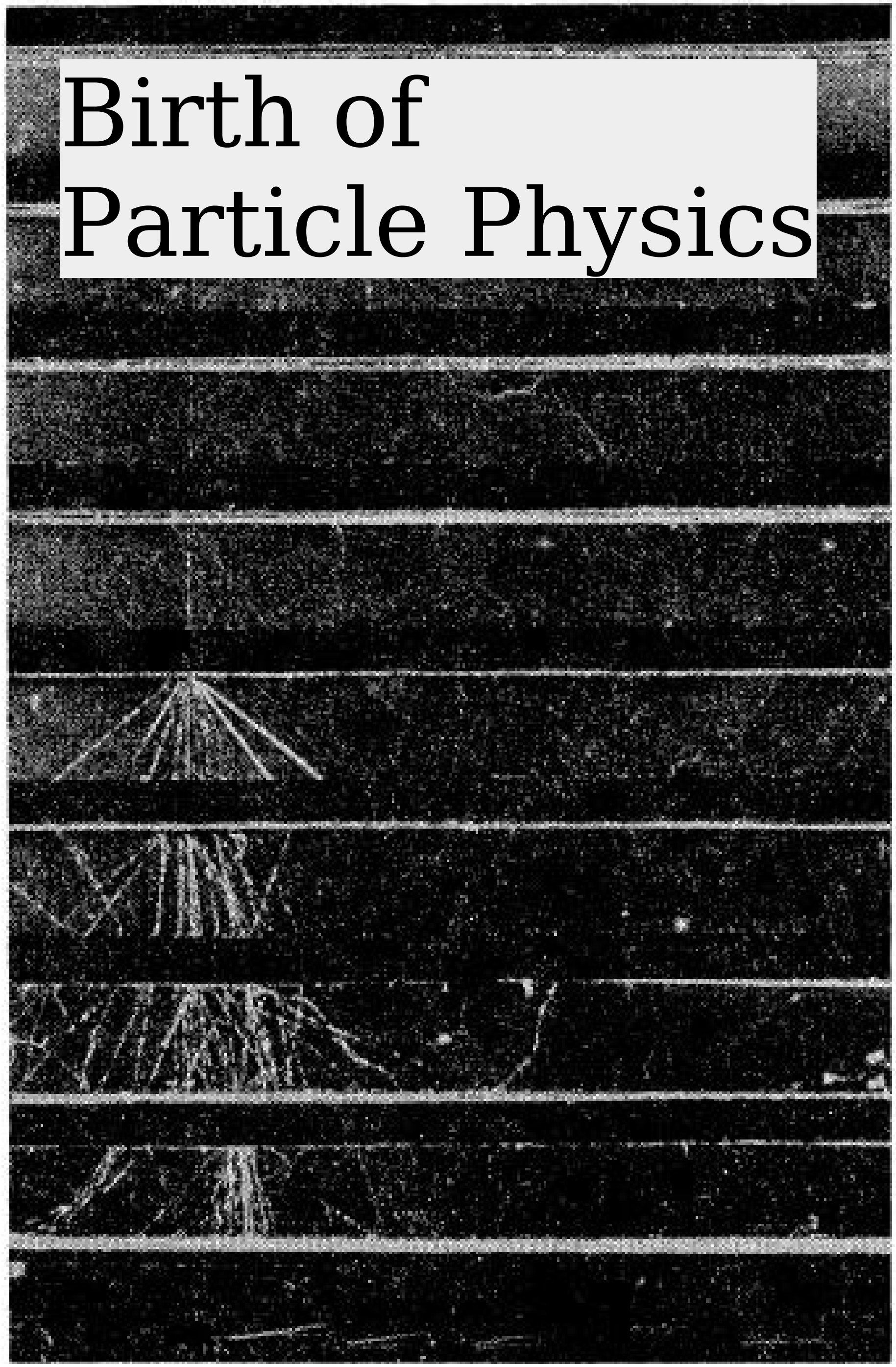
Viktor HESS (1912)



The beginning of
“High Energy Astrophysics”
the discovery of Cosmic Rays

Birth of Particle Physics



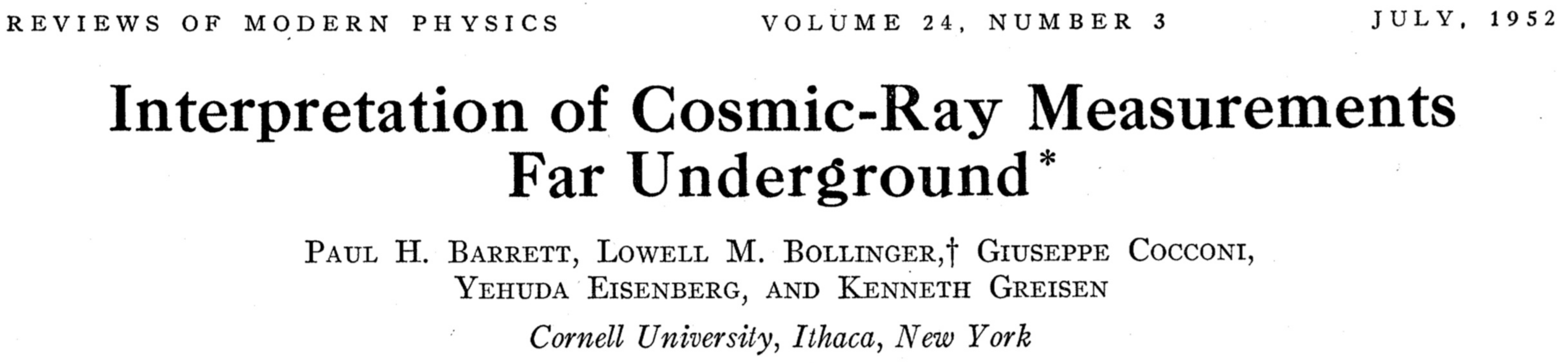


e^{+}

$\mu^{\mp}$

$\pi^{\mp}$ π°

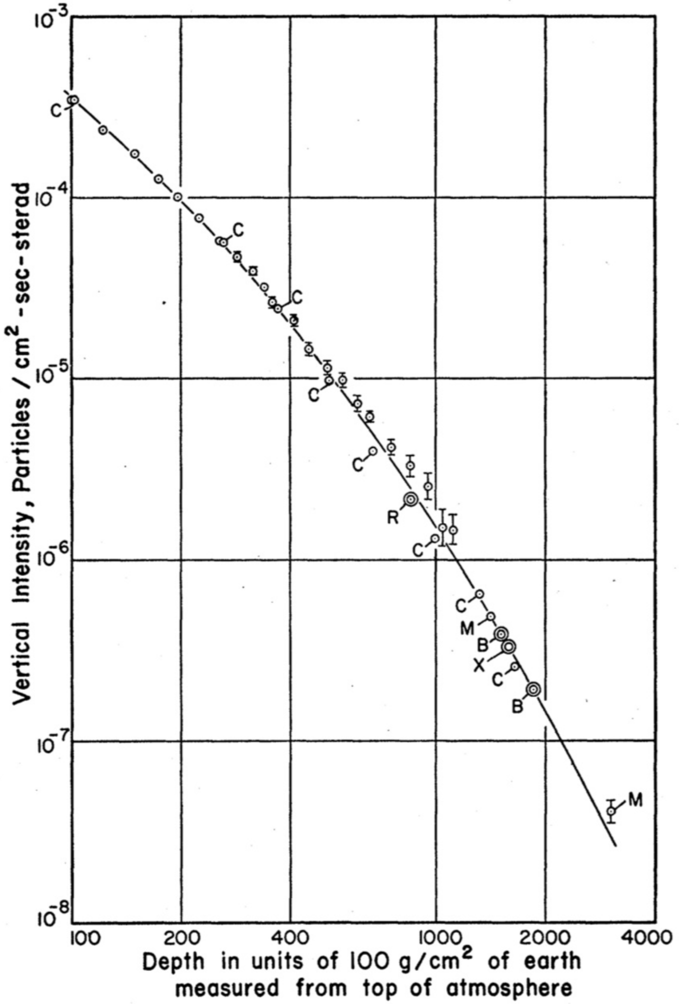
$K^{\pm}$ K° $\overline{K}_0$

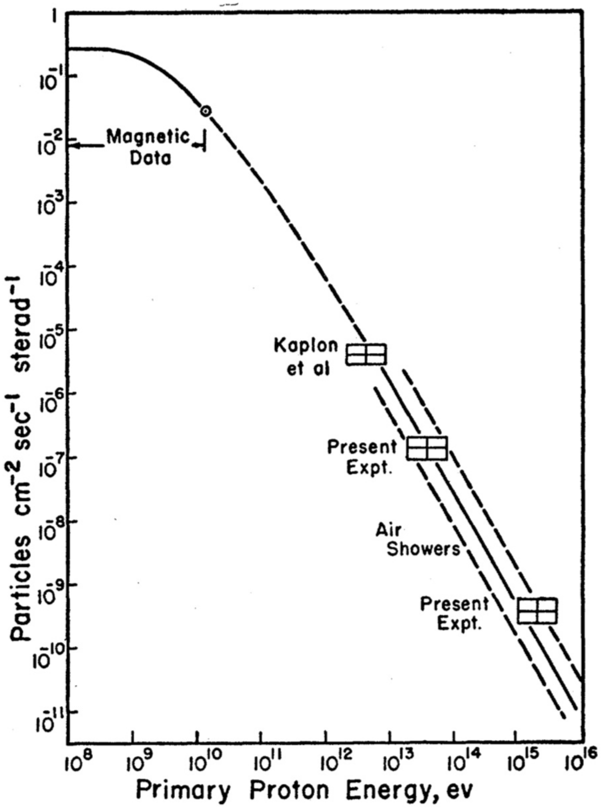


REVIEWS OF MODERN PHYSICS VOLUME 24, NUMBER 3 JULY, 1952

Interpretation of Cosmic-Ray Measurements Far Underground*

PAUL H. BARRETT, LOWELL M. BOLLINGER,† GIUSEPPE COCCONI,
YEHUDA EISENBERG, AND KENNETH GREISEN
Cornell University, Ithaca, New York





Reconstruct the
Cosmic Ray spectrum

Flux of Atmospheric Neutrinos

Cosmic Ray Showers in the Earth Atmosphere

$$p + \mathrm{Air} \to p\ n, \quad \pi^+\ \pi^-\ \pi^\circ\ \ K^+\ K^-\ K^\circ\ \overline{K}^\circ\ \ \ldots$$

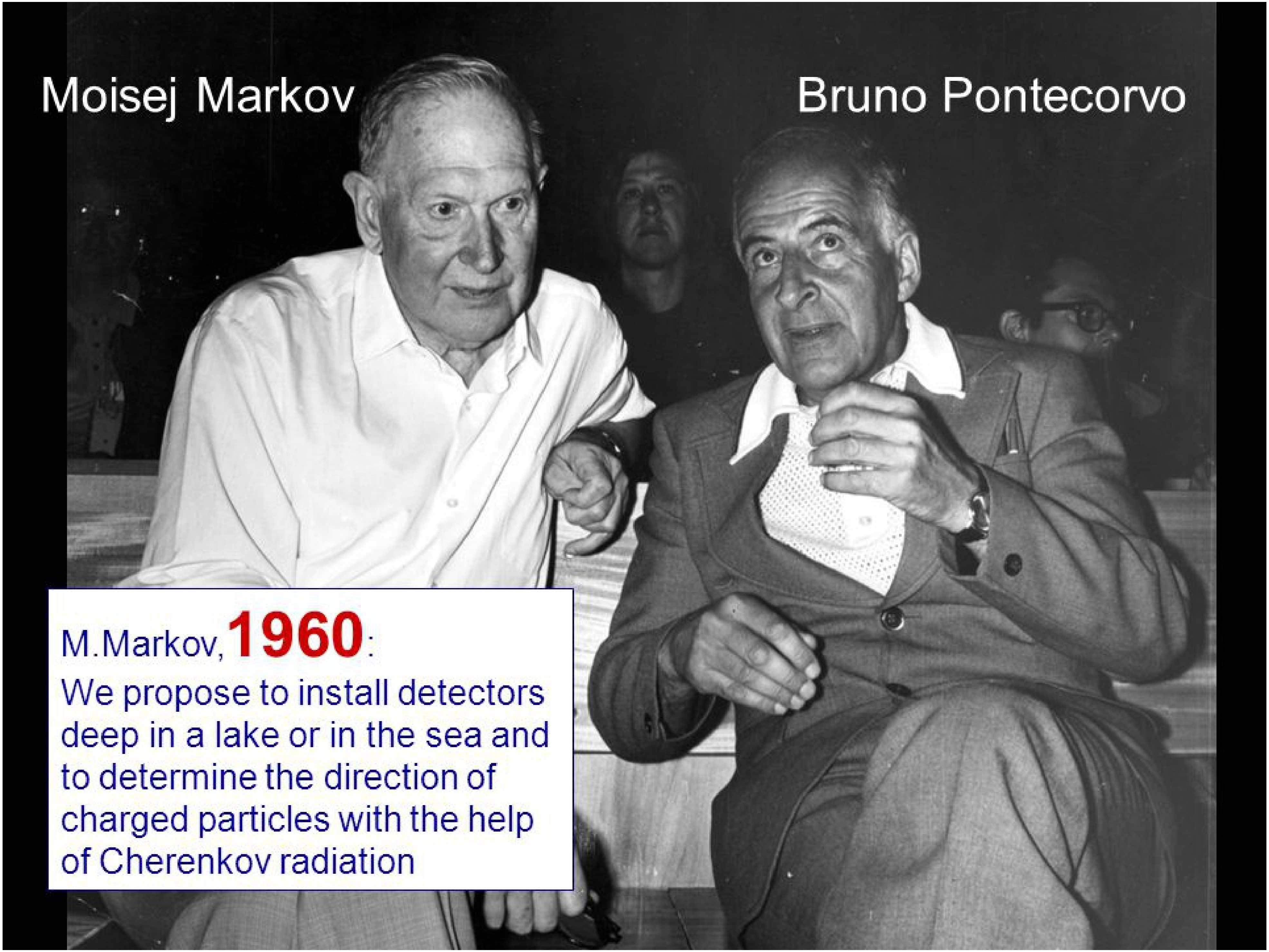
$$\begin{aligned} \pi^+ \to\ &\mu^+\ \nu_\mu \\ &\hookrightarrow \overline{\nu}_\mu\ e^+\ \nu_e \end{aligned}$$

There *must be* a flux of
"cosmic neutrinos"
[atmospheric neutrinos]

Is it detectable ?

Are there (high energy) neutrinos
Generated from astrophysical Sources ?

Is Neutrino Astronomy Possible ?



M.Markov, **1960**:

We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation

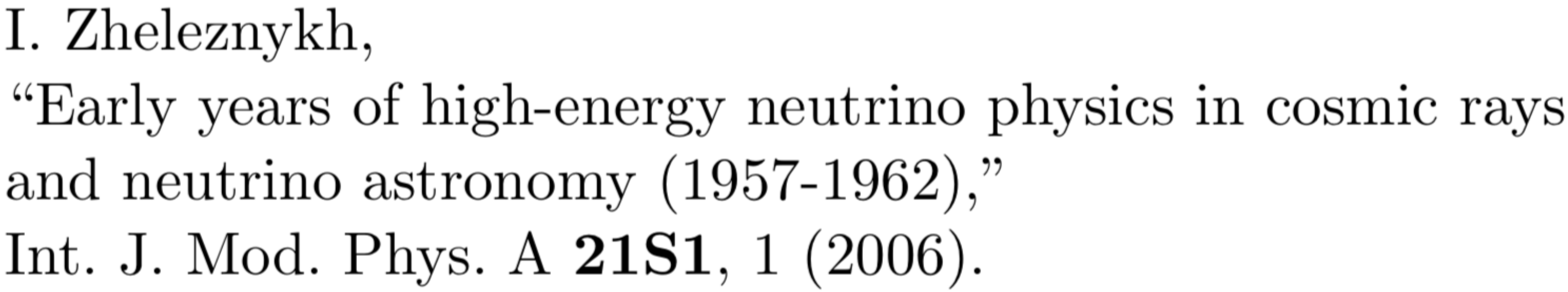
“Visionaries” in the Soviet Union

M. A. Markov and I. M. Zheleznykh,
“On high energy neutrino physics in cosmic rays,”
Nucl. Phys. **27**, 385 (1961).

B. Pontecorvo and Y. Smorodinsky,
“The neutrino and the density of matter in the universe,”
Zh. Eksp. Teor. Fiz. **41**, 239 (1961).

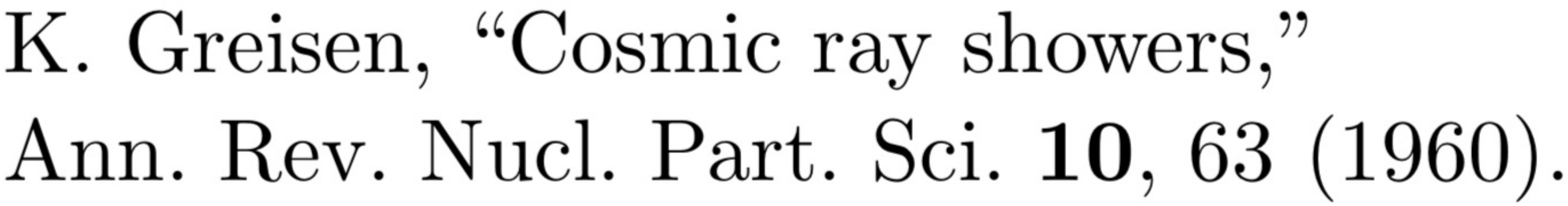
B. Pontecorvo and A. E. Chudakov,
“Neutrinos and the cosmic ray intensity at great depths,”
11th International Conference on High-energy Physics (ICHEP 62)
4-11 Jul 1962. Geneva, Switzerland

Fascinating review by a key participant:



I. Zheleznykh,
“Early years of high-energy neutrino physics in cosmic rays and neutrino astronomy (1957-1962),”
Int. J. Mod. Phys. A **21S1**, 1 (2006).

[Poster here]

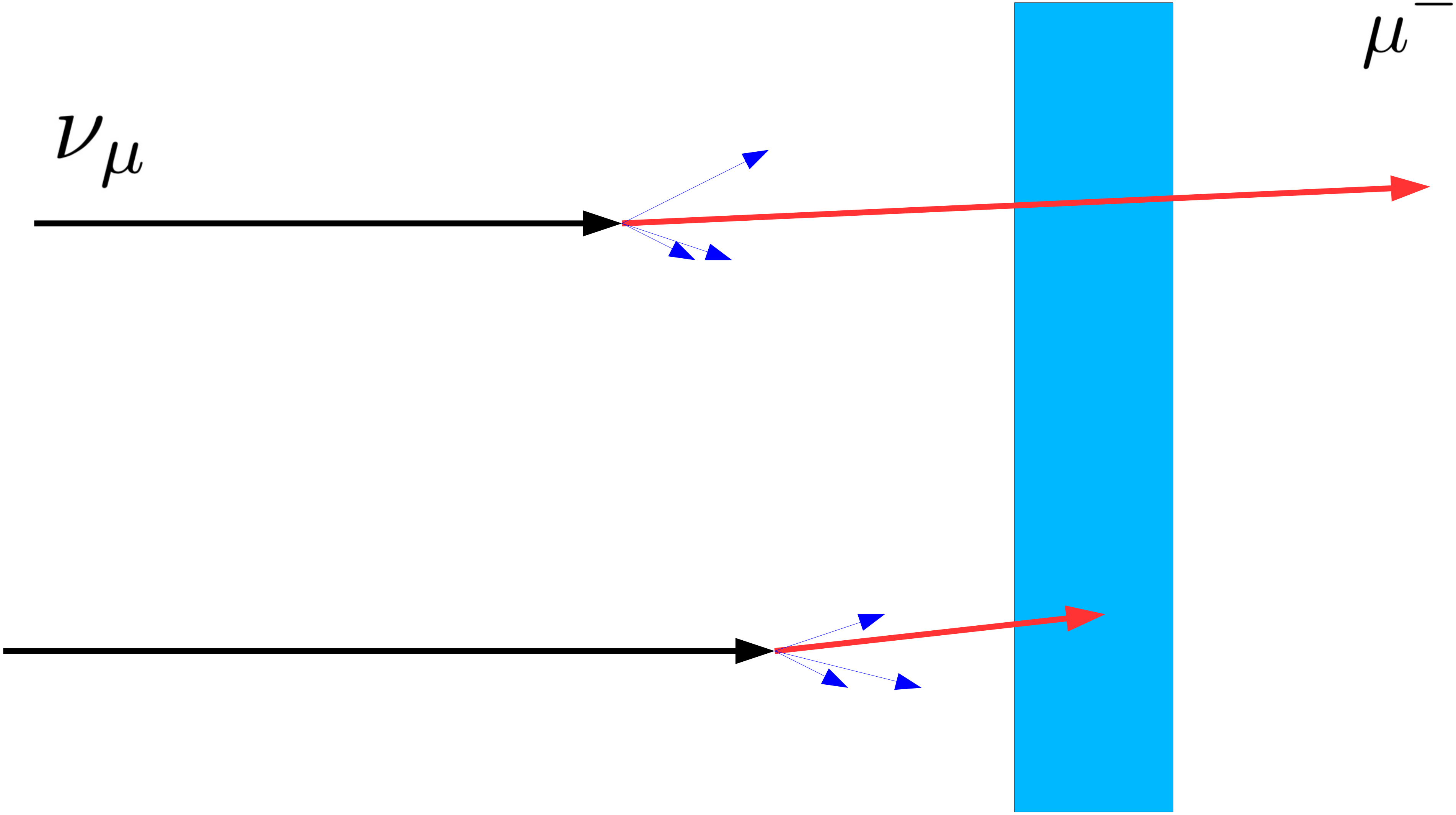


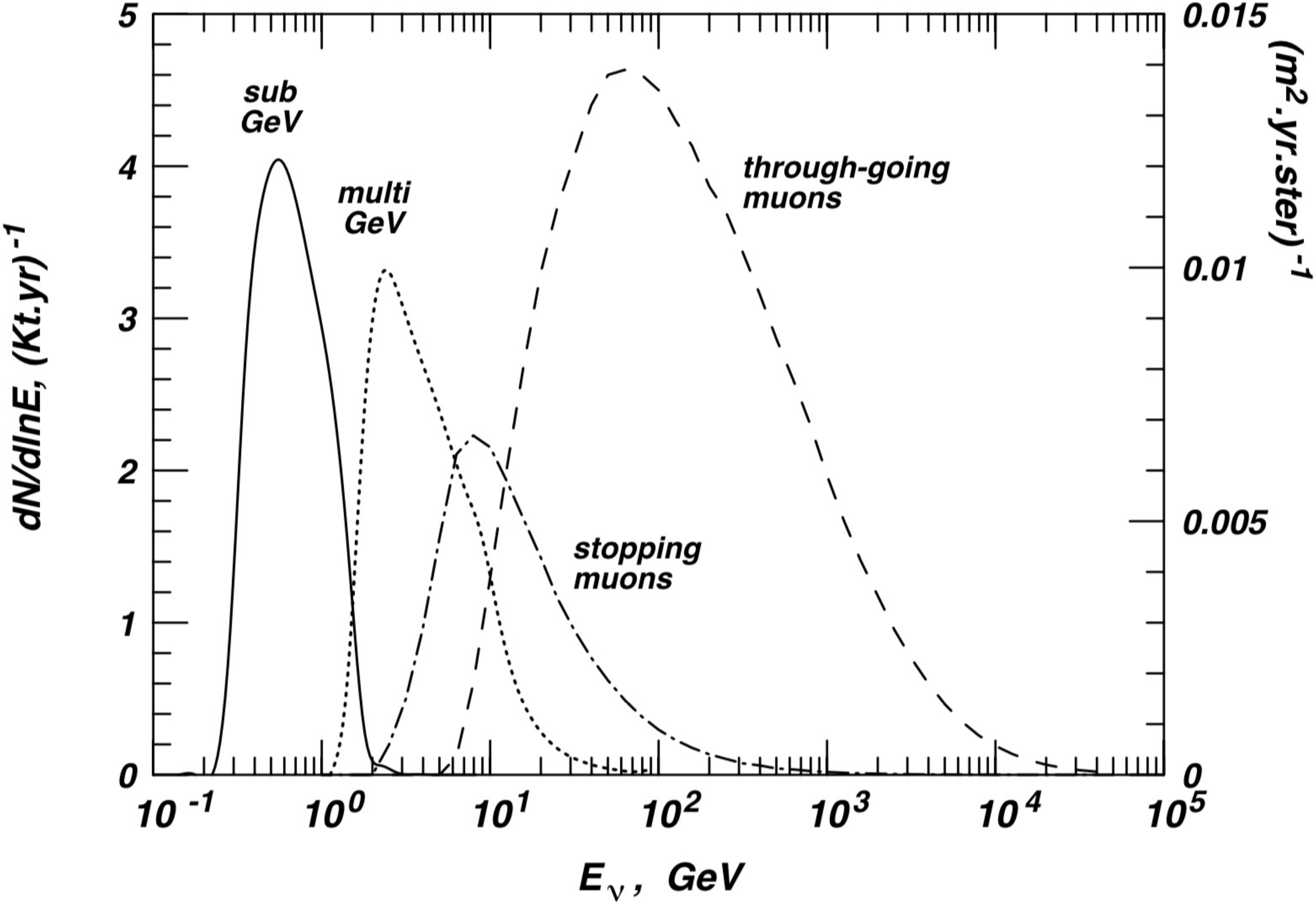
K. Greisen, “Cosmic ray showers,”
Ann. Rev. Nucl. Part. Sci. **10**, 63 (1960).

Neutrino Induced Muons

$$\nu_\mu + N \rightarrow \mu^- + \ldots$$

$$\overline{\nu}_\mu + N \rightarrow \mu^+ + \ldots$$





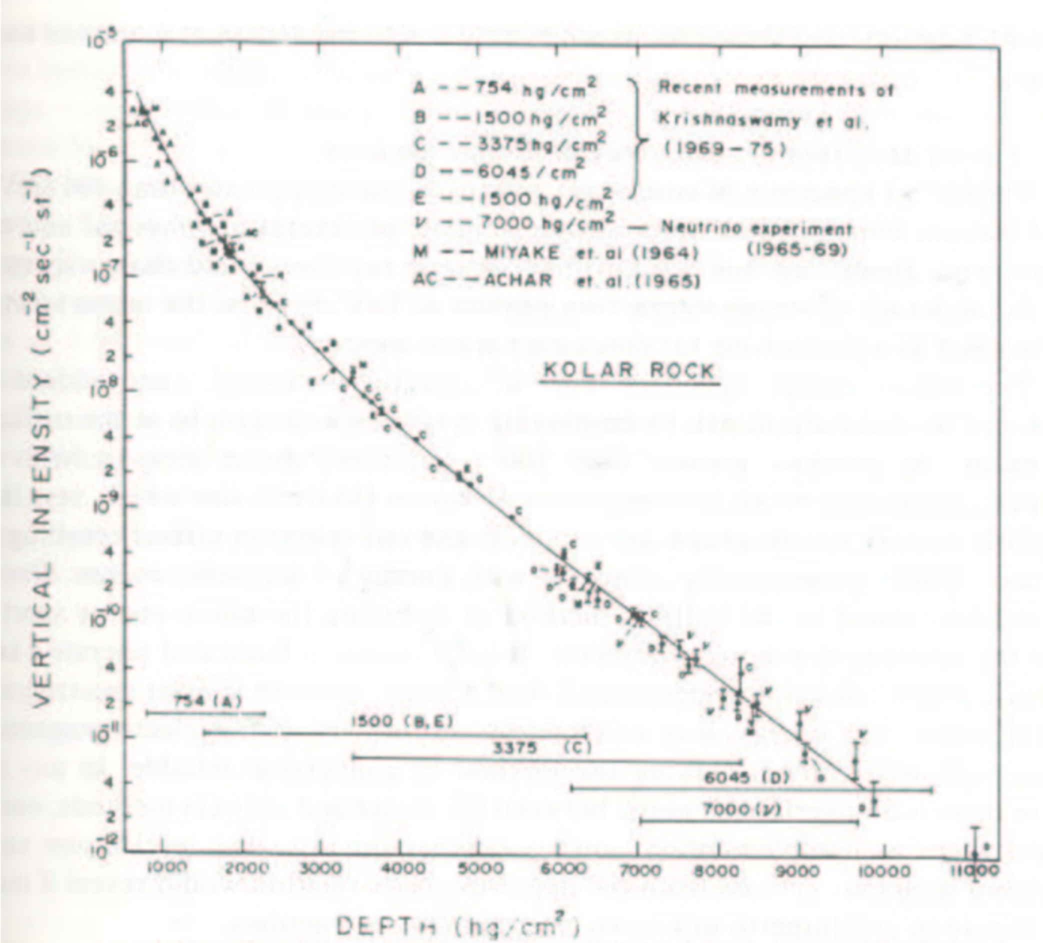
dN/dlnE, (Kt.yr)$^{-1}$
$(m^2.yr.ster)^{-1}$
sub GeV
multi GeV
through-going muons
stopping muons
0
1
2
3
4
5
0
0.005
0.01
0.015
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
E_ν, GeV

The first observations of Atmospheric Neutrinos

C. V. Achar *et al.*,
"Detection of muons produced by cosmic ray neutrinos deep underground,"
Phys. Lett. **18**, 196 (1965).

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, G. R. Smith, J. P. F. Sellschop and B. Meyer,
"Evidence for high-energy cosmic ray neutrino interactions,"
Phys. Rev. Lett. **15**, 429 (1965).

Kolar Gold Field Mine in India

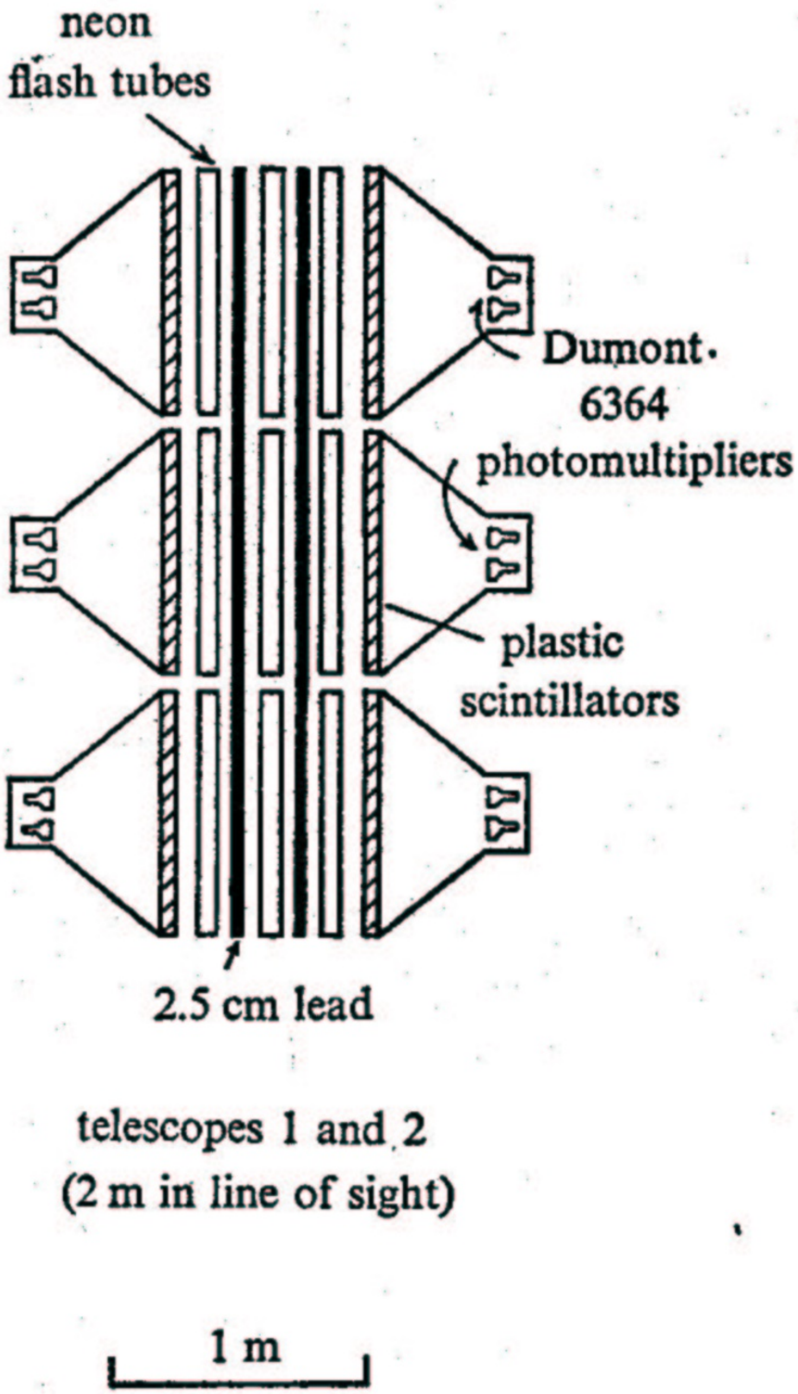


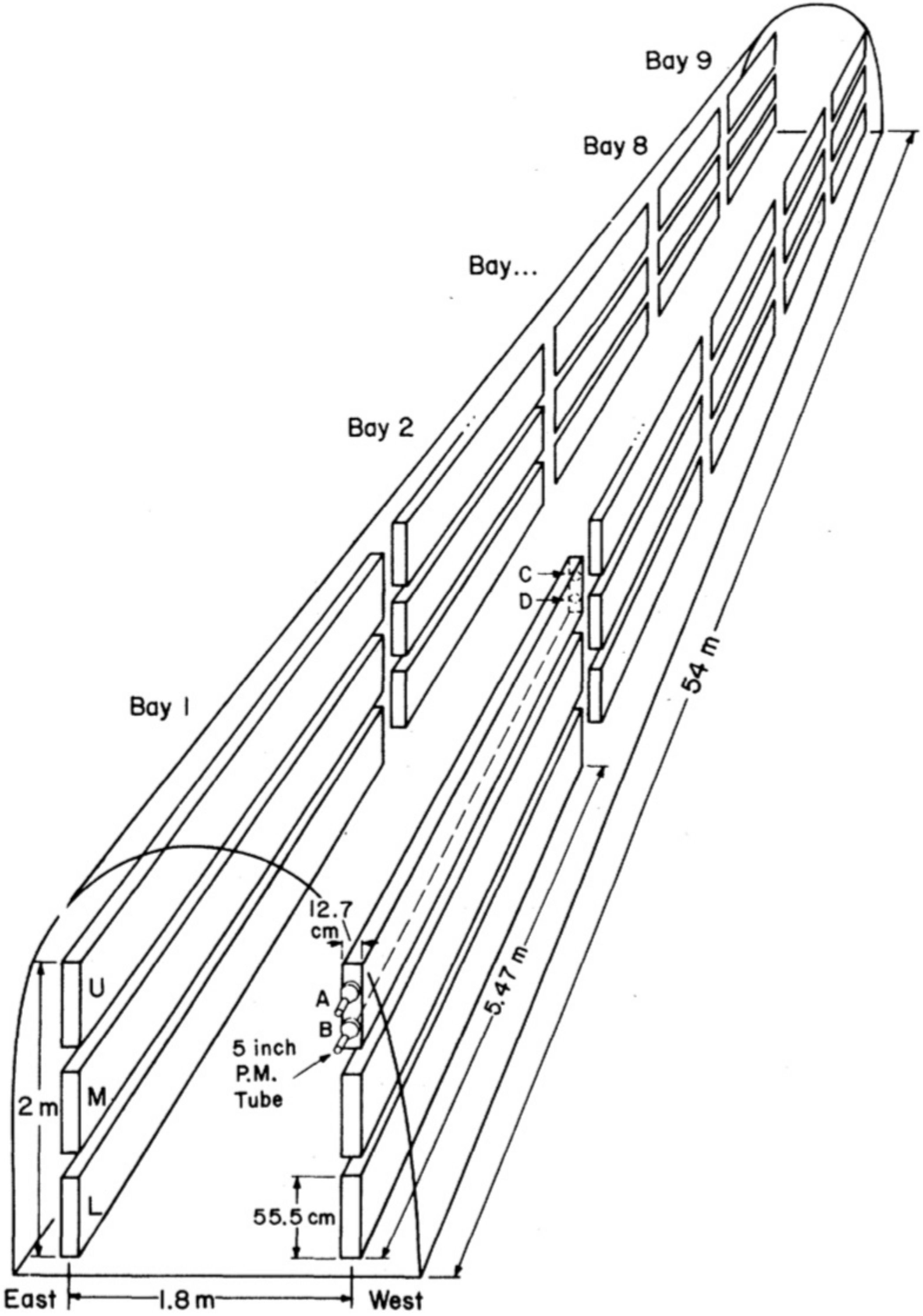
THE CONSOLIDATED DEPTH-INTENSITY RELATION FROM ALL WORKS DONE UNDER KOLAR ROCK

M. G. K. Menon, P. V. Ramana Murthy, B. V. Sreekantan and S. Miyake,
"Cosmic-ray intensity at great depths and neutrino experiments,"
Nuovo Cim. **30**, 1208 (1963).

William R. Kropp and Marshall F. Crouch,
“Some reminiscences of the CWI Atmospheric Neutrino Experiment”.

In early 1963 great excitement gripped Fred Reines “Neutrino Group” at the Cae Institute of Technology. Fred recognized that a PhD thesis of P.V.Ramana Murthy of the Tata Institute of Fundamental Research, Bombay showed that at depth attainable in the mines of the Kolar Gold Field in Southern India it might be possible for him and its group to carry out an experinent of which he had long dreamed.


neon
flash tubes
Dumont·
6364
photomultipliers
plastic
scintillators
2.5 cm lead
telescopes 1 and 2
(2 m in line of sight)
1 m

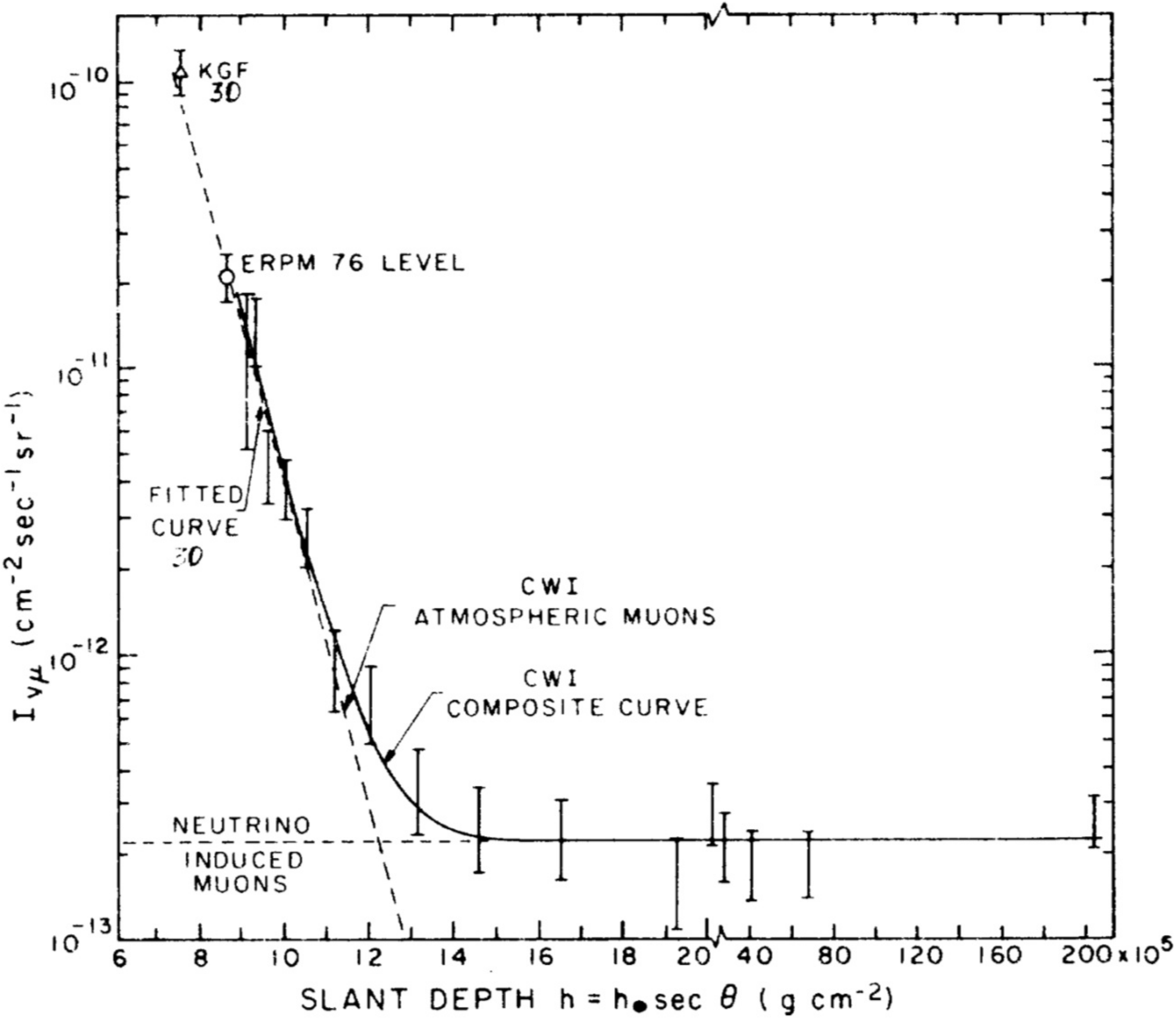

Bay 9
Bay 8
Bay...
Bay 2
Bay 1
C
D
54 m
12.7 cm
U
A
B
5 inch P.M. Tube
M
2 m
5.47 m
L
55.5 cm
East
1.8 m
West

William R. Kropp, Mildred M. Rie, Linda Price,
“Neutrinos and other Matters: Selected works of Frederick Reines’,”
World Scientific (1991)

William R. Kropp and Marshall F. Crouch,
“Some reminiscences of the CWI Atmospheric Neutrino Experiment”.

> [. . .] The mines couldn’t make much sense of our efforts to detect neutrinos. After many attempts at understanding out activities they gave up and dubbed us “Goggafangers” – literally the bug catchers. Fred [Reines] of course had a special title, he was the “Makulu Bass Goggafanger”, the Big Boss Bug Catcher.

> [. . .] As might be imagined, politics were an ever present issue throughout the duration of the experiment (1963–1971).... troubling political problem were a continuing feature of the experiment both is South Africa and on our university campuses.


KGF
30
ERPM 76 LEVEL
FITTED
CURVE
30
CWI
ATMOSPHERIC MUONS
CWI
COMPOSITE CURVE
NEUTRINO
INDUCED
MUONS
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$I_{\nu\mu}$ (cm^{-2} sec^{-1} sr^{-1})
6
8
10
12
14
16
18
20
40
80
120
160
200 x 10^5
SLANT DEPTH h = h$_\bullet$ sec θ (g cm^{-2})

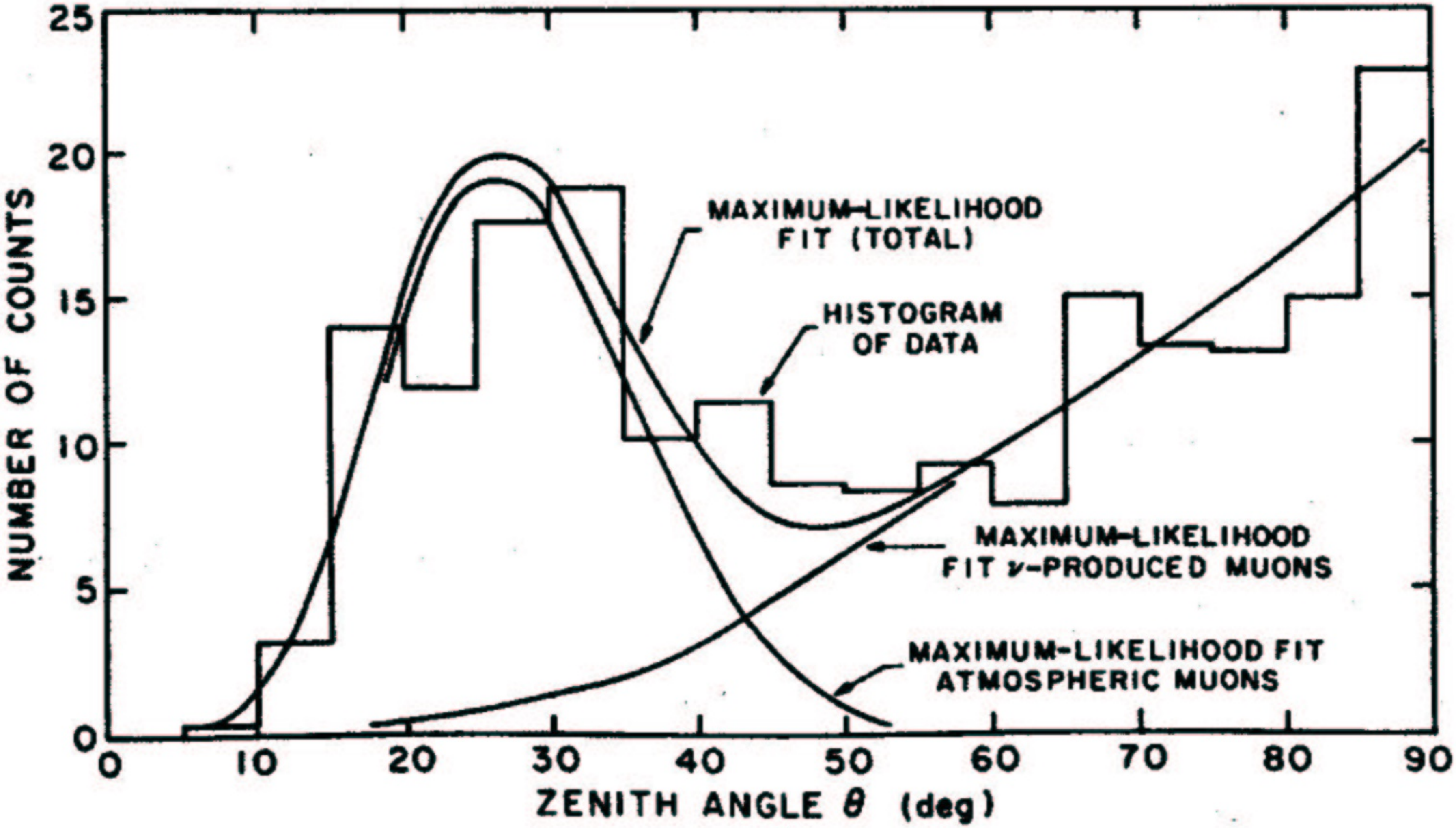
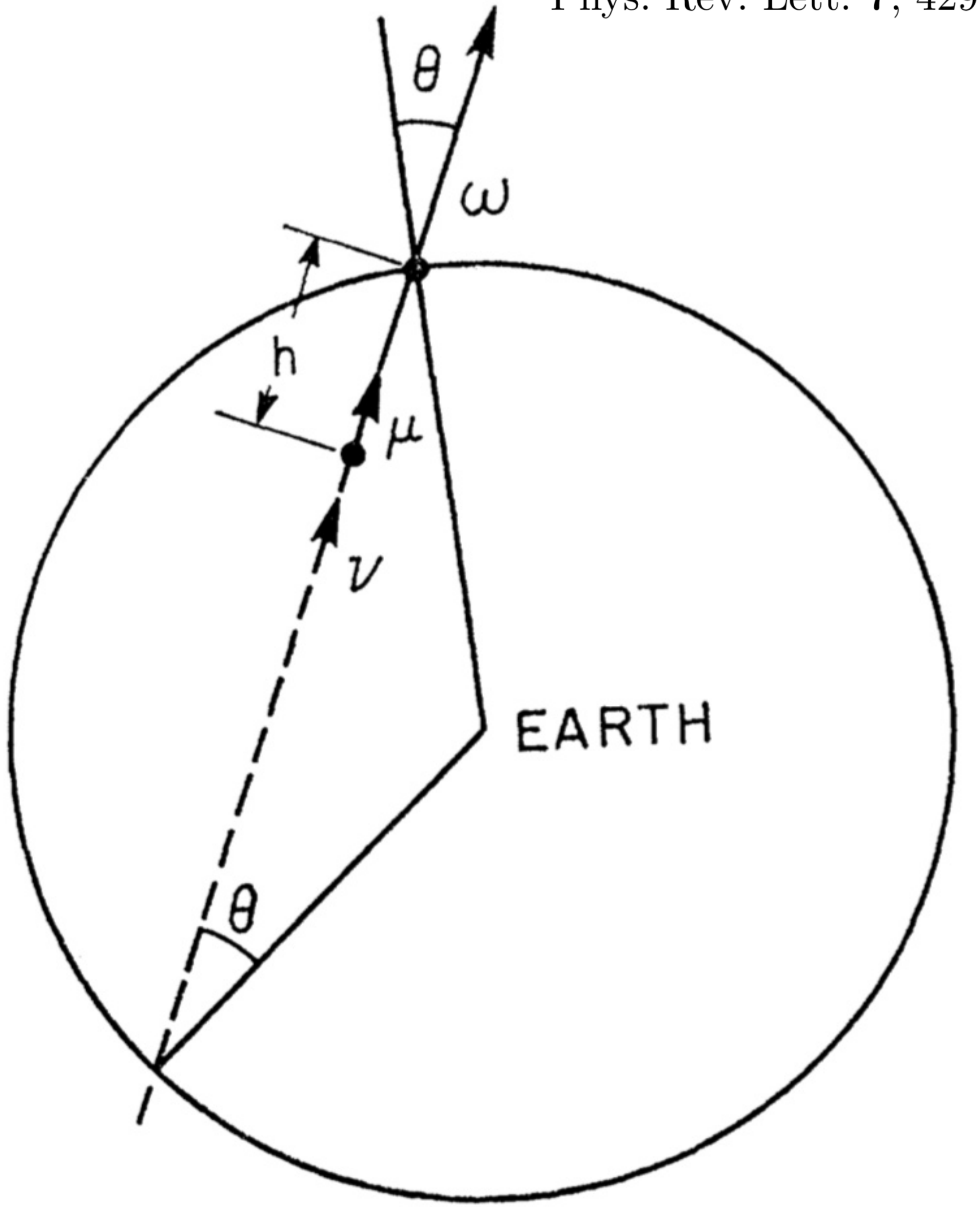


Fig. 9 Zenith angle distribution of events in the ERPM experiment, South Africa.

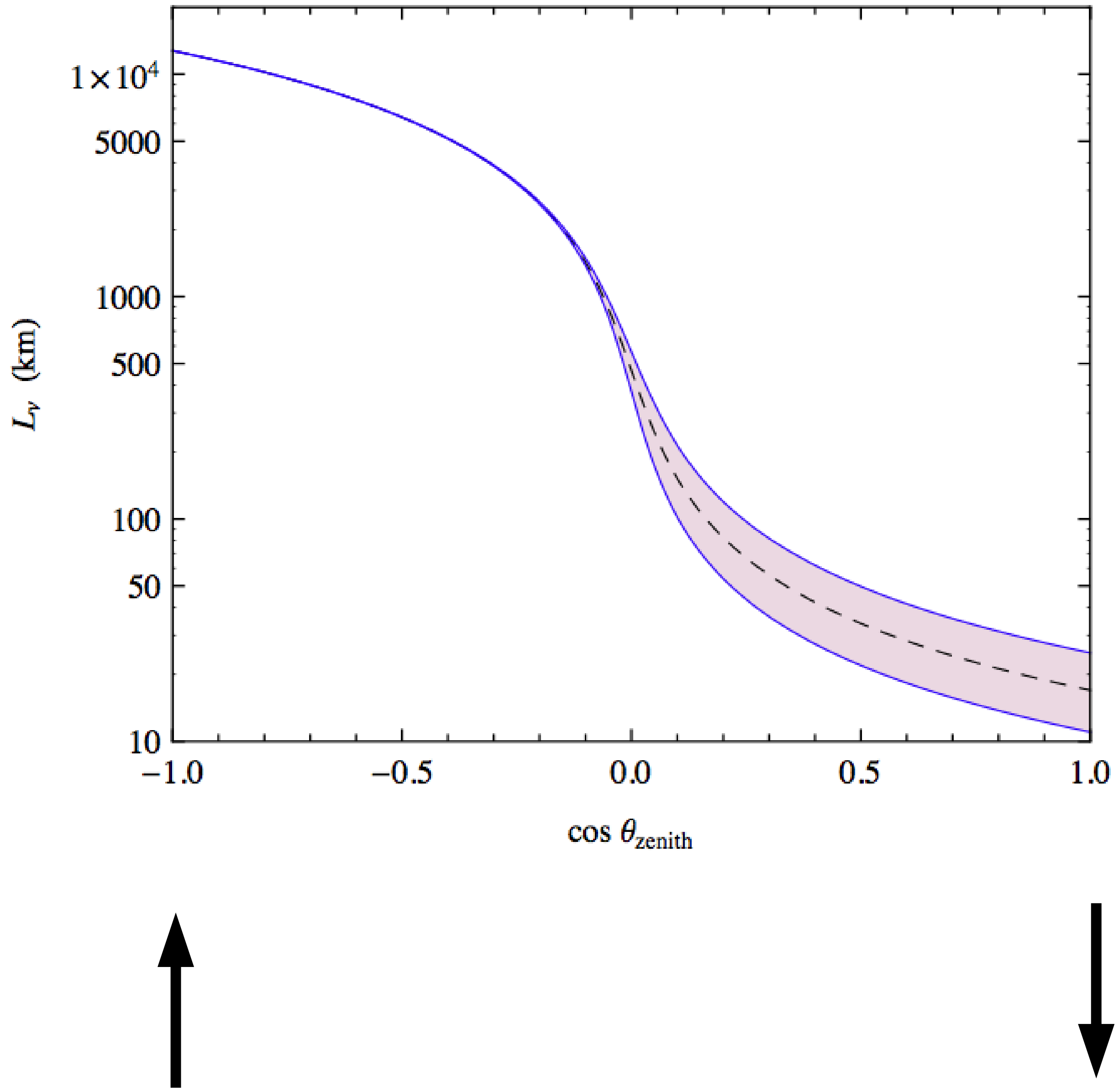
T. D. Lee, C. N. Yang and P. Markstein,
"Production Cross-section of Intermediate Bosons by Neutrinos in the Coulomb Field of Protons and Iron,"
Phys. Rev. Lett. **7**, 429 (1961).



$$\nu_\mu + Z \longrightarrow \mu^- + W^+ + Z$$

$$L = -R_{\oplus}\ \cos\theta_z + \sqrt{R_{\oplus}^2 \cos^2\theta_z + 2hR_{\oplus} + h^2}$$

$\langle h \rangle \simeq 20$ Km



$$L = 2R_{\oplus}\,|\cos\theta_z| \simeq 12,700\,|\cos\theta_z|\ \text{km}$$

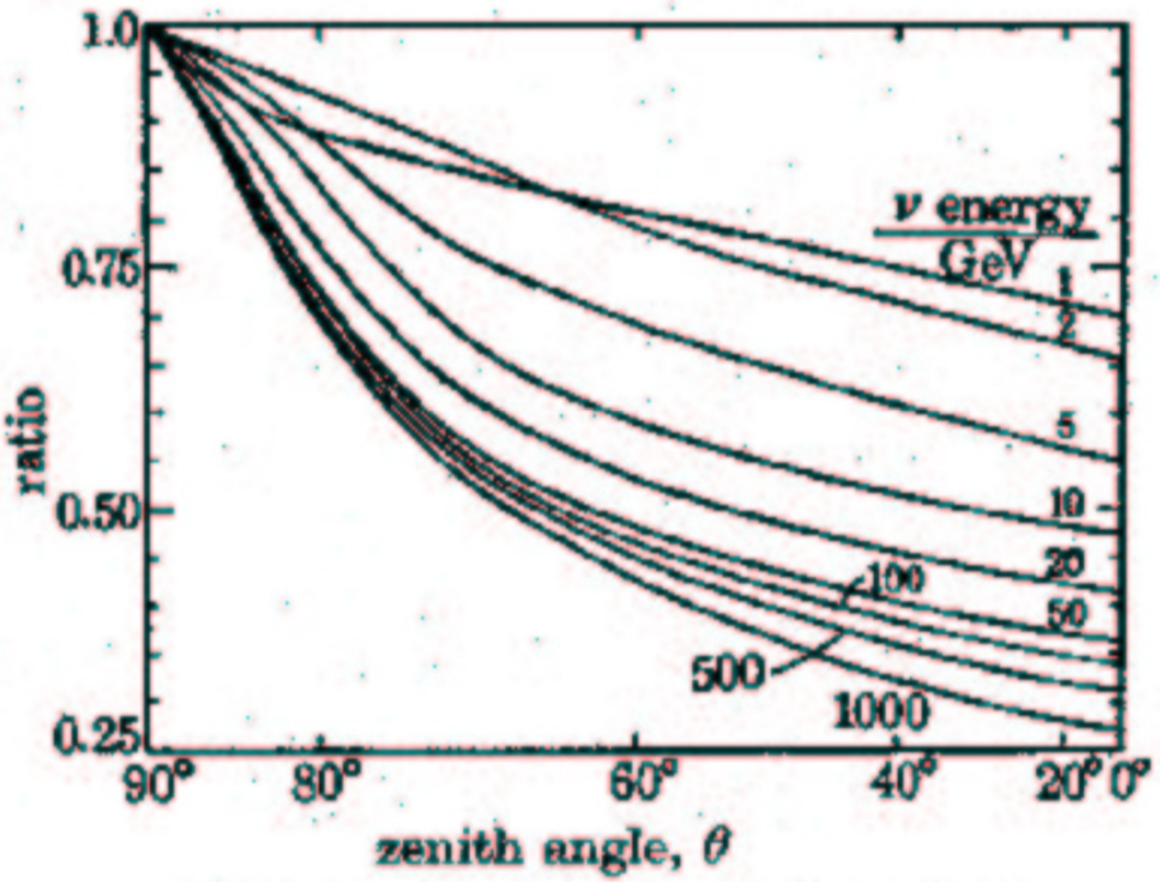
$\cos\theta_z < 1$

$$L = \sqrt{2hR_{\oplus}} \simeq 500\ \text{Km}$$

$\cos\theta \approx 0$

$$L = \frac{h}{\cos\theta_z} \approx \frac{20\ \text{Km}}{\cos\theta_z}$$

$\cos\theta_z > 1$



(*b*) intensity relative to that at 90°,
as a function of energy

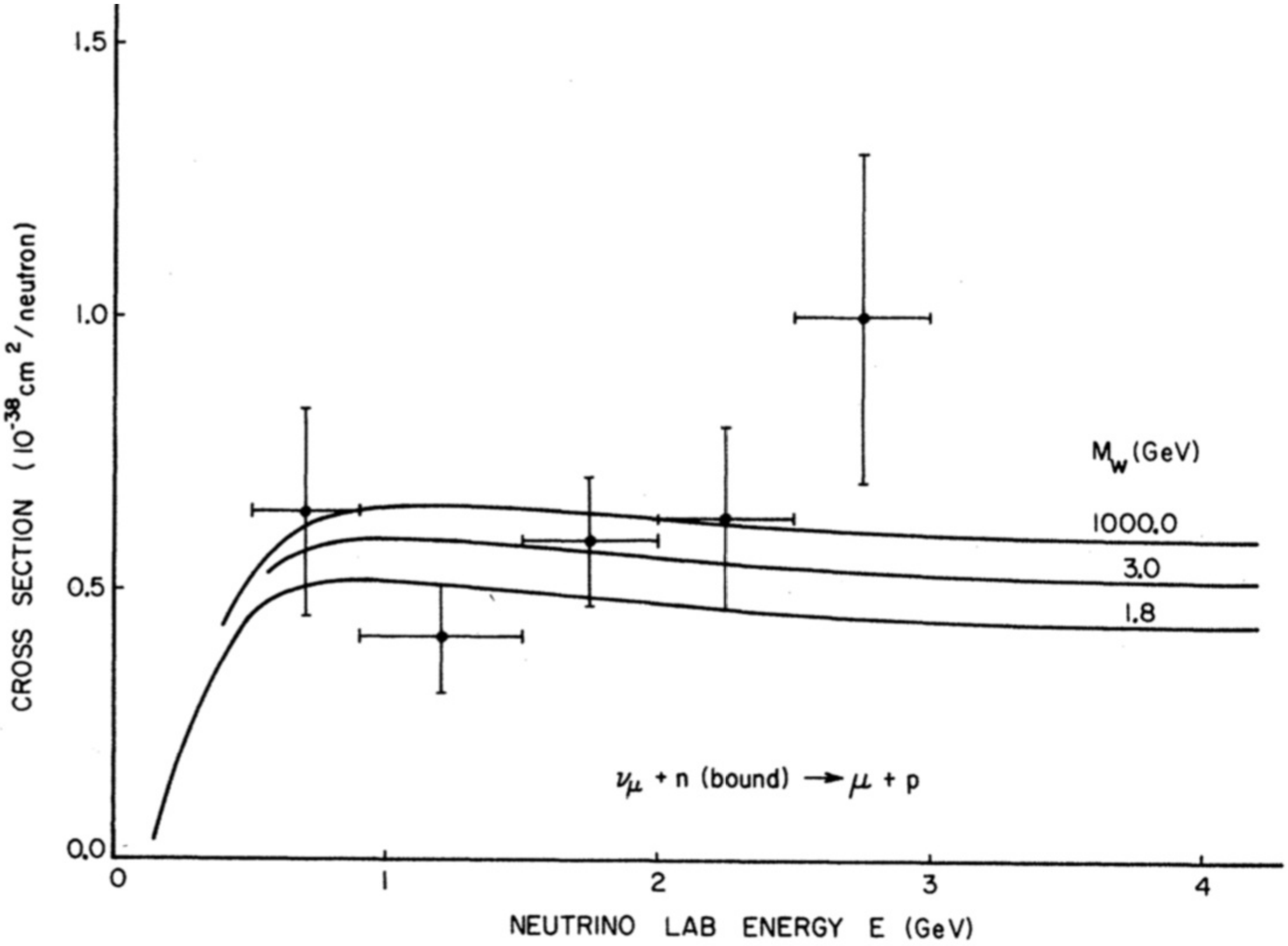
J.L. Osborne Proc. Phys. Soc. 86, 93 (1965)

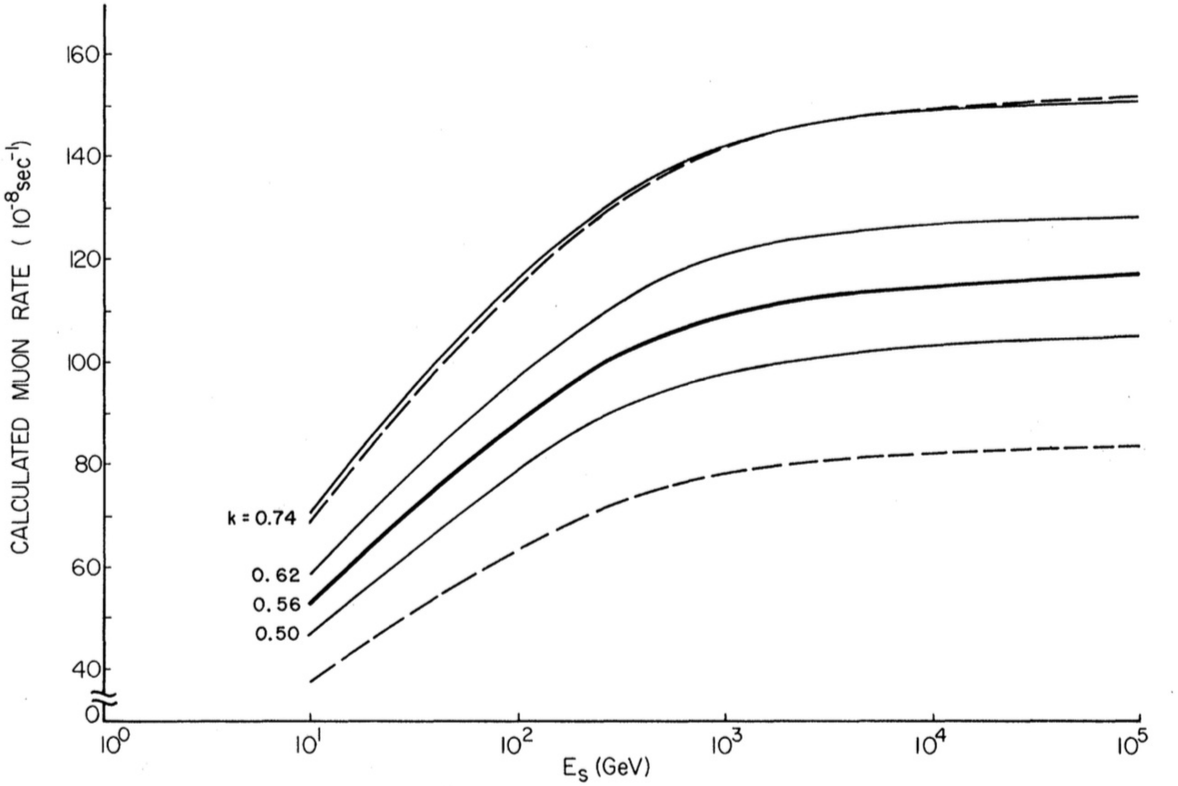
F. Reines, W. R. Kropp, H. W. Sobel, H. S. Gurr, J. Lathrop, M. F. Crouch, J. P. F. Sellschop and B. S. Meyer,
"Muons produced by atmospheric neutrinos: Experiment,"
Phys. Rev. D **4**, 80 (1971).

H. H. Chen, W. R. Kropp, H. W. Sobel and F. Reines,
"Muons produced by atmospheric neutrinos: Analysis,"
Phys. Rev. D **4**, 99 (1971).

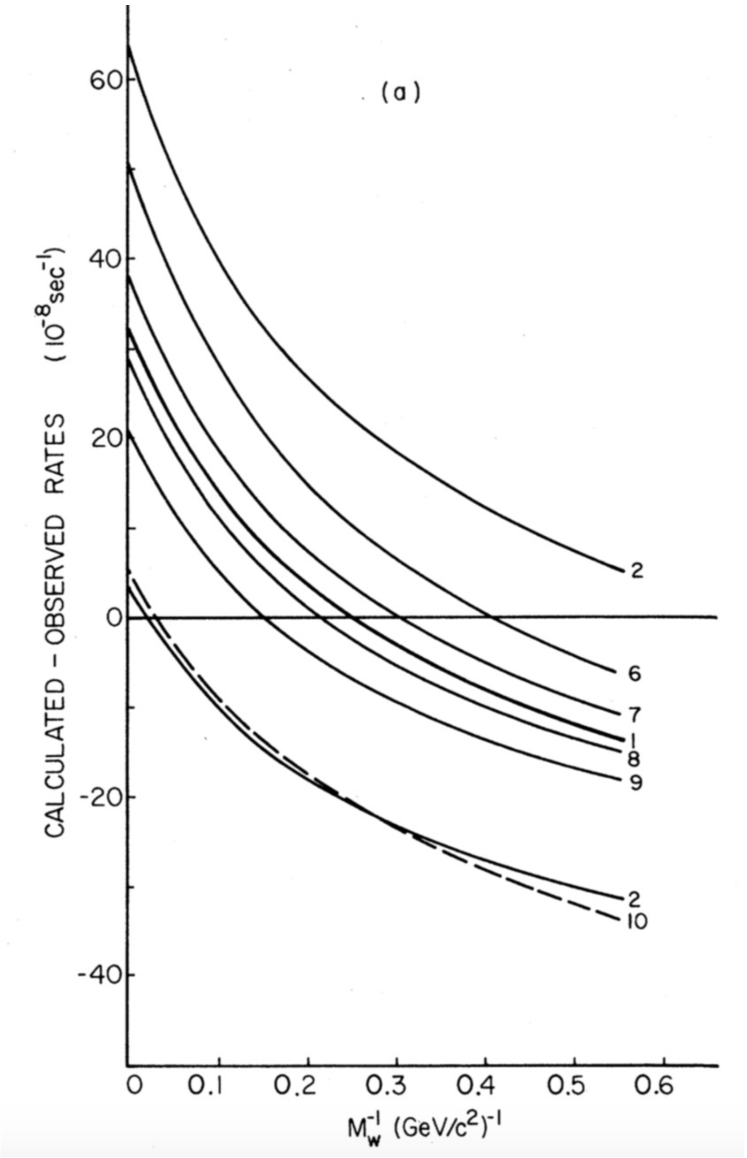
M. F. Crouch, P. B. Landecker, J. F. Lathrop, F. Reines, W. G. Sandie, H. W. Sobel, H. Coxell and J. P. F. Sellschop,
"Cosmic Ray Muon Fluxes Deep Underground: Intensity Versus Depth, and the Neutrino Induced Component,"
Phys. Rev. D **18**, 2239 (1978).

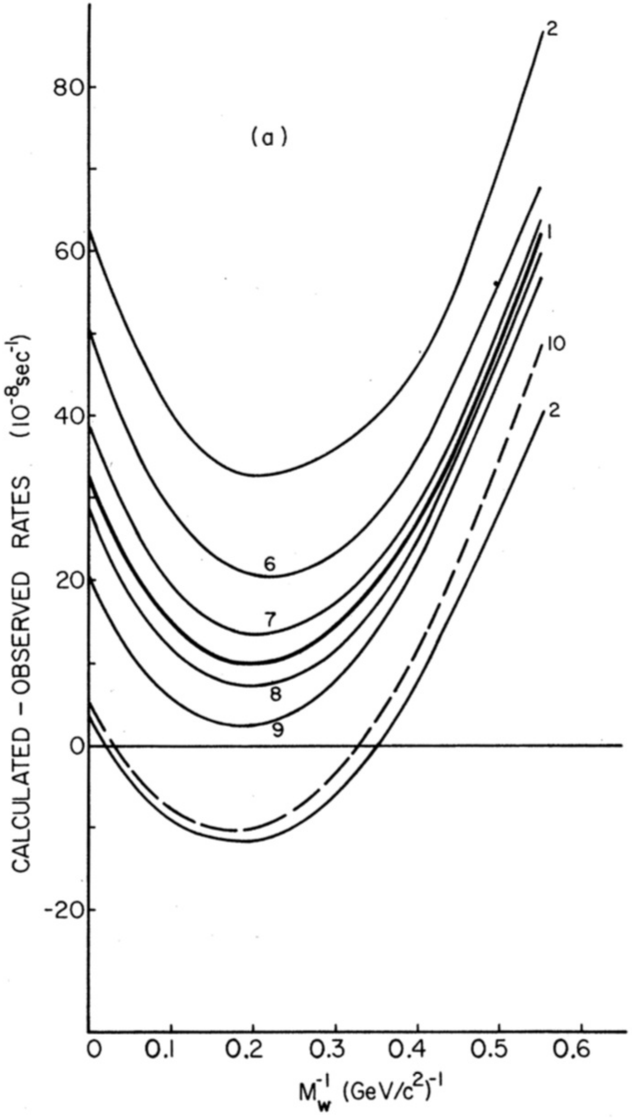
The neutrino cross section in 1971





$$M_W = \left(\frac{1}{3} m_p E_s\right)^{1/2}$$





Study of the
neutrino cross section

$$0.02 \lesssim M_W{}^{-1} \lesssim 0.35 \ (\mathrm{GeV}/c^2)^{-1}$$

$$45 \gtrsim M_W \gtrsim 2.9 \ (\mathrm{GeV}/c^2)$$

Neutrino Astronomy !

[celestial coordinates of the directions of Interesting events]

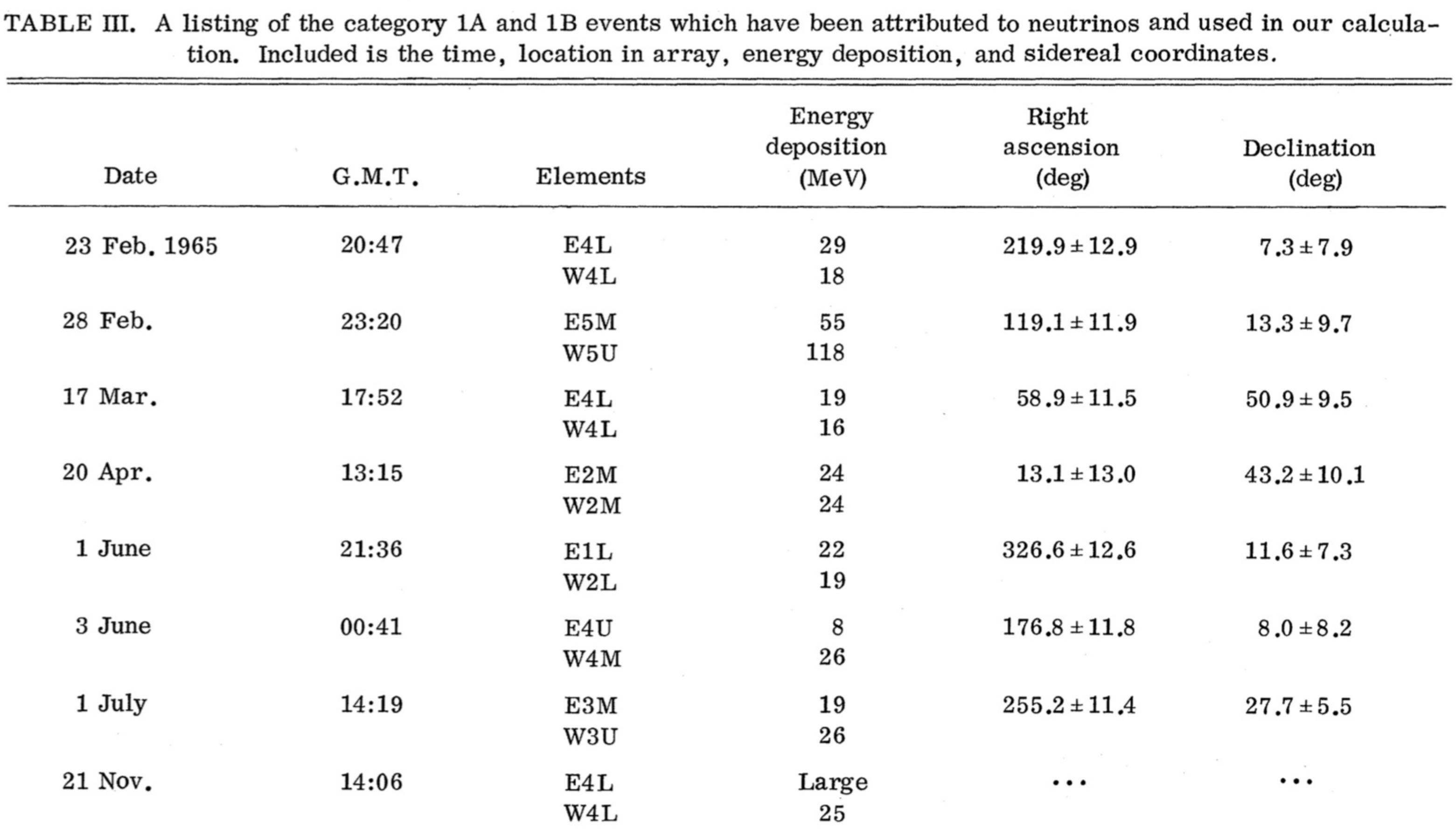


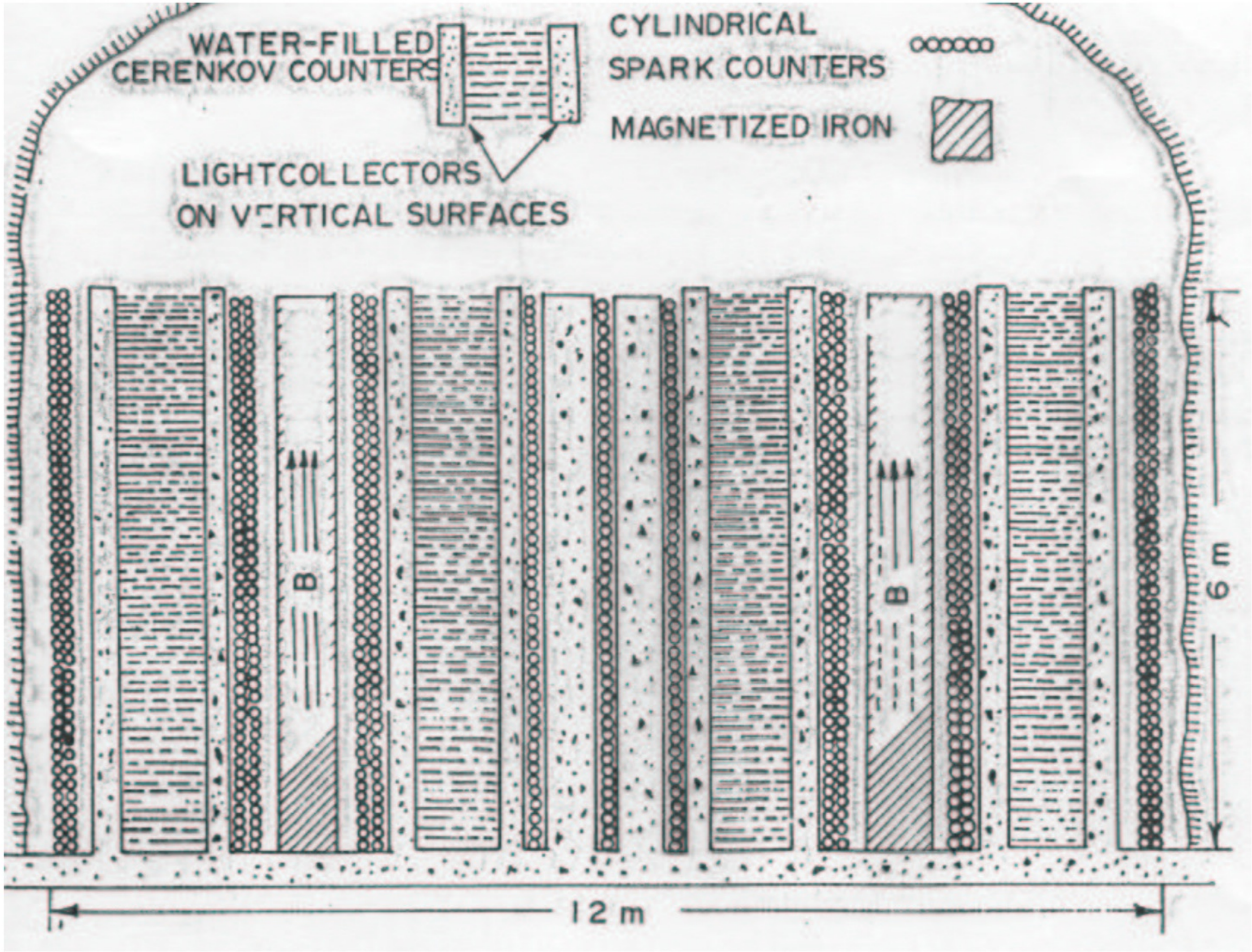
TABLE III. A listing of the category 1A and 1B events which have been attributed to neutrinos and used in our calculation. Included is the time, location in array, energy deposition, and sidereal coordinates.

Date	G.M.T.	Elements	Energy deposition (MeV)	Right ascension (deg)	Declination (deg)
23 Feb. 1965	20:47	E4L W4L	29 18	219.9 ± 12.9	7.3 ± 7.9
28 Feb.	23:20	E5M W5U	55 118	119.1 ± 11.9	13.3 ± 9.7
17 Mar.	17:52	E4L W4L	19 16	58.9 ± 11.5	50.9 ± 9.5
20 Apr.	13:15	E2M W2M	24 24	13.1 ± 13.0	43.2 ± 10.1
1 June	21:36	E1L W2L	22 19	326.6 ± 12.6	11.6 ± 7.3
3 June	00:41	E4U W4M	8 26	176.8 ± 11.8	8.0 ± 8.2
1 July	14:19	E3M W3U	19 26	255.2 ± 11.4	27.7 ± 5.5
21 Nov.	14:06	E4L W4L	Large 25	···	···

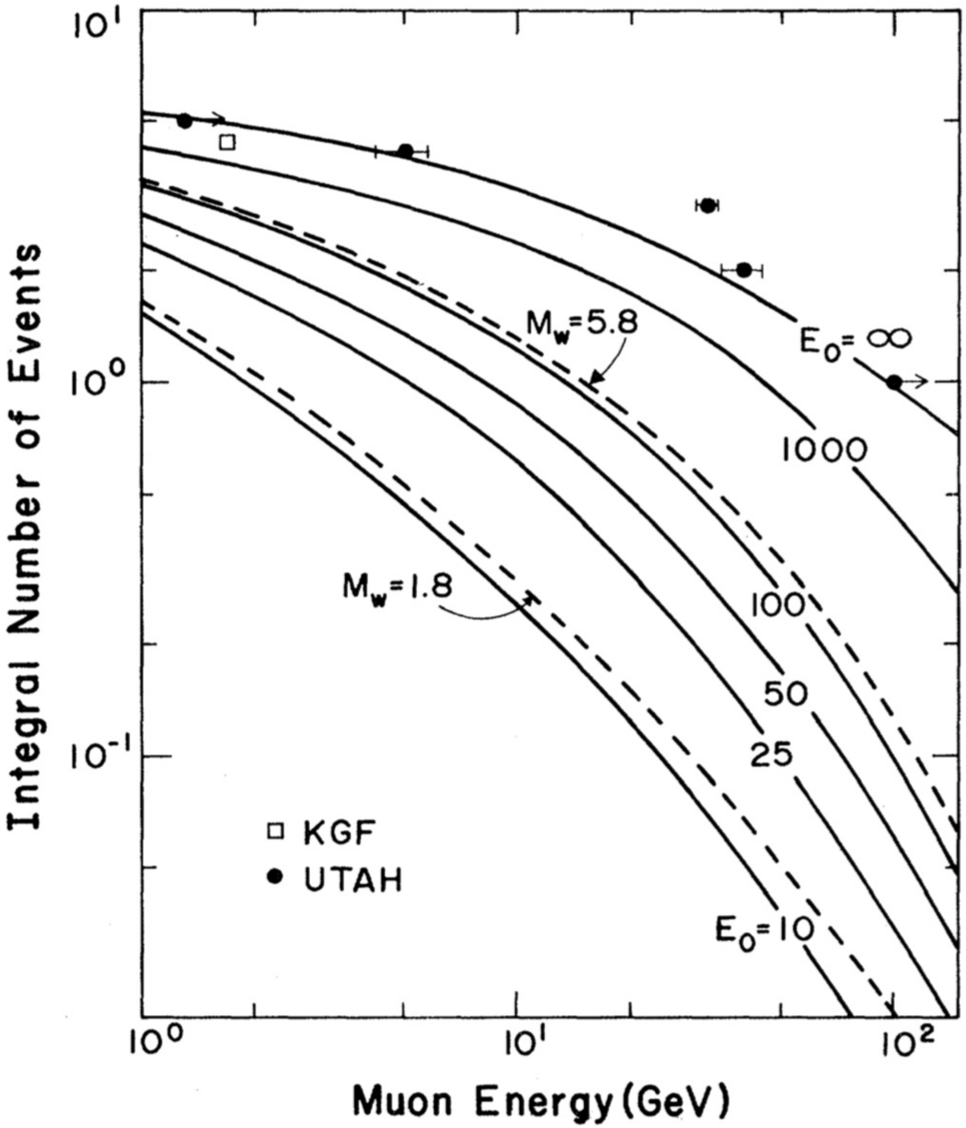
Neutrino detector in a Utah salt mine.

Fast timing (versus of muon)
Magnetized Iron

Shallow depth 1500 m.w.e.
only up-going
(nu-induced) muons



H. E. Bergeson, G. L. Cassiday and M. B. Hendricks,
“Neutrino-induced muons deep underground,”
Phys. Rev. Lett. **31**, 66 (1973).



603 days live time

10^6 down going muons

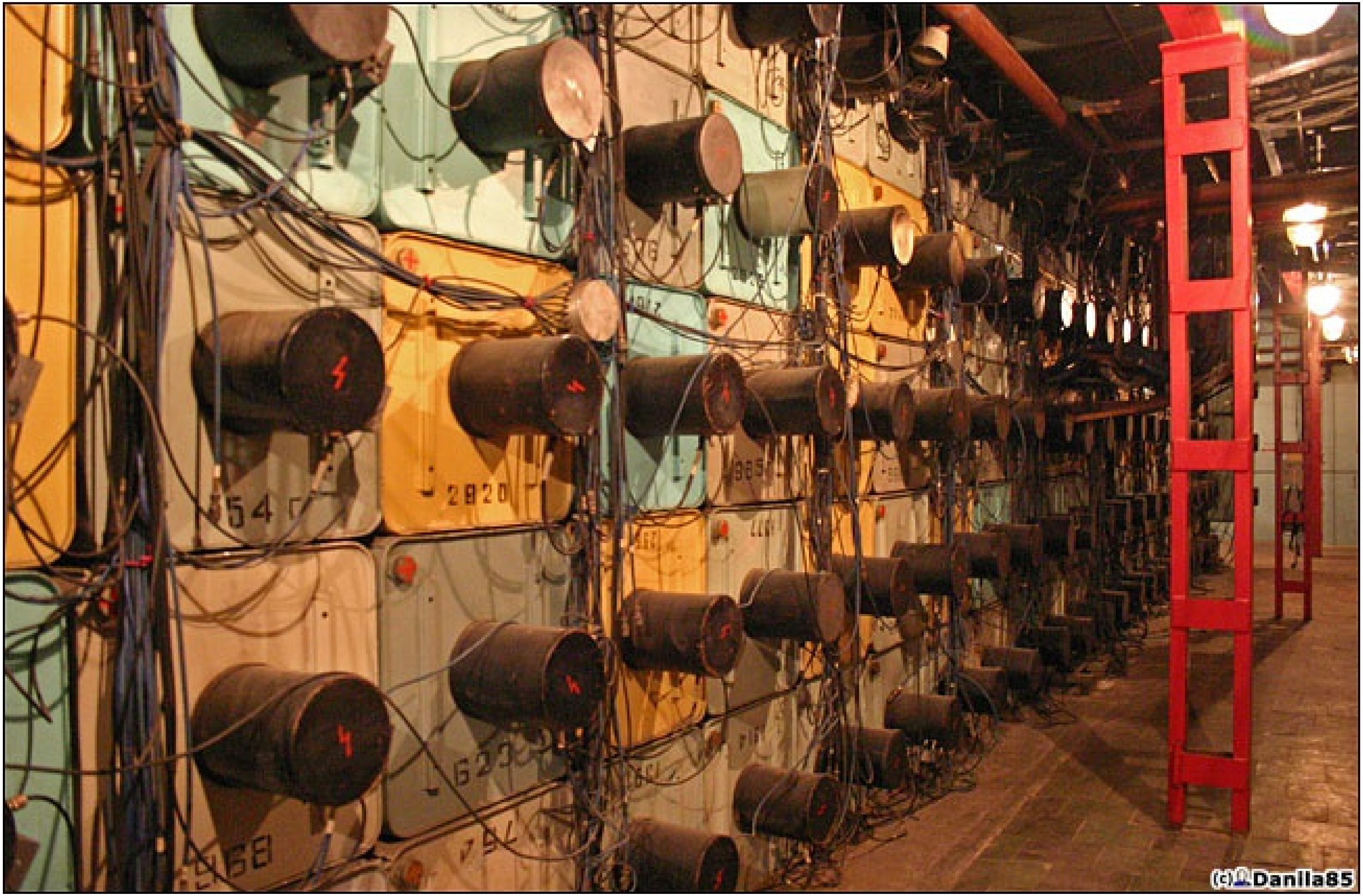
5 up-going muons
(spectrum !)

1σ, 2σ, and 3σ

$E_0 > 320$, 80, and 29 GeV

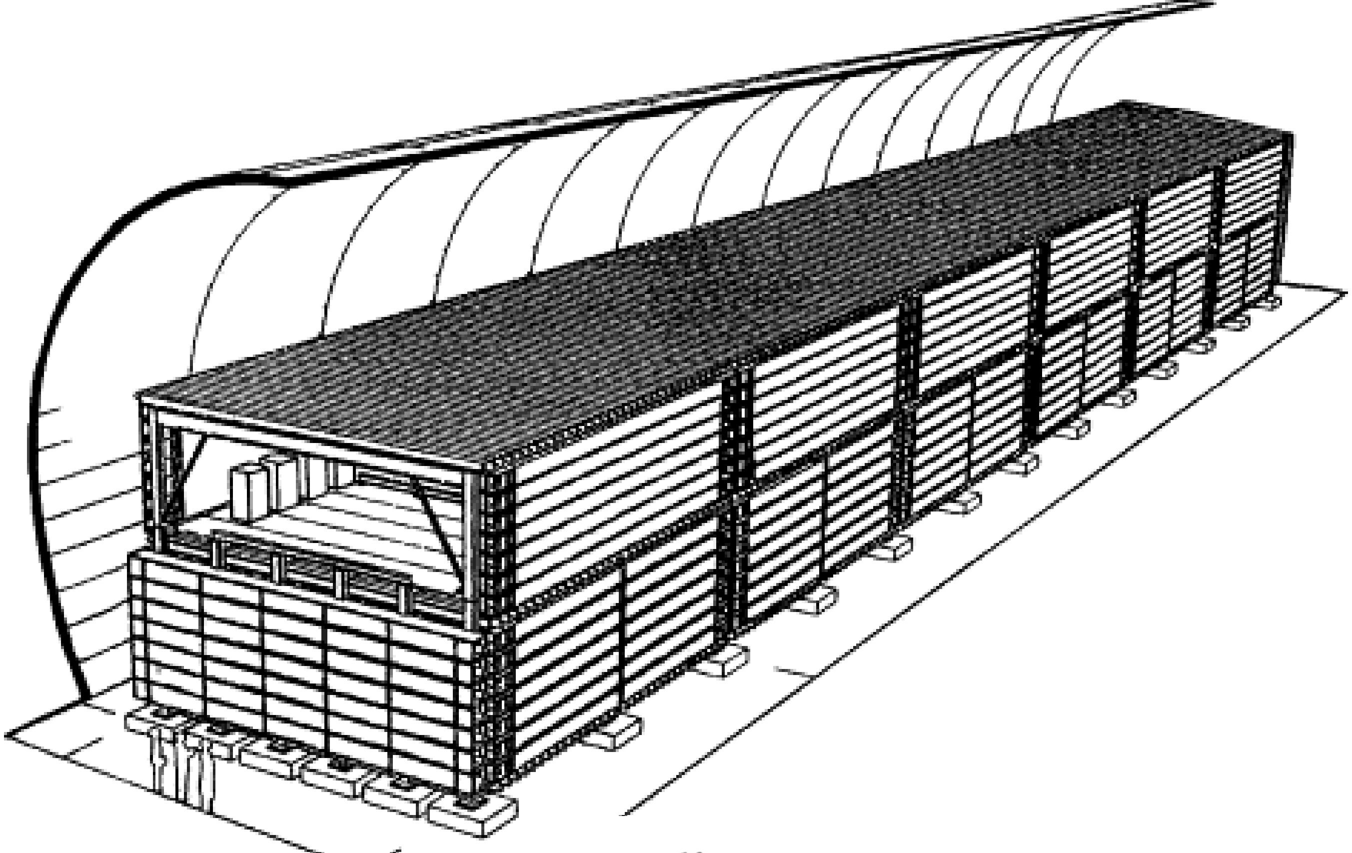
$M_W > 10$, 5, and 3 GeV

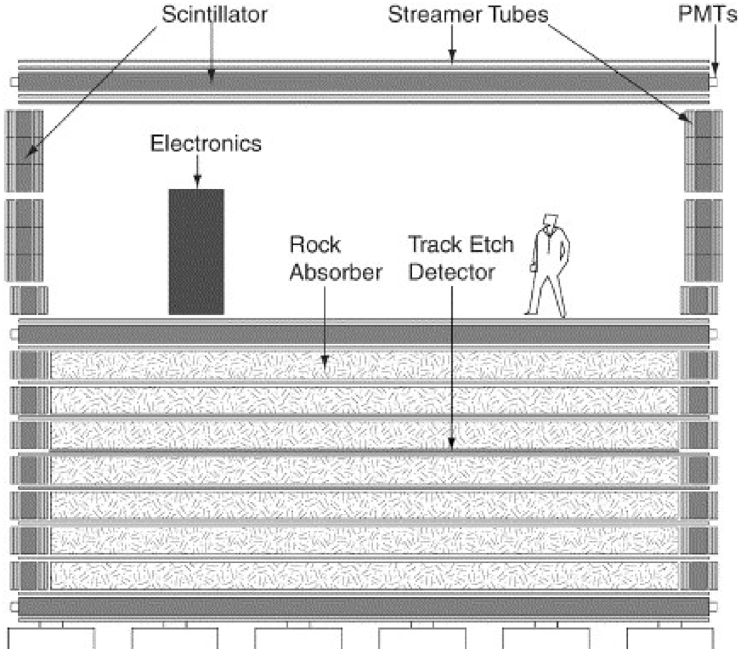
Baxsan Neutrino telescope

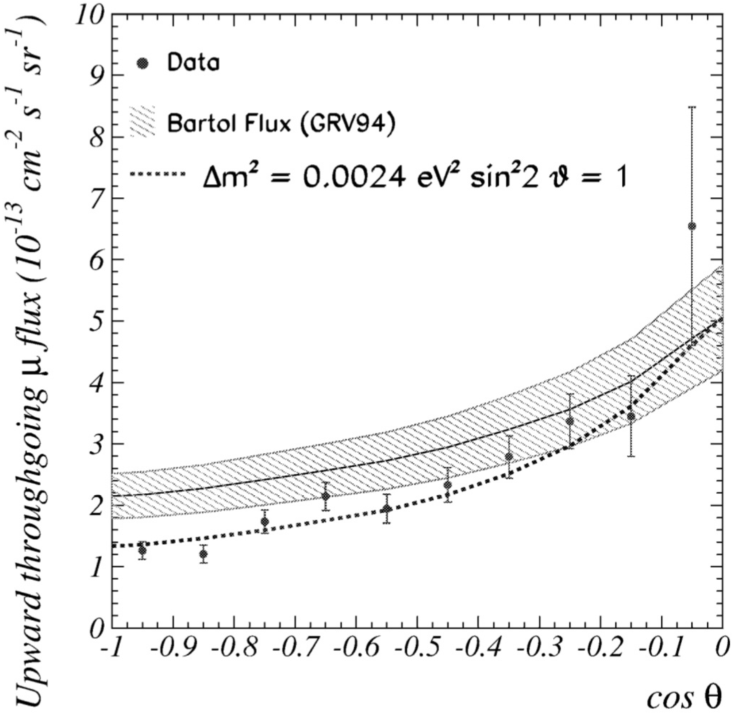



(c)Danila85

MACRO detector at Gran Sasso

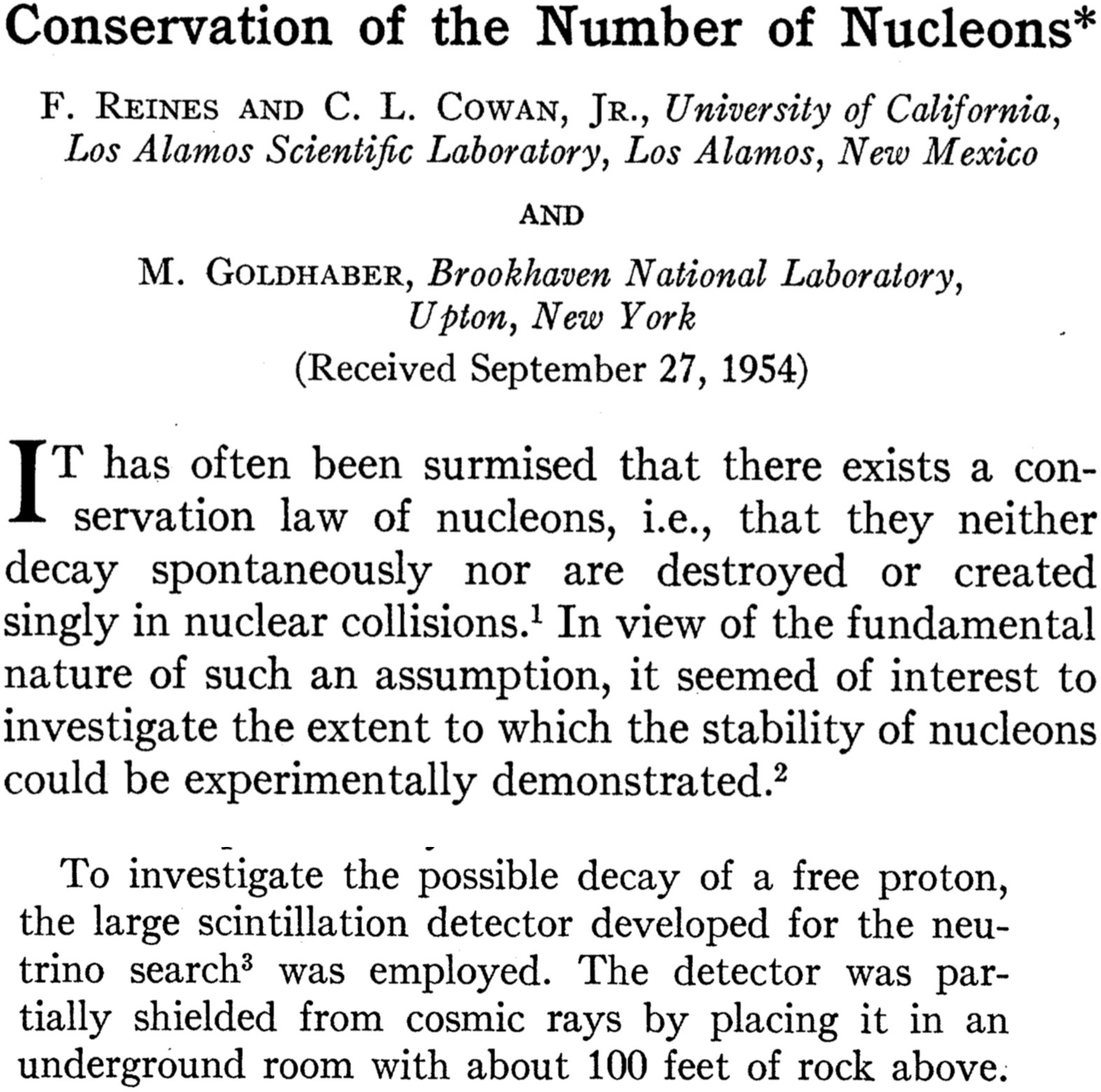






PROTON DECAY

Physical Review 96, 1157 (1954)



Conservation of the Number of Nucleons*

F. REINES AND C. L. COWAN, JR., *University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

AND

M. GOLDHABER, *Brookhaven National Laboratory, Upton, New York*

(Received September 27, 1954)

IT has often been surmised that there exists a conservation law of nucleons, i.e., that they neither decay spontaneously nor are destroyed or created singly in nuclear collisions.[1] In view of the fundamental nature of such an assumption, it seemed of interest to investigate the extent to which the stability of nucleons could be experimentally demonstrated.[2]

To investigate the possible decay of a free proton, the large scintillation detector developed for the neutrino search[3] was employed. The detector was partially shielded from cosmic rays by placing it in an underground room with about 100 feet of rock above.

First limit: 10^{21} yr

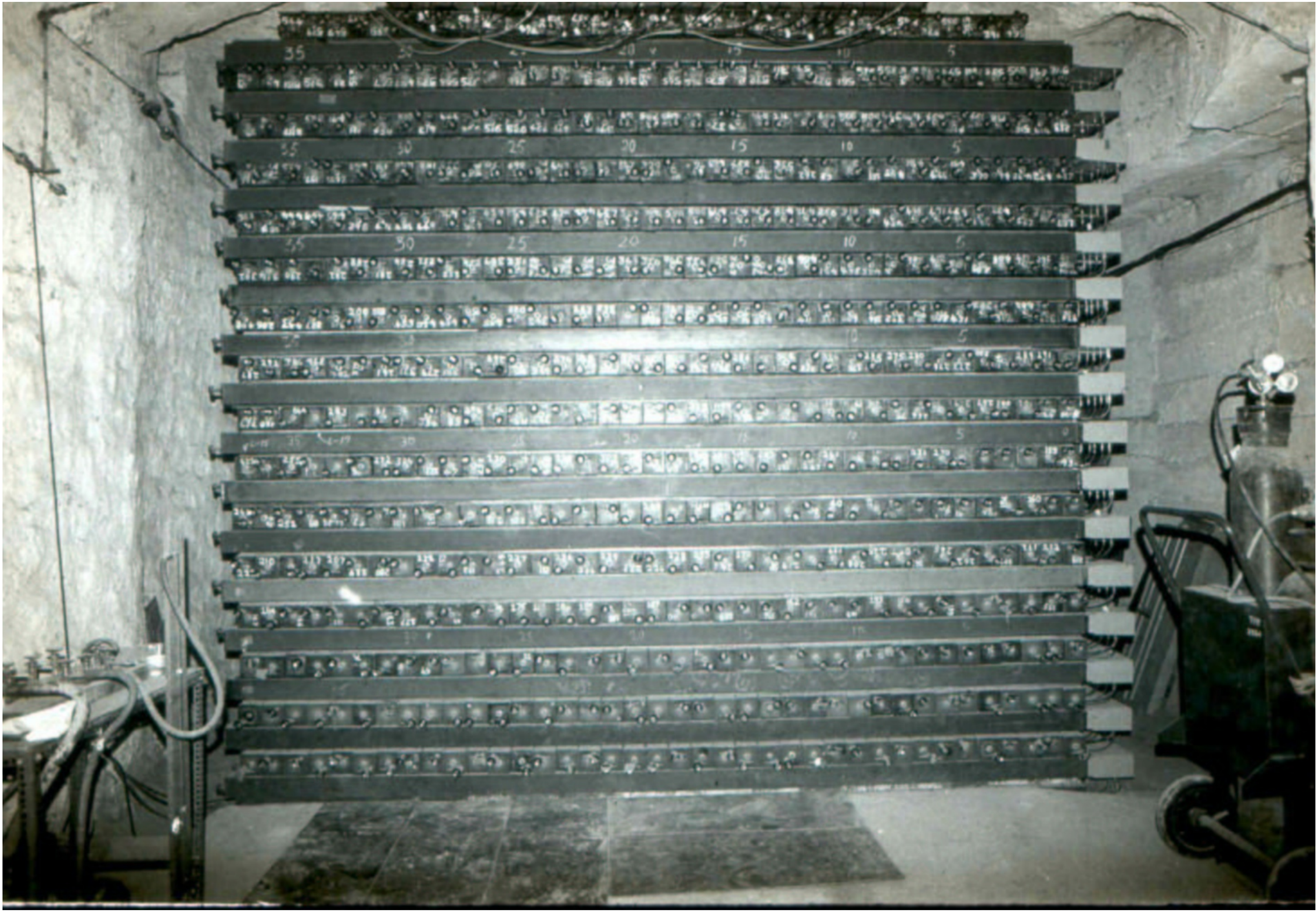
H. S. Gurr, W. R. Kropp, F. Reines and B. Meyer,
“Experimental test of baryon conservation,”
Phys. Rev. **158**, 1321 (1967).

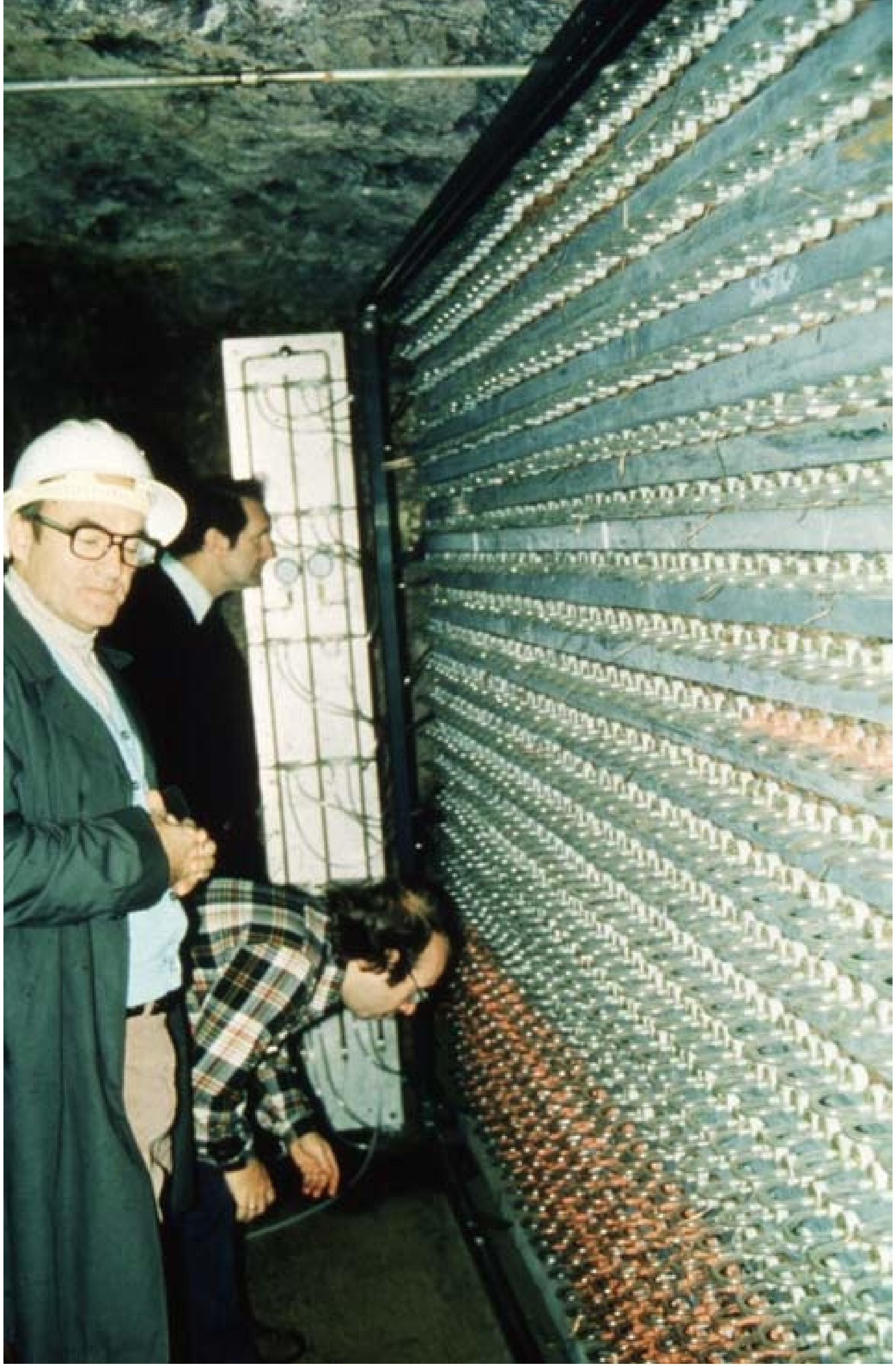
The data give no evidence for the existence of nucleon decay. Lower limits on the half-life of the nucleon from 2×10^{28} to 8×10^{29} yr depending on the assumed decay mode are established. It is seen that the atmospheric muon neutrino serves as the major source of background in the present experiment. If it were possible to positively identify all muon neutrino events, improved half-life limits could be established.

J. C. Pati and A. Salam,
“Is Baryon Number Conserved?,”
Phys. Rev. Lett. **31**, 661 (1973).

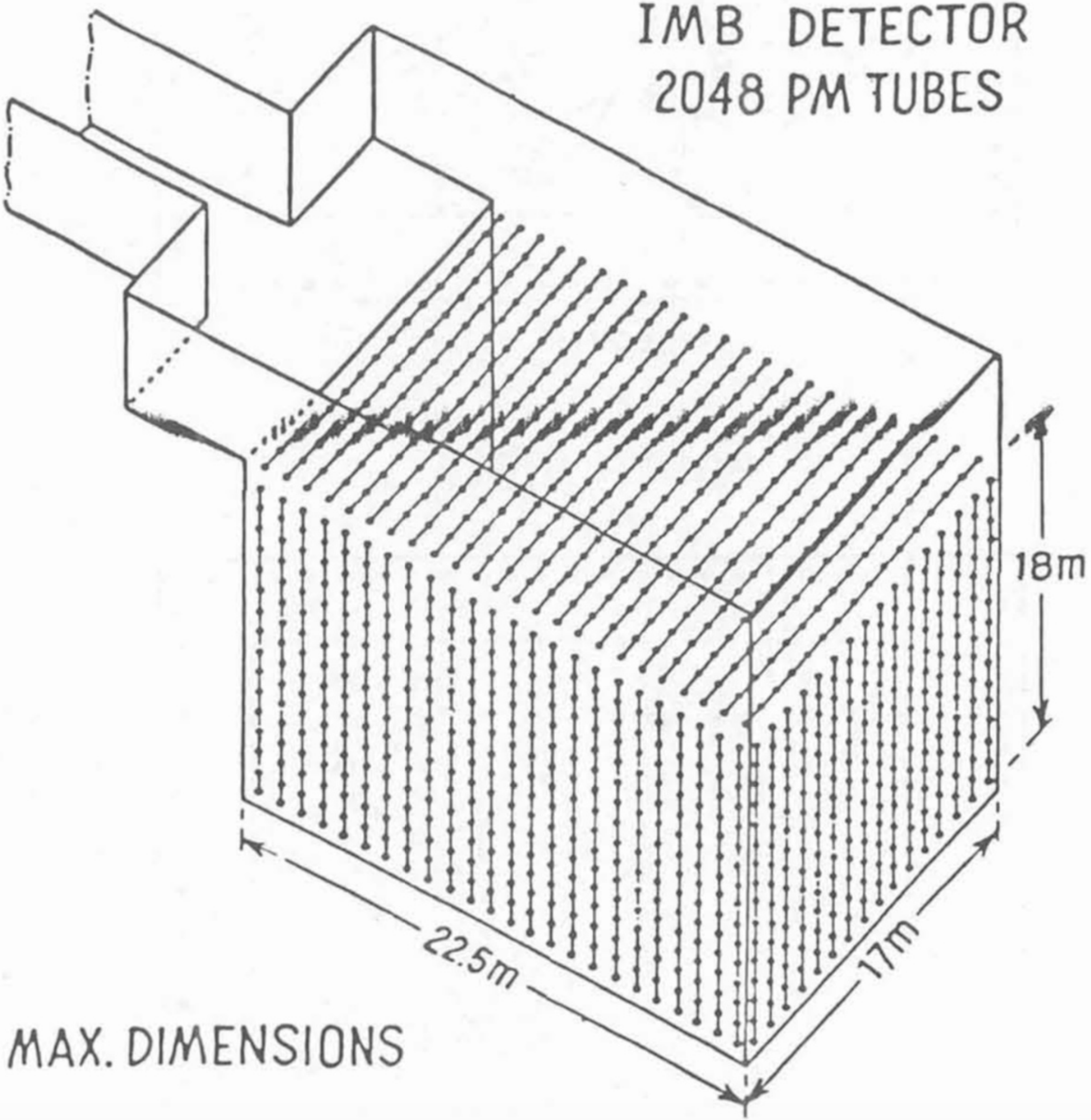
H. Georgi and S. L. Glashow,
“Unity of All Elementary Particle Forces,”
Phys. Rev. Lett. **32**, 438 (1974).

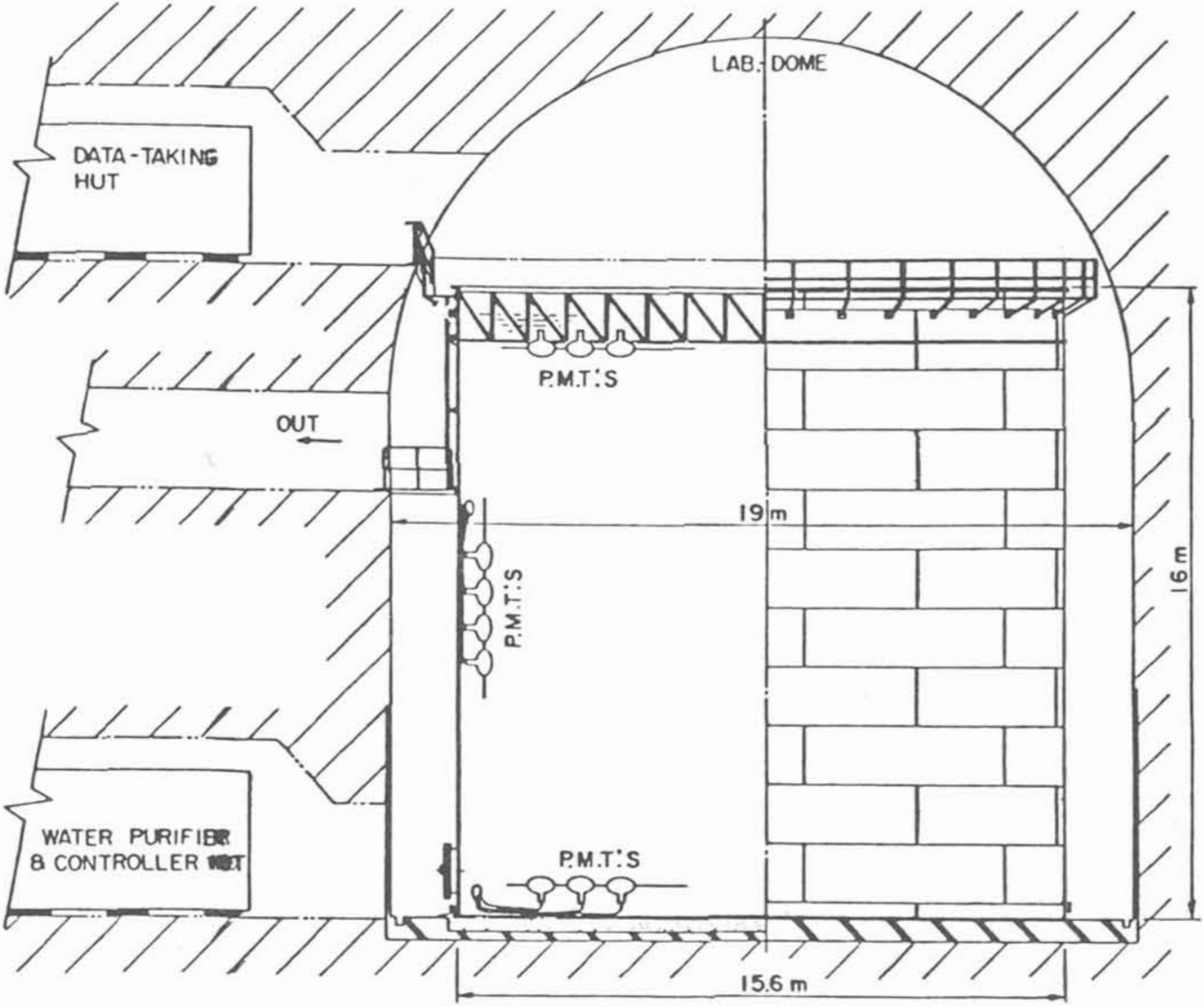
H. Georgi, H. R. Quinn and S. Weinberg,
“Hierarchy of Interactions in Unified Gauge Theories,”
Phys. Rev. Lett. **33**, 451 (1974).


35 30 25 20 15 10 5
35 30 25 20 15 10 5
35 30 25 20 15 10 5
35 30 25 20 15 10 5

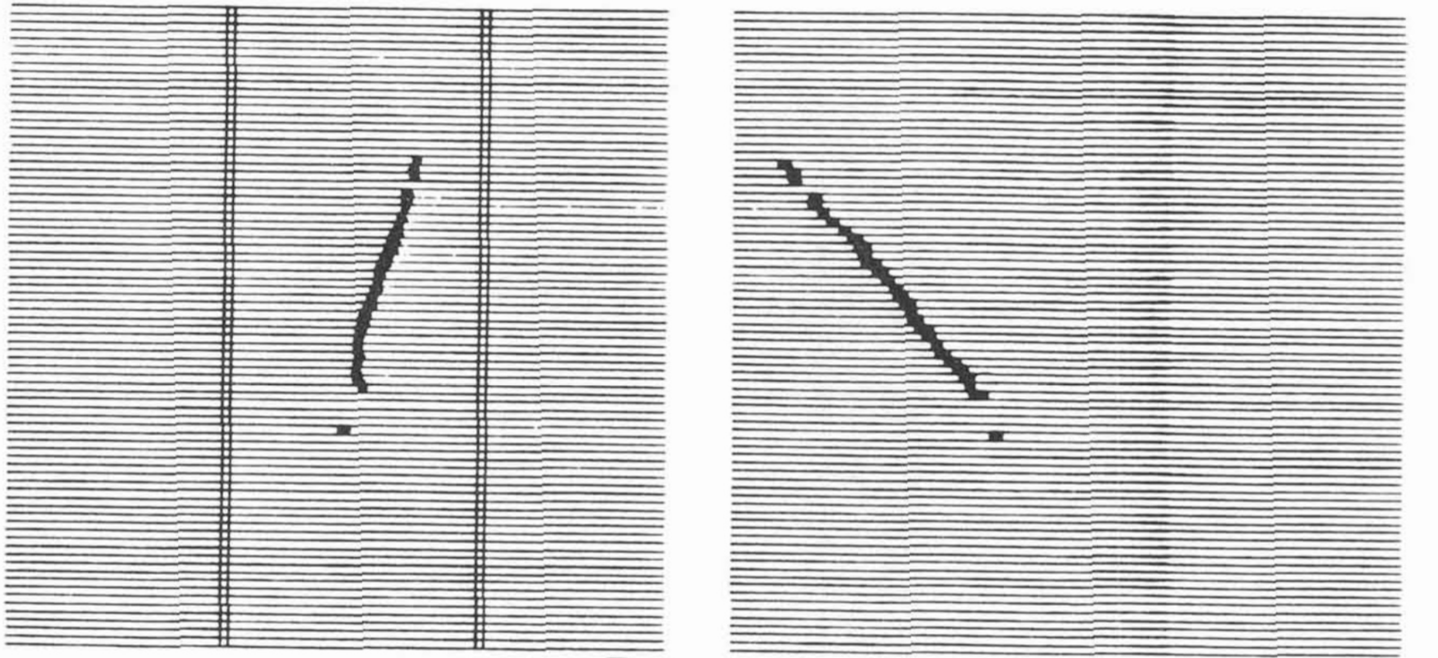


Soudan 1
detector

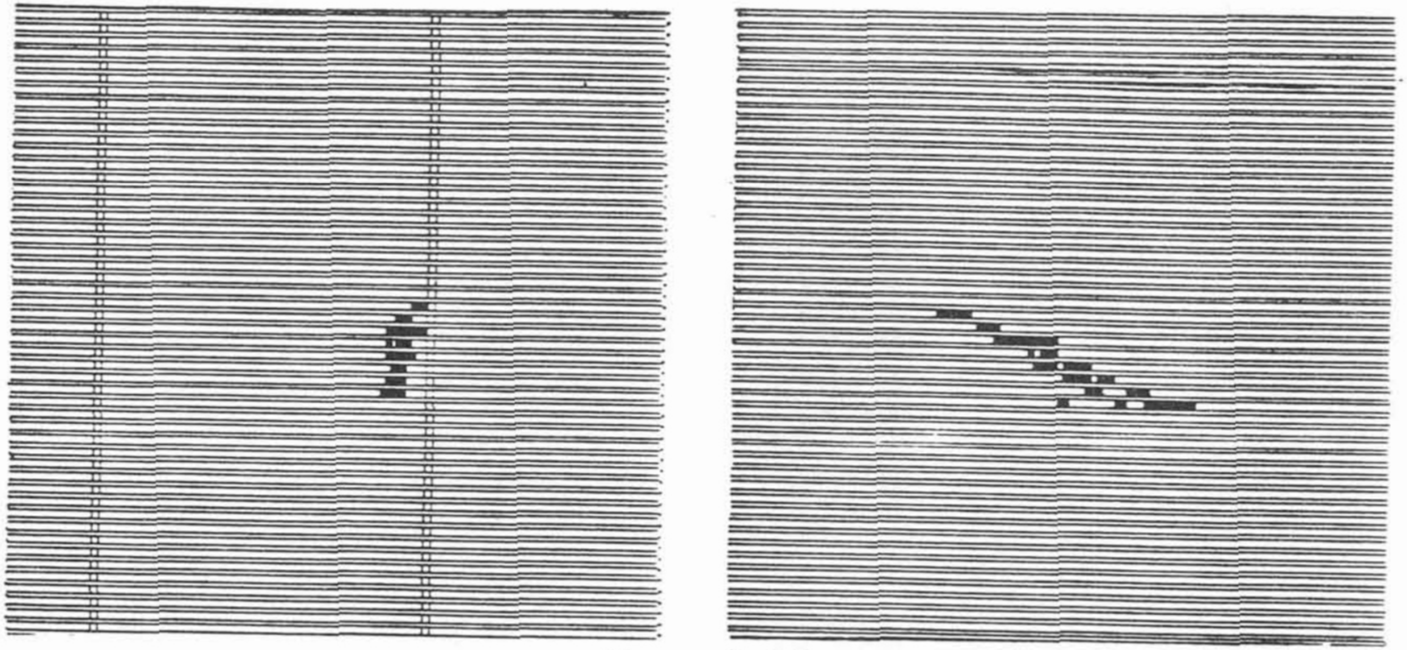

IMB DETECTOR
2048 PM TUBES
18m
22.5m
17m
MAX. DIMENSIONS


LAB. DOME
DATA-TAKING HUT
OUT
P.M.T.'S
P.M.T.'S
19 m
16 m
WATER PURIFIER
& CONTROLLER HUT
P.M.T.'S
15.6 m

NUSEX: contained events



Event 15



Event 14

The “Anomaly"

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

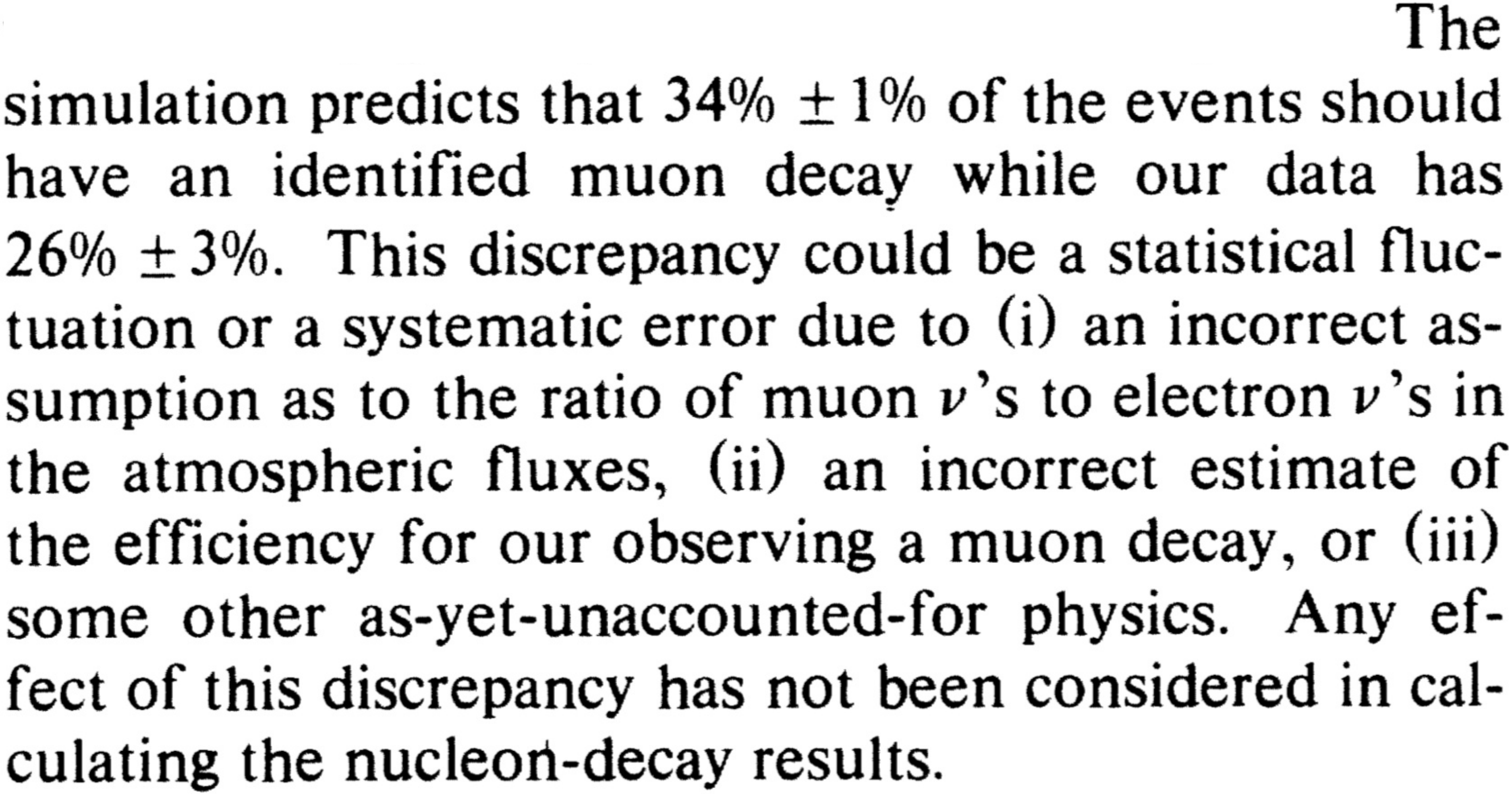
Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

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
University of Michigan, Ann Arbor, Michigan 48109
Brookhaven National Laboratory, Upton, New York 11973
Cleveland State University, Cleveland, Ohio 44115
University of Hawaii, Honolulu, Hawaii 96822
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.



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.

T. J. Haines *et al.* [IMB Collaboration]
“Calculation of Atmospheric Neutrino Induced Backgrounds in a Nucleon Decay Search,”
Phys. Rev. Lett. **57**, 1986 (1986).

M. Nakahata *et al.* [Kamiokande Collaboration],
"Atmospheric Neutrino Background and Pion Nuclear Effect for Kamioka Nucleon Decay Experiment,"
J. Phys. Soc. Jap. **55**, 3786 (1986).

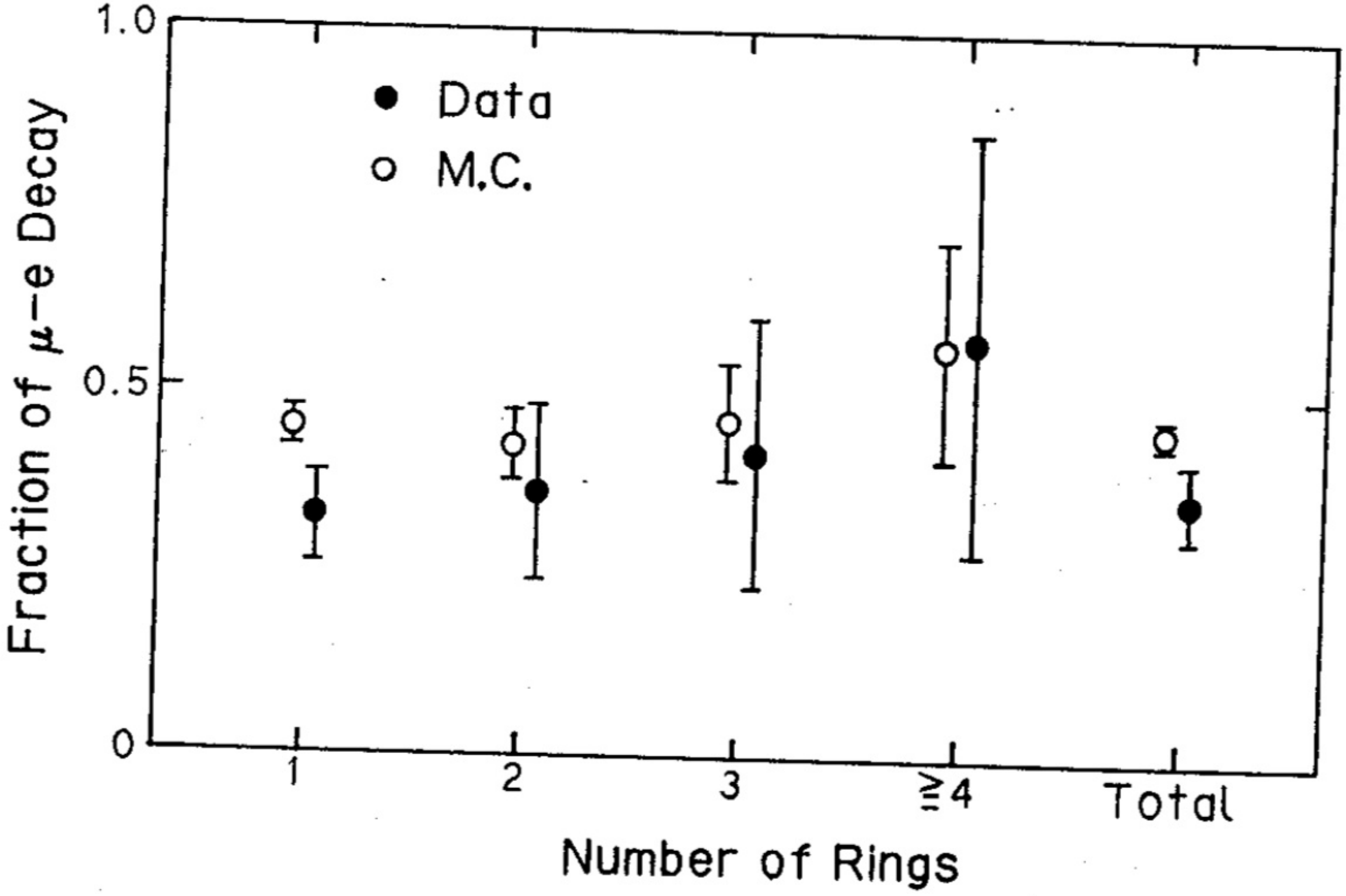


Fig. 19

Volume 205, number 2,3 PHYSICS LETTERS B 28 April 1988

EXPERIMENTAL STUDY OF THE ATMOSPHERIC NEUTRINO FLUX

K.S. HIRATA, T. KAJITA, M. KOSHIBA, M. NAKAHATA, S. OHARA, Y. OYAMA, N. SATO,
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E.W. BEIER, L.R. FELDSCHER, E.D. FRANK, W. FRATI, S.B. KIM, A.K. MANN,
F.M. NEWCOMER, R. VAN BERG, W. ZHANG
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

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AT&T Bell Laboratories, Holmdel, NJ 07922, USA

Received 25 January 1988

We have observed 277 fully contained events in the KAMIOKANDE detector. The number of electron-like single-prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single-prong events is 59 ± 7% (statistical error) of the predicted number of the Monte Carlo calculation. We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.

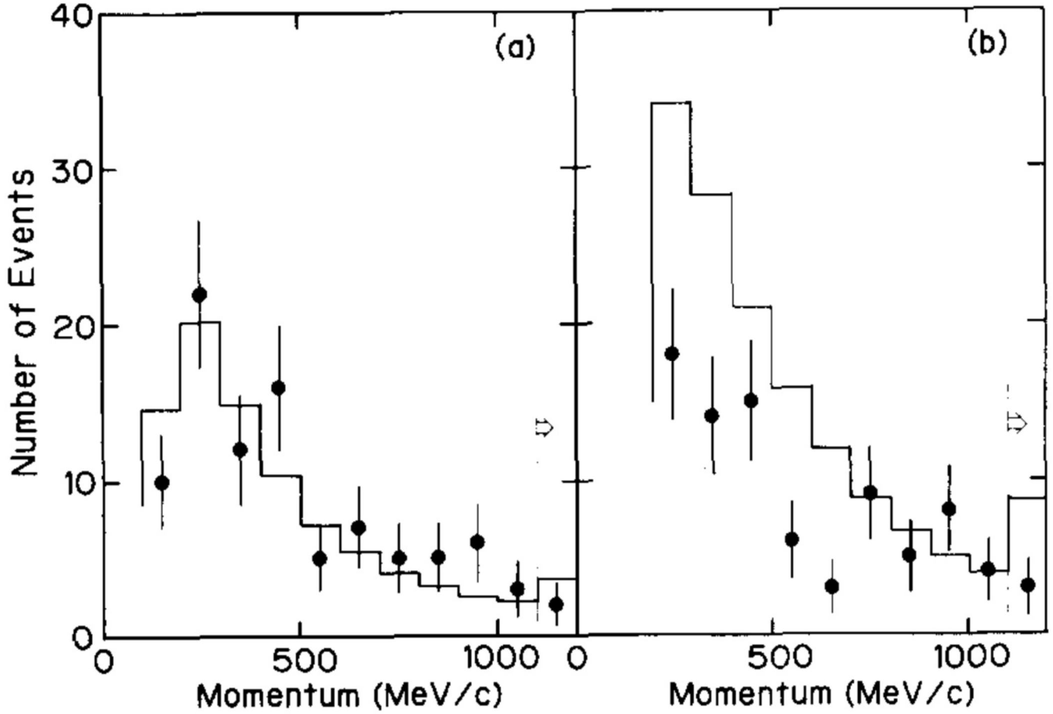


Fig. 1. Momentum distributions for: (a) electron-like events and (b) muon-like events. The last momentum bin sums all events with their momenta larger than 1100 MeV/c. The histograms show the distributions expected from atmospheric neutrino interactions.

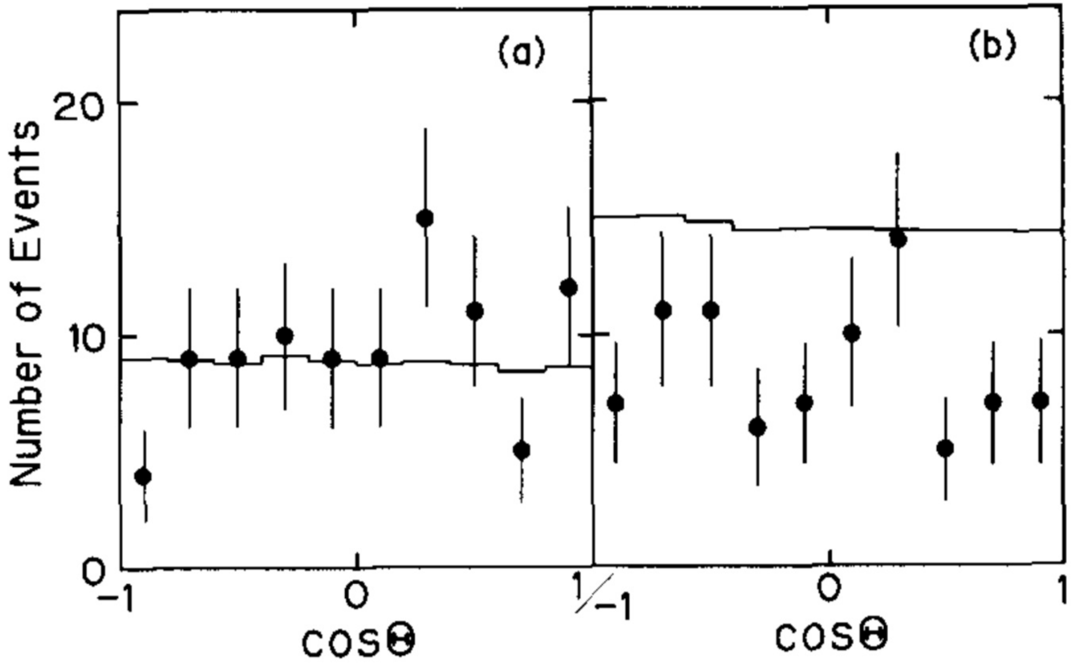


Fig. 2. Zenith angle distributions for: (a) electron-like events and (b) muon-like events. $\cos\Theta=1$ corresponds to downward-going events. The histograms show the distributions expected from atmospheric neutrino interactions.

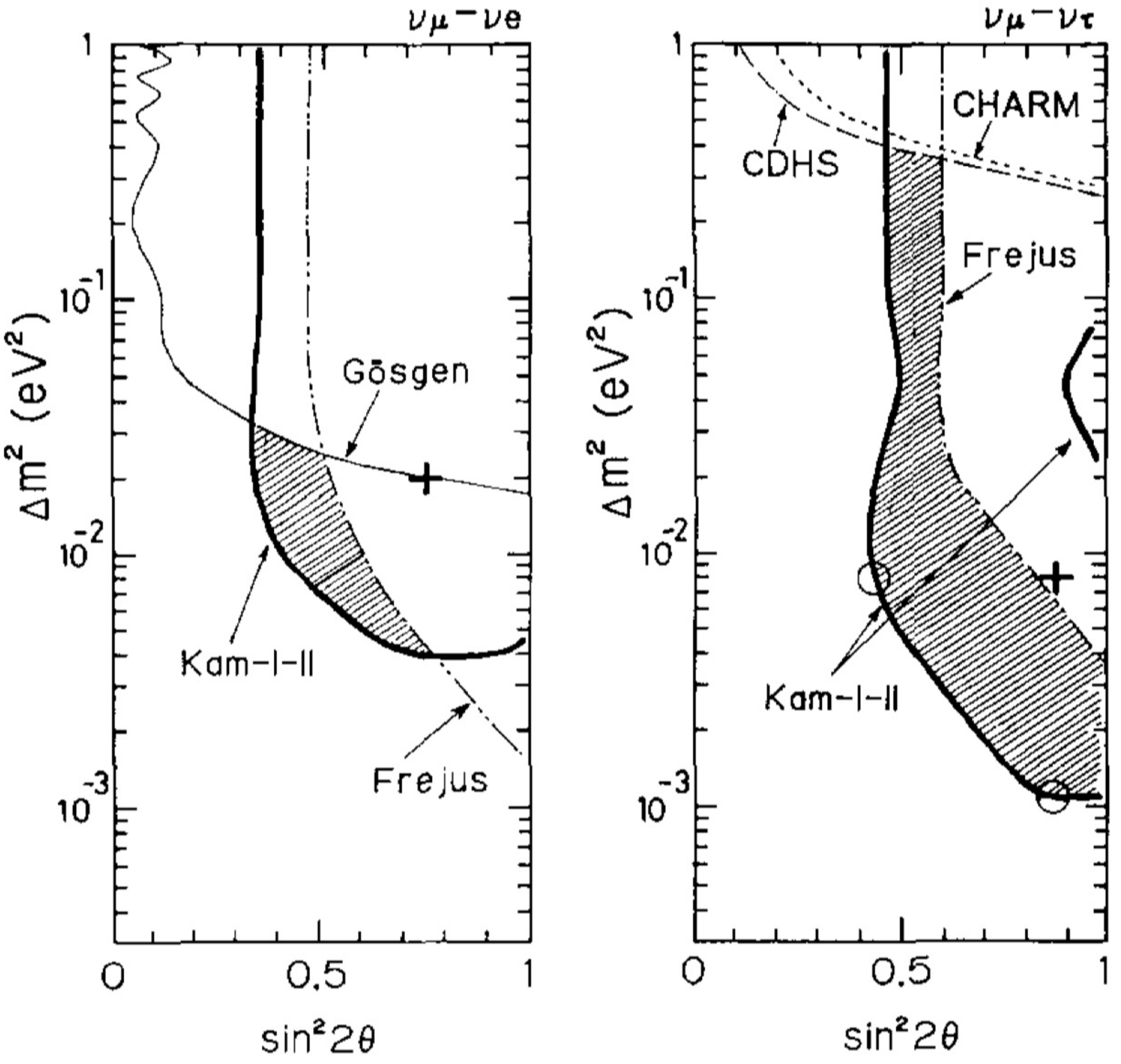
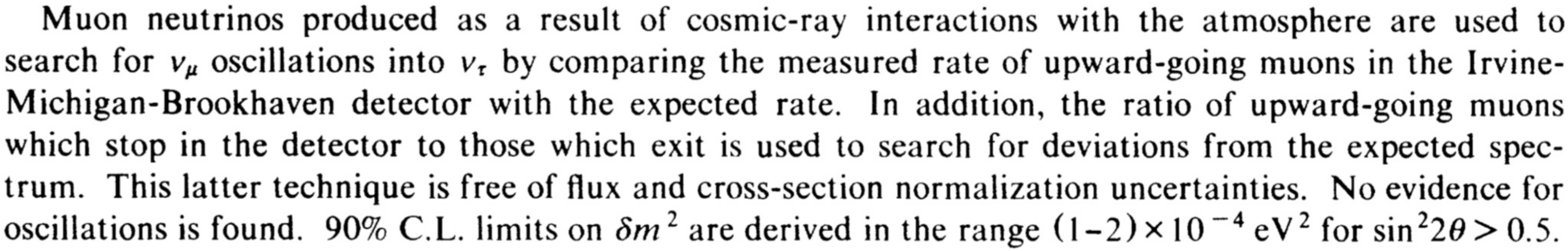
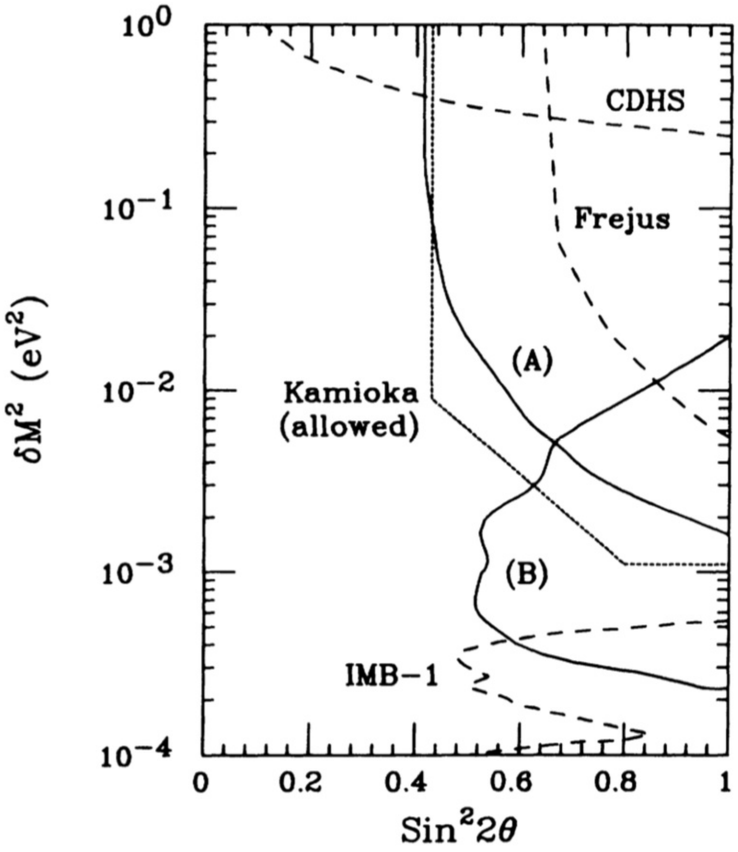


Fig. 4. The allowed neutrino oscillation parameters at 90% CL from the Kam-I–II data, for the case of $\nu_\mu \leftrightarrow \nu_e$ (left), and $\nu_\mu \leftrightarrow \nu_\tau$ (right). The best fit parameter sets are shown by crosses. The two open circles in the figure for $\nu_\mu \leftrightarrow \nu_\tau$ indicate the points which are used in figs. 2 and 3. All the other experimental results [13,22–24] show excluded regions.

R. Becker-Szendy *et al.*, [IMB Collaboration]
"A Search for muon-neutrino oscillations with the IMB detector,"
Phys. Rev. Lett. **69**, 1010 (1992).



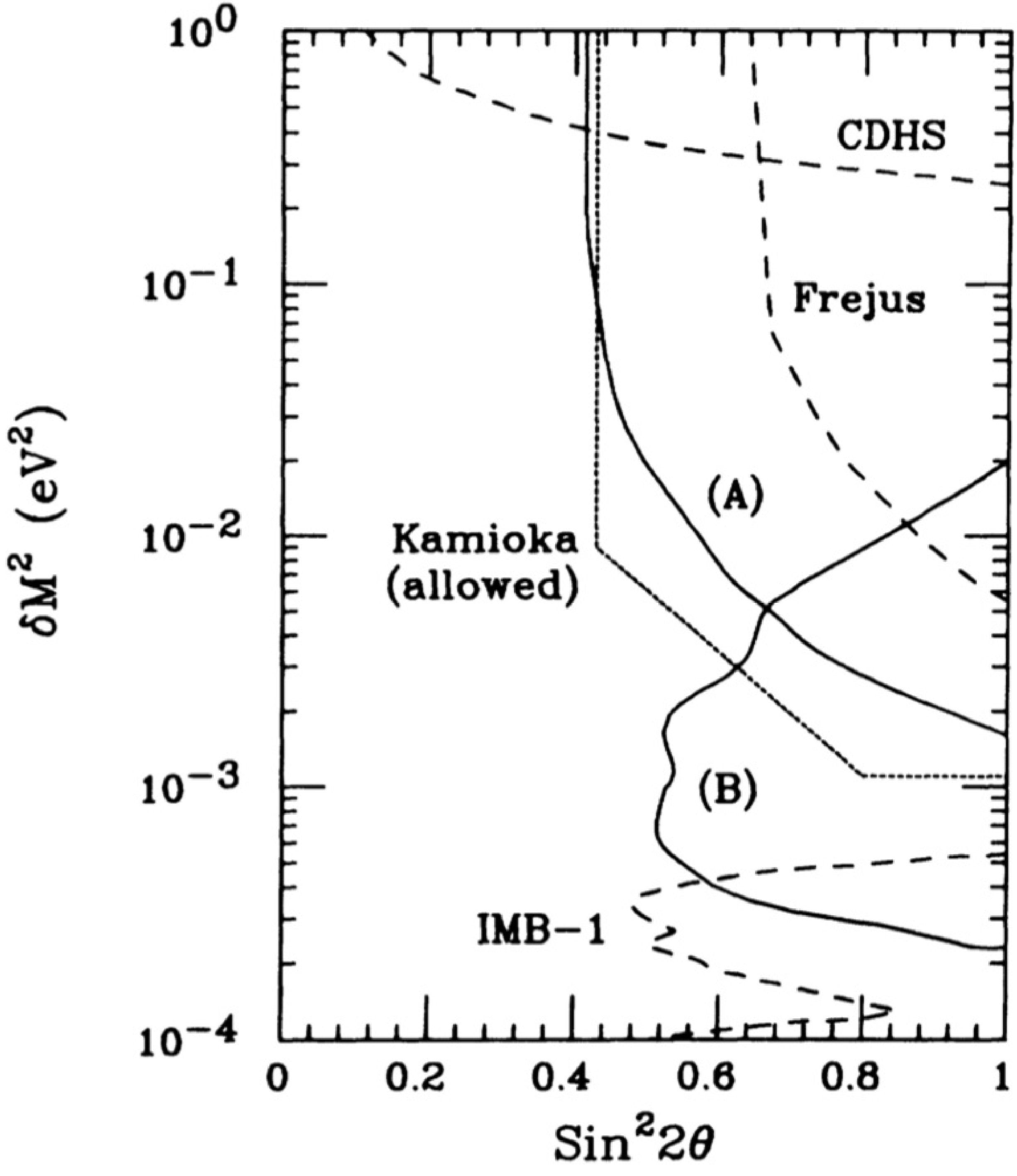
Muon neutrinos produced as a result of cosmic-ray interactions with the atmosphere are used to search for ν_μ oscillations into ν_τ by comparing the measured rate of upward-going muons in the Irvine-Michigan-Brookhaven detector with the expected rate. In addition, the ratio of upward-going muons which stop in the detector to those which exit is used to search for deviations from the expected spectrum. This latter technique is free of flux and cross-section normalization uncertainties. No evidence for oscillations is found. 90% C.L. limits on δm^2 are derived in the range $(1-2)\times 10^{-4}$ eV^2 for $\sin^2 2\theta > 0.5$.



IMB

and

up-going muons



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
δM^2 (eV^2)
0
0.2
0.4
0.6
0.8
1
$\mathrm{Sin}^2 2\theta$
CDHS
Frejus
(A)
Kamioka
(allowed)
(B)
IMB−1

Systematic errors

[in experiment or in the predictions]

or

NEW PHYSICS ?

$$\dot{N}_{\nu,\text{events}} =$$

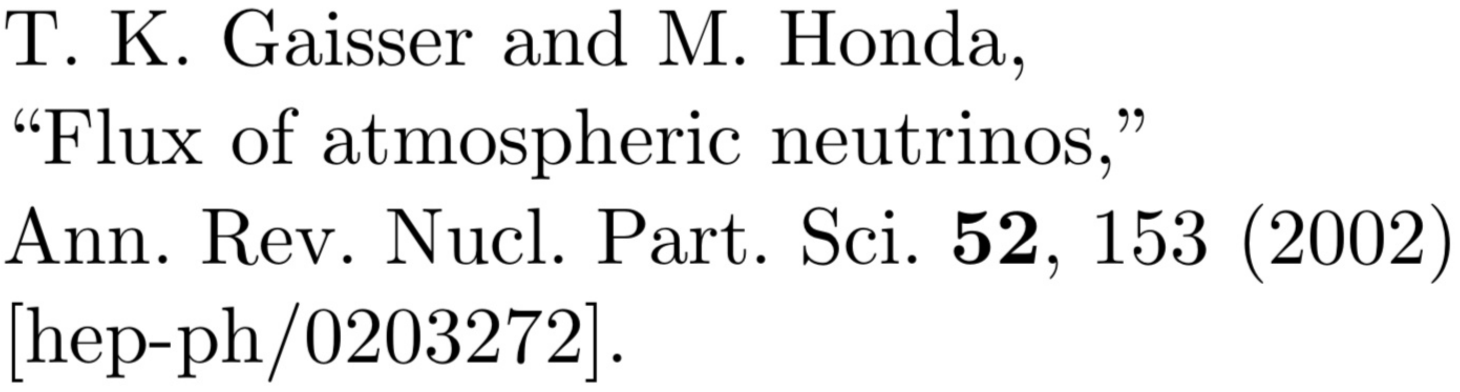
$$\phi_{\mathrm{CR}}(E_0) \otimes \begin{bmatrix}\text{Solar}\\ \text{Modulations}\end{bmatrix} \otimes \begin{bmatrix}\text{Geomagnetic}\\ \text{effects}\end{bmatrix}$$

$$\otimes\ \sigma_{p\mathrm{Air}\rightarrow\pi^{\pm},K^{\pm,0}} \otimes \begin{bmatrix}\text{Weak}\\ \text{Decays}\end{bmatrix} \otimes \begin{bmatrix}\text{Shower}\\ \text{Calculation}\end{bmatrix}$$

$$\otimes\ \sigma_{\nu A}(E_\nu) \otimes \begin{bmatrix}\text{Detector}\\ \text{Properties}\end{bmatrix}$$

$$
\begin{aligned}
\dot{N}_{\nu,\text{events}} = {} & \\
& \phi_{\text{CR}}(E_0) \otimes \left[\begin{array}{l}\text{Solar}\\ \text{Modulations}\end{array}\right] \otimes \left[\begin{array}{l}\text{Geomagnetic}\\ \text{effects}\end{array}\right] \\
& \otimes\ \sigma_{p\text{Air}\to\pi^{\pm},K^{\pm,0}} \otimes \left[\begin{array}{l}\text{Weak}\\ \text{Decays}\end{array}\right] \otimes \left[\begin{array}{l}\text{Shower}\\ \text{Calculation}\end{array}\right] \\
& \otimes \boxed{\left[\begin{array}{l}\text{Neutrino}\\ \text{Propagation}\end{array}\right]} \\
& \otimes\ \sigma_{\nu A}(E_\nu) \otimes \left[\begin{array}{l}\text{Detector}\\ \text{Properties}\end{array}\right]
\end{aligned}
$$

Calculations of the Atmospheric Neutrino Flux



T. K. Gaisser and M. Honda,
“Flux of atmospheric neutrinos,”
Ann. Rev. Nucl. Part. Sci. **52**, 153 (2002)
[hep-ph/0203272].

Main channel for Atmospheric neutrinos

$$\pi^+ \to \mu^+ \; \nu_\mu$$

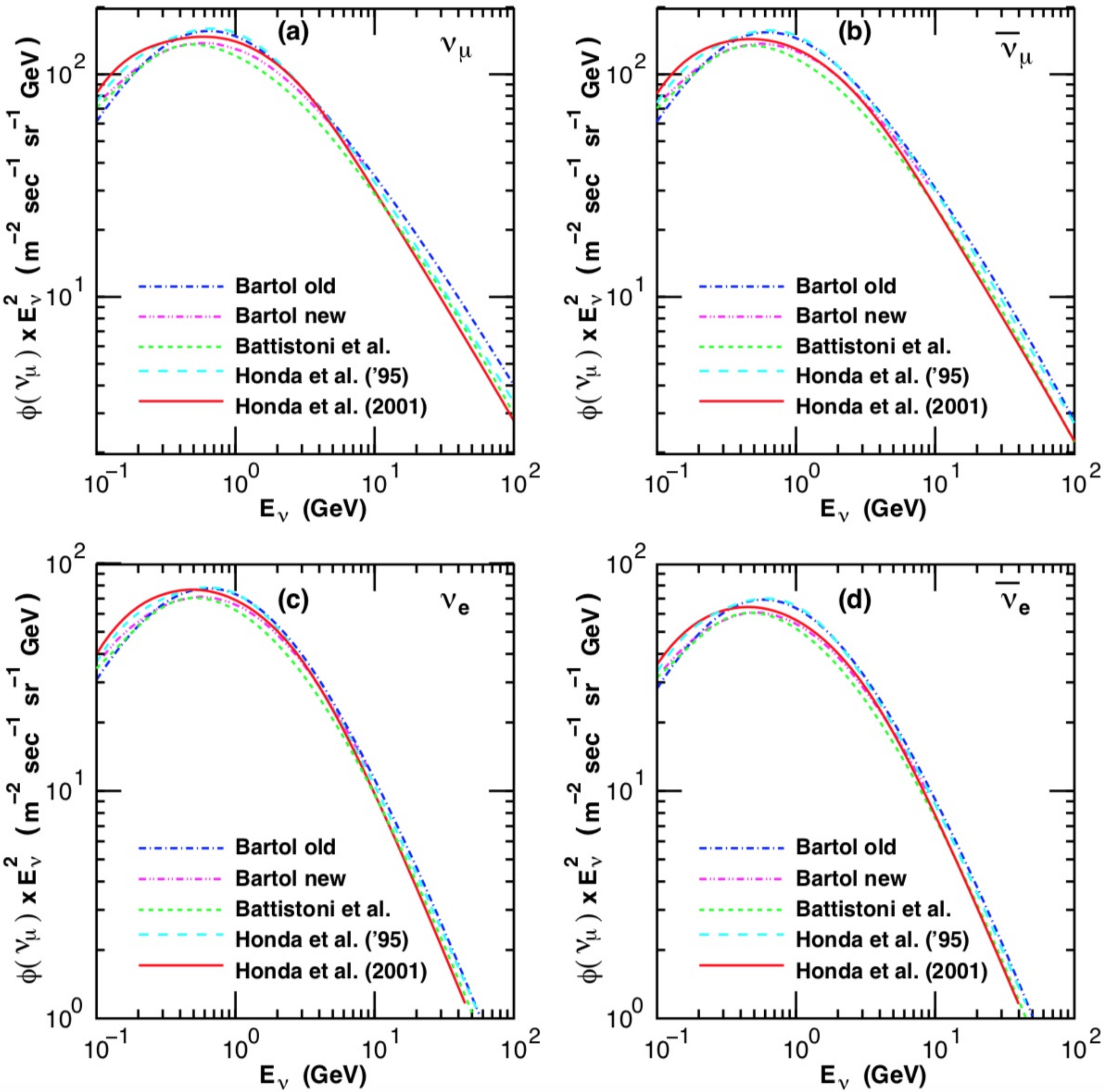
$$\hookrightarrow \overline{\nu}_\mu \; e^+ \; \nu_e$$

+ Charge conjugate channel

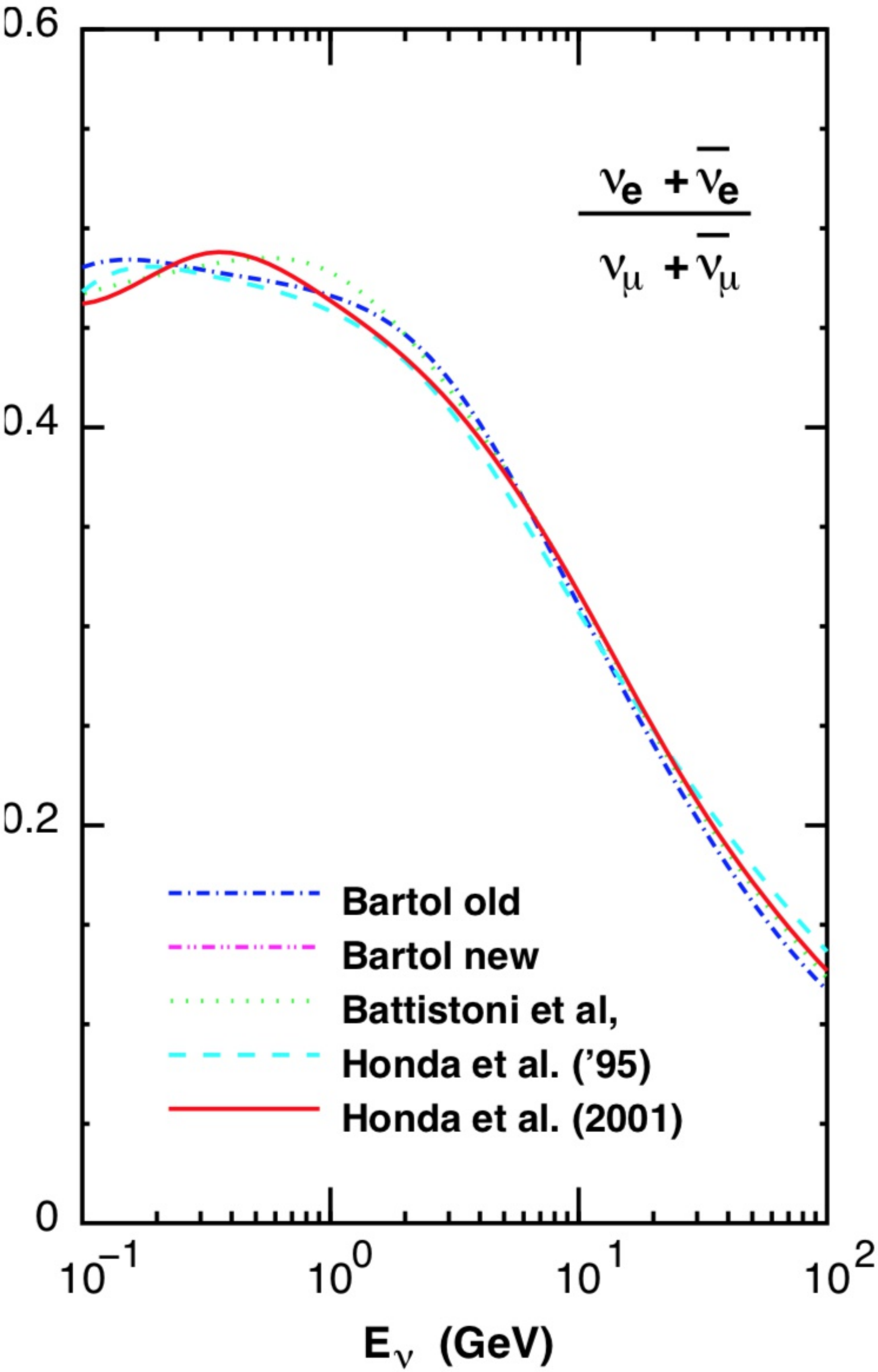
1. Robust "relation" between
   muon and electron neutrinos
   [Generated by the same source]

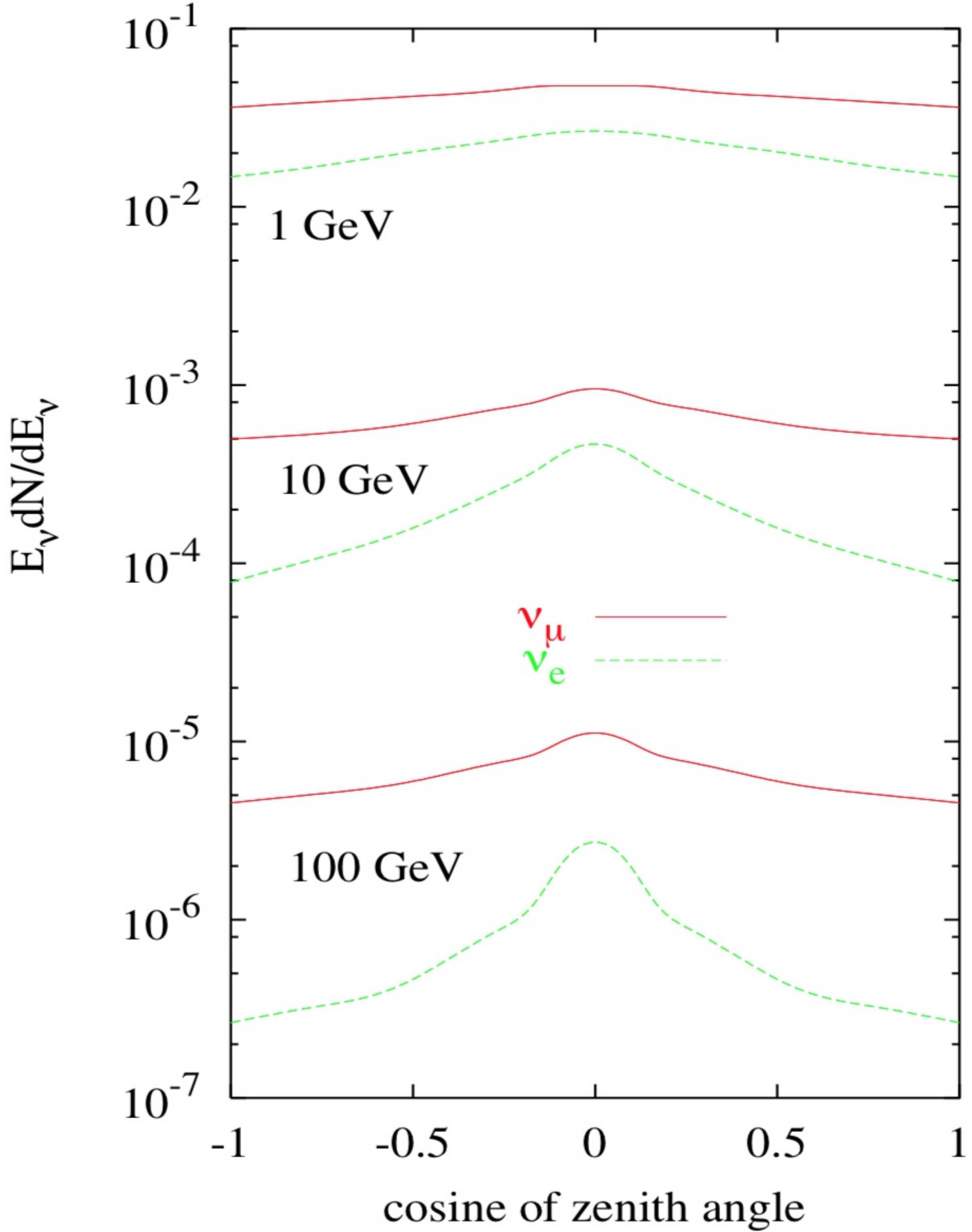
2. Possibility of "monitoring"
   of the neutrino beam using muons.

3. Up-Down symmetry

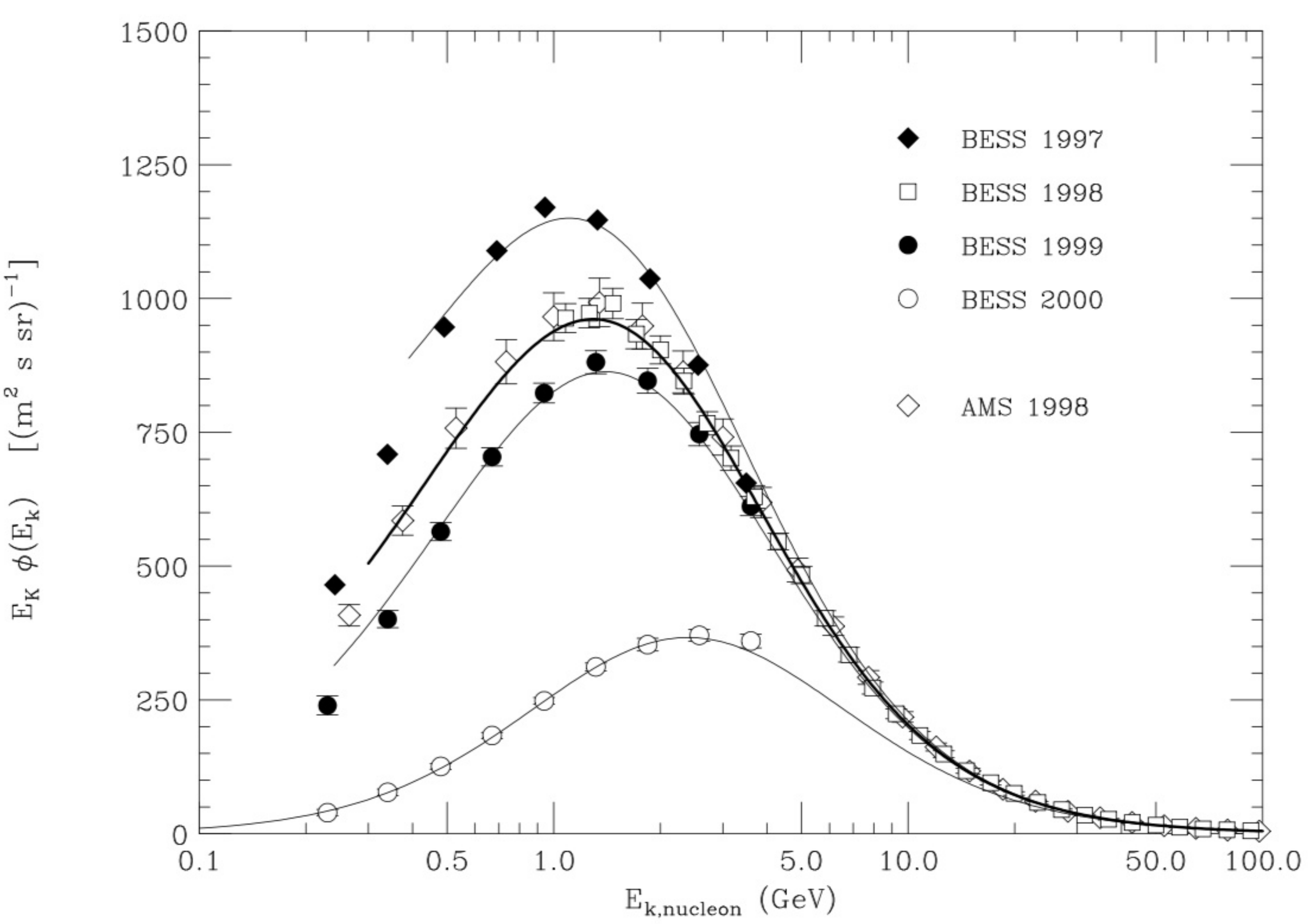

(a)
ν_μ
(b)
$\overline{\nu}_\mu$
(c)
ν_e
(d)
$\overline{\nu}_e$
$\phi(\nu_\mu) \times E_\nu^2$ ($m^{-2} sec^{-1} sr^{-1}$ GeV)
E_ν (GeV)
10^{-1}
10^0
10^1
10^2
Bartol old
Bartol new
Battistoni et al.
Honda et al. ('95)
Honda et al. (2001)

Neutrino Flavor Ratio



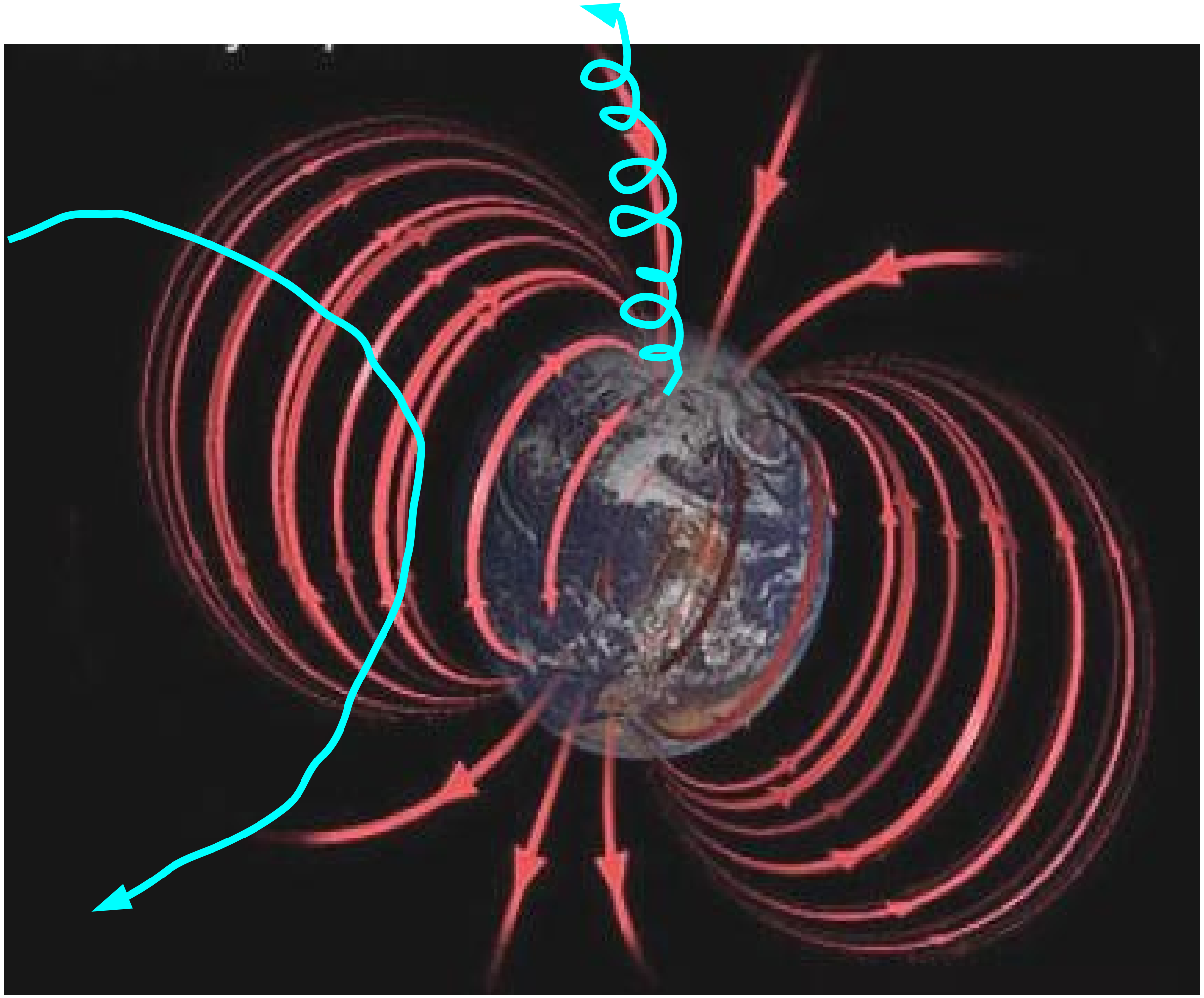

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$E_\nu dN/dE_\nu$
1 GeV
10 GeV
100 GeV
ν_μ
ν_e
-1
-0.5
0
0.5
1
cosine of zenith angle

Solar Modulations



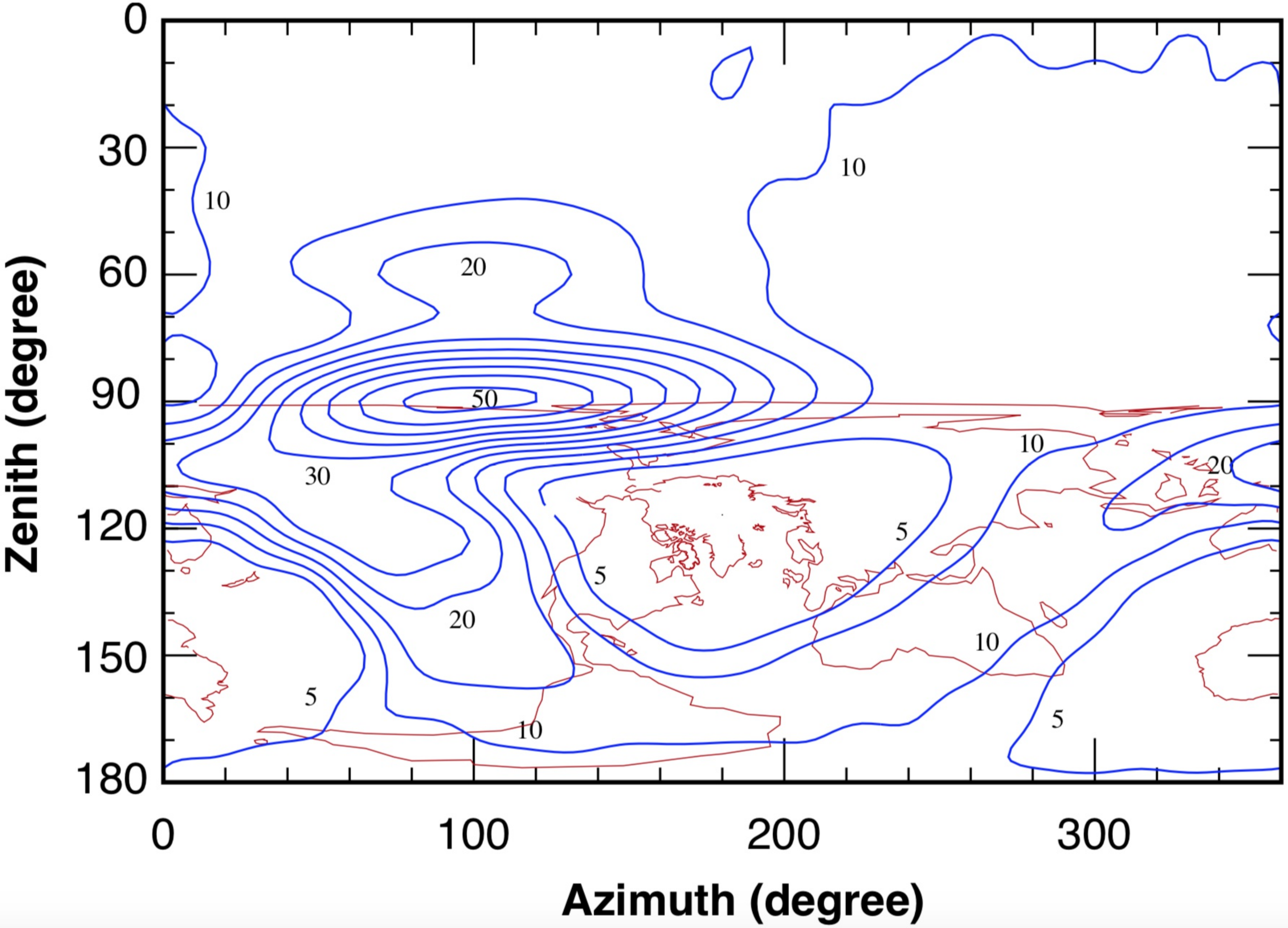
Relativistic charged particles. [Latitude effect]

Mostly protons (+ ionized nuclei) [East-West effect]



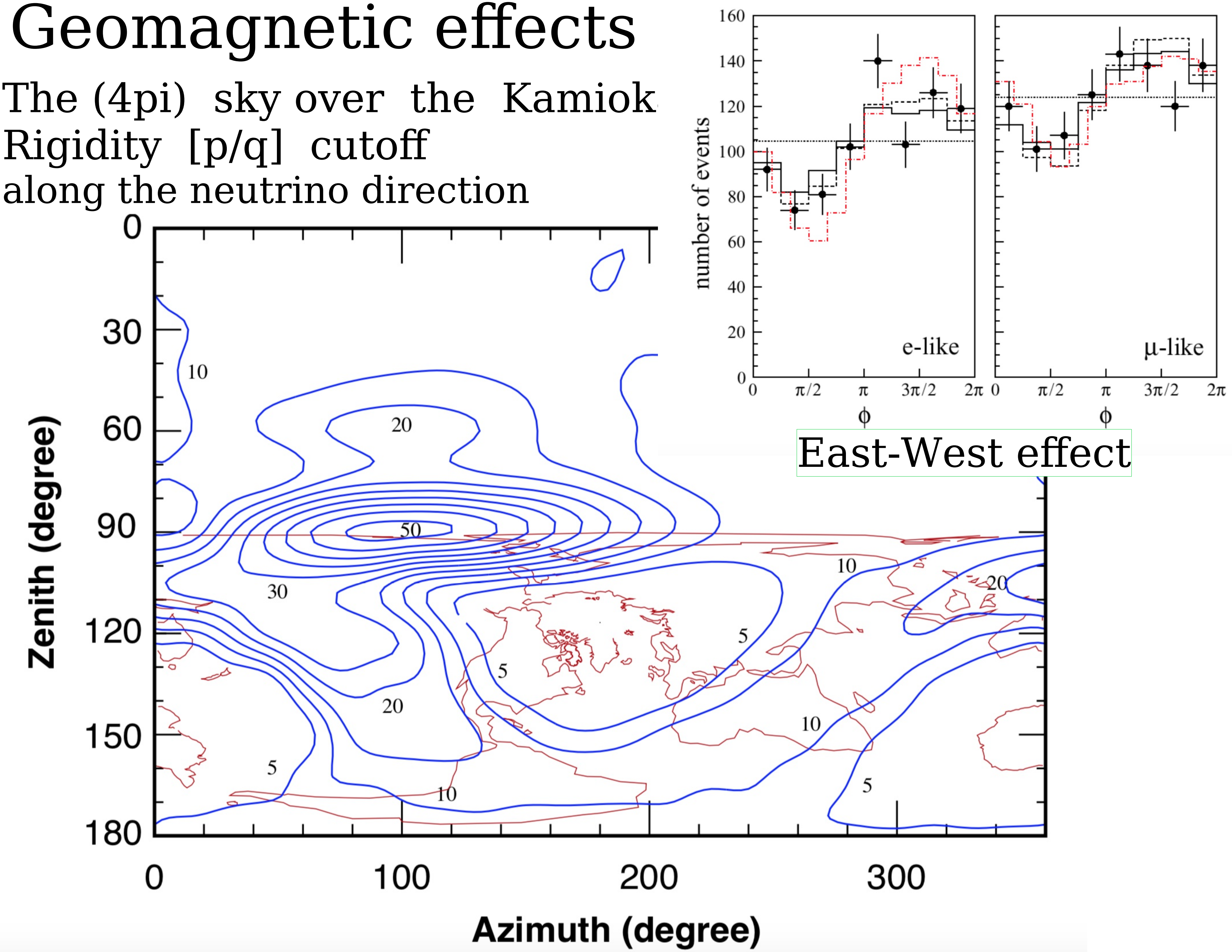
Geomagnetic effects

The (4pi) sky over the Kamiokande site
Rigidity [p/q] cutoff
along the neutrino direction



Geomagnetic effects

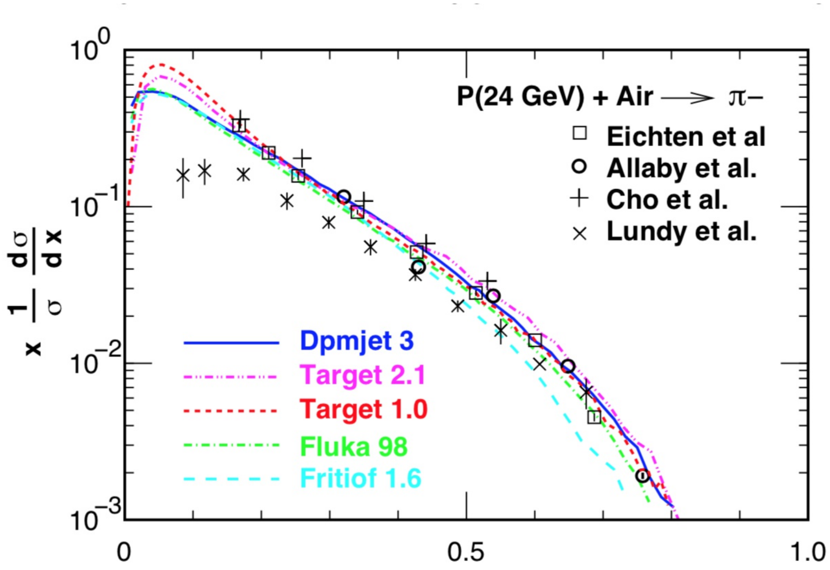
The (4pi) sky over the Kamiok
Rigidity [p/q] cutoff
along the neutrino direction



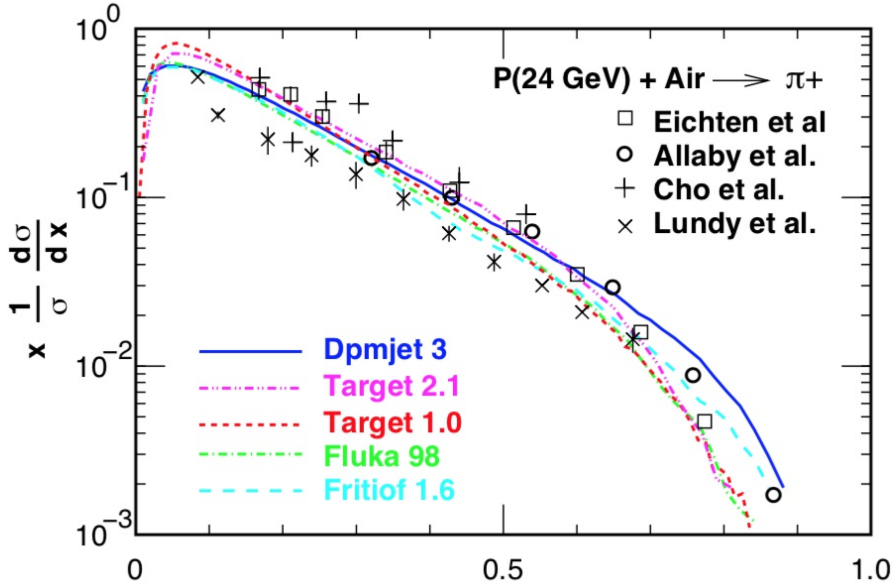
East-West effect

Modeling of hadronic Interactions [Spectra of final state particles] (*largest source of uncertainty*)

$$p + {}^{16}\mathrm{O} \rightarrow \pi^{\pm} + \ldots$$

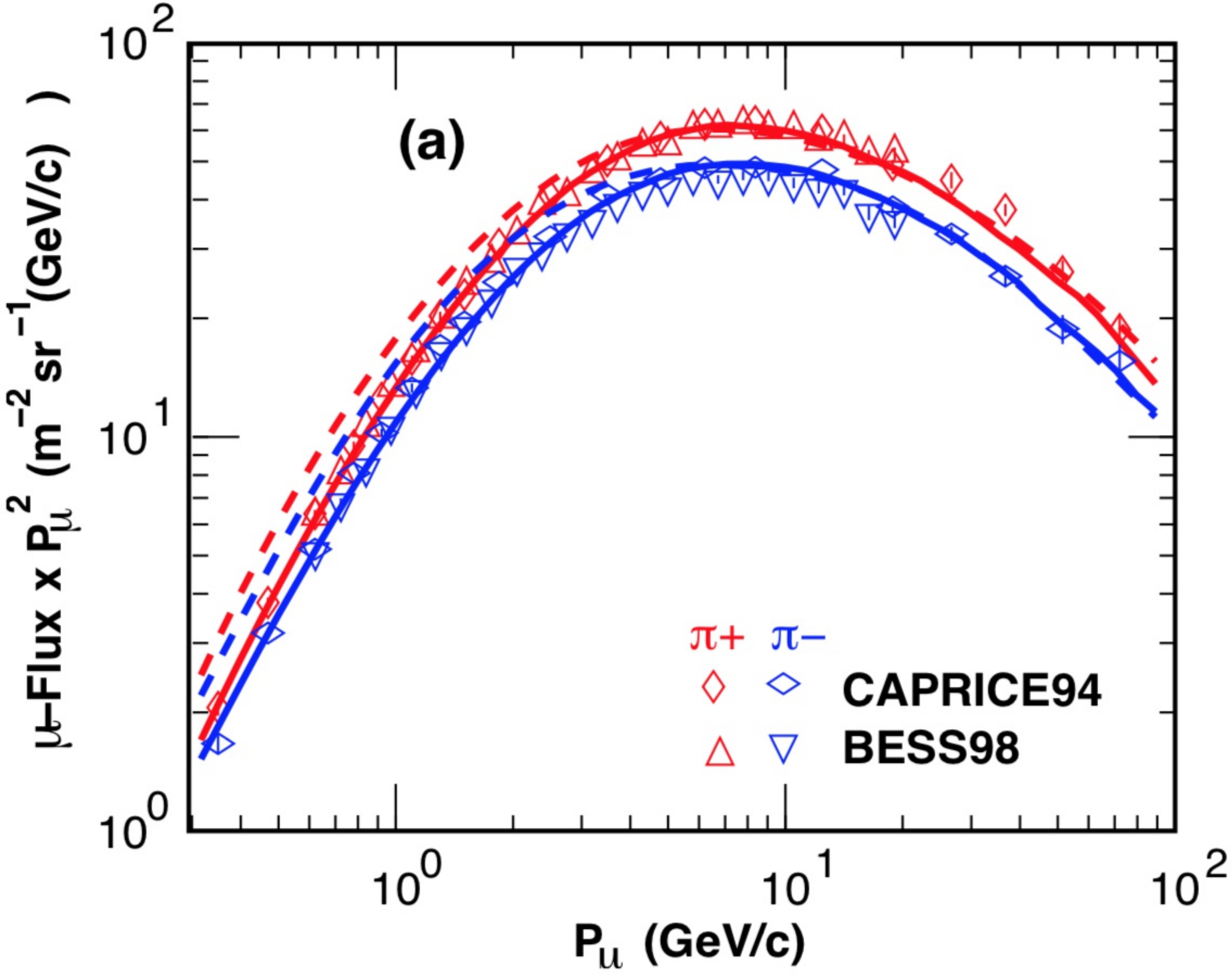


$$x = E/E_0$$



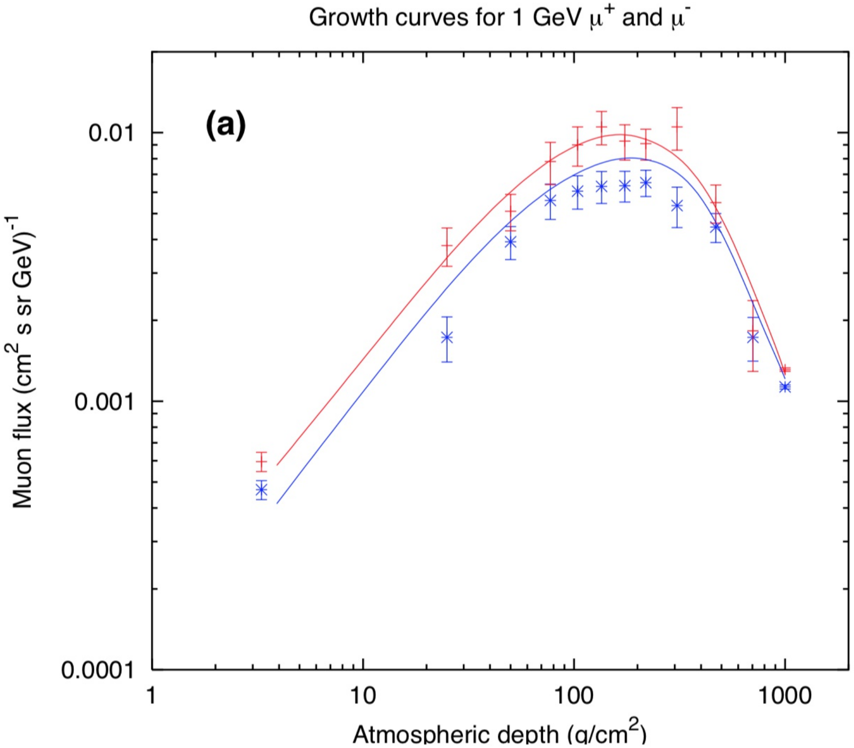
$$x = E/E_0$$

Calibrate the atmospheric neutrino calculation with *muon observations*

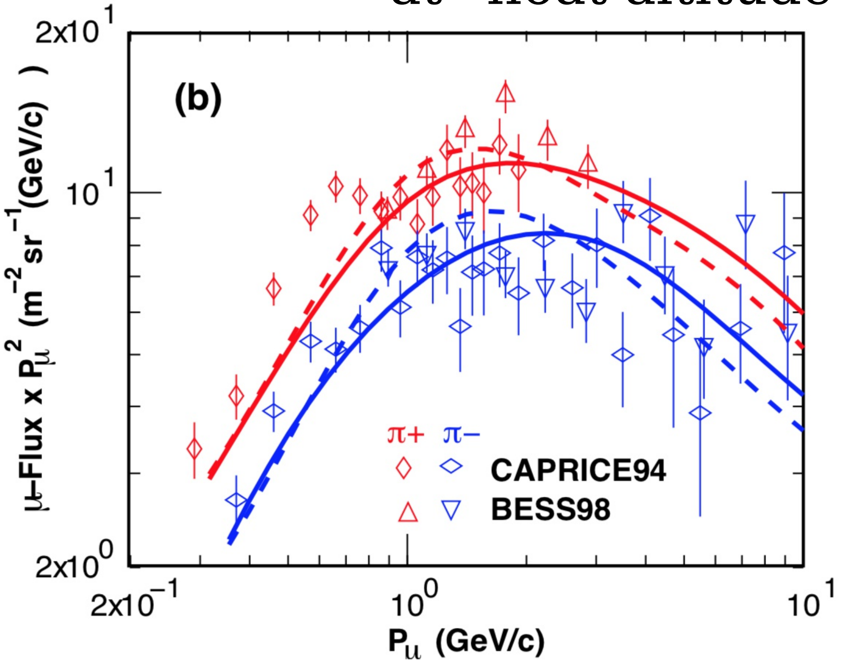


Difficulty: Most of the muons that are more "intimately associated" with GeV neutrinos do not reach the surface of the Earth (because they *decay in flight*).

Solution: Measure the muons at high altitude [balloon measurements during the travel to the stratosphere]

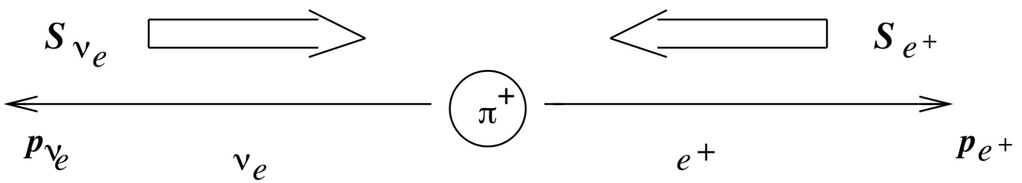


Measurements at "float altitude"

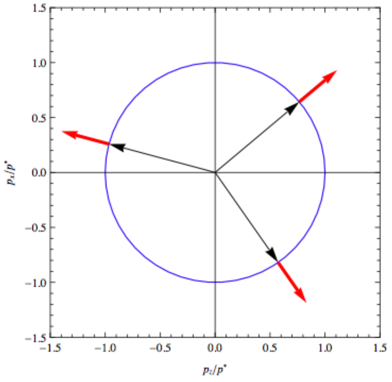


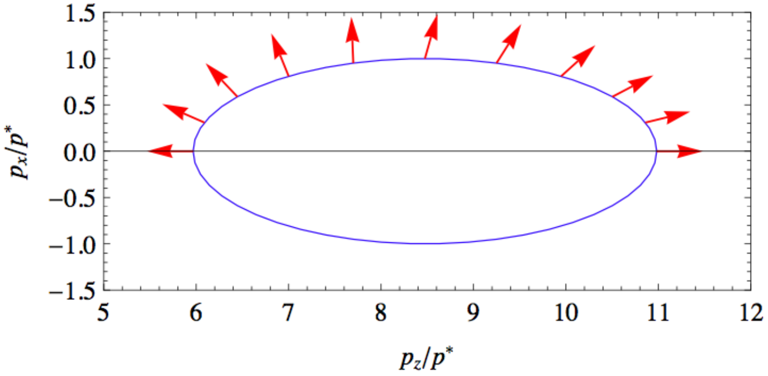
The “Muon Polarization crisis” (1998)

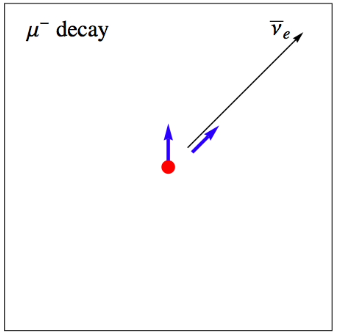
[Muons created in a well defined spin state]

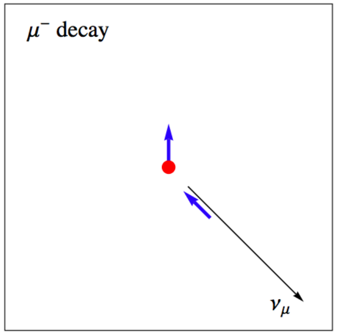


$$R_\pi \equiv \frac{\Gamma(\pi^+ \to e^+ + \nu_e)}{\Gamma(\pi^+ \to \mu^+ + \nu_\mu)} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_\pi^2 - m_e}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28 \times 10^{-4}$$



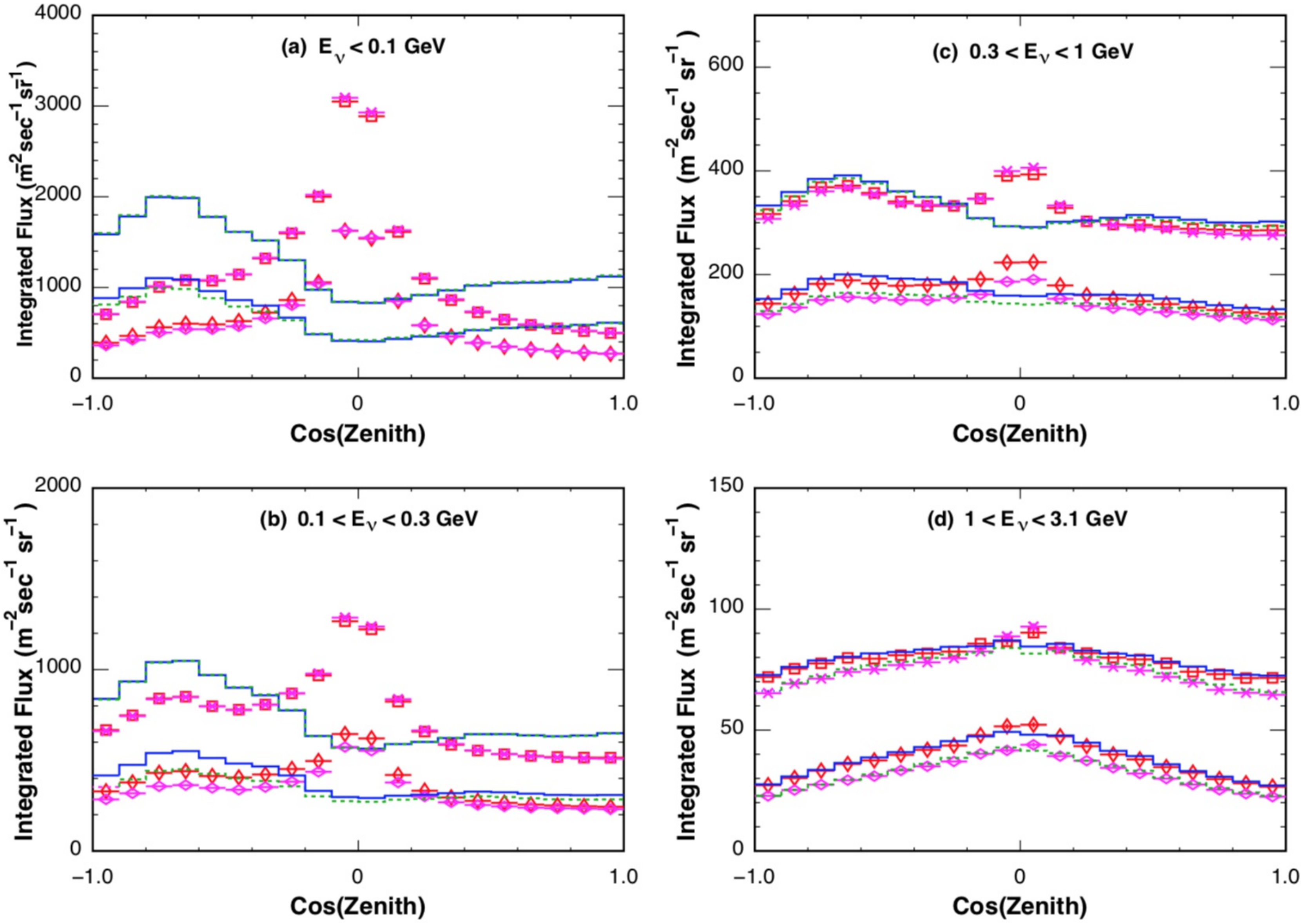






“3-Dimensional” versus “1-Dimensional”

1D: Neutrino collinear with primary Cosmic Ray



Alternative interpretations of the “atmospheric neutrino problem”

Proton decay [p → e+ nu nu]

Neutrino Decay

Oscillations into sterile neutrinos

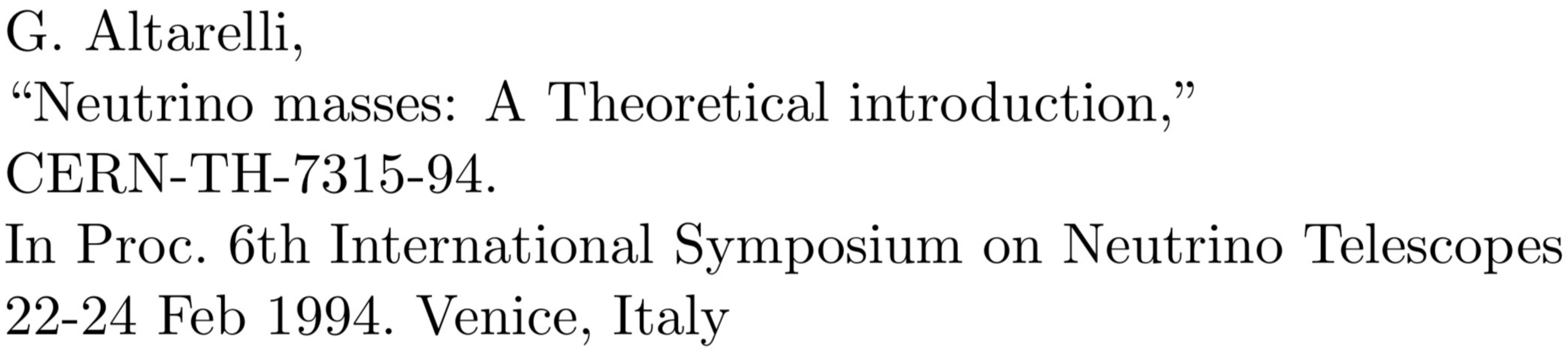
Flavor Changing Neutral Currents

Violations of Equivalence Principle

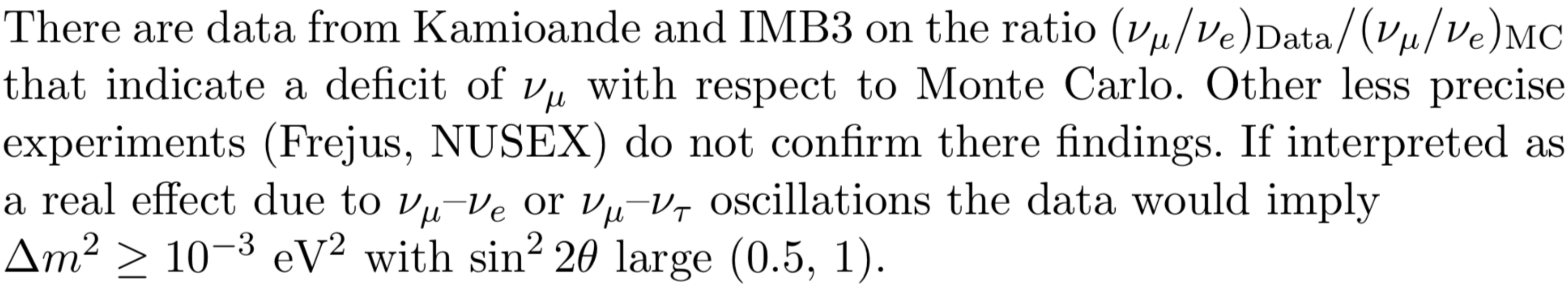
The doubts of theorists

and of

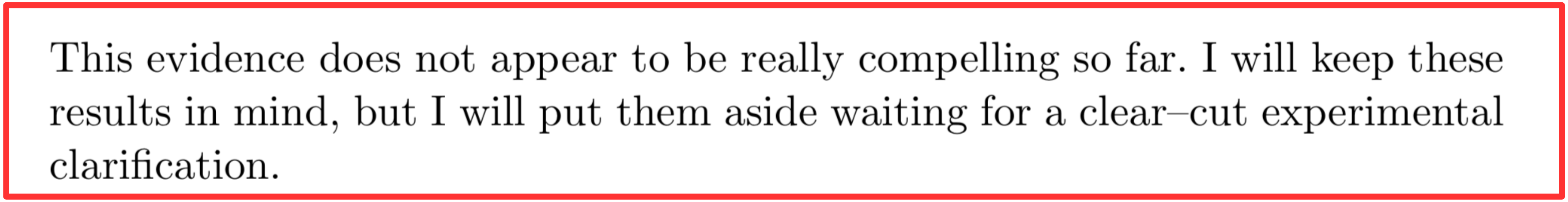
the “Physics Community”



G. Altarelli,
"Neutrino masses: A Theoretical introduction,"
CERN-TH-7315-94.
In Proc. 6th International Symposium on Neutrino Telescopes
22-24 Feb 1994. Venice, Italy



There are data from Kamioande and IMB3 on the ratio $(\nu_\mu/\nu_e)_{\rm Data}/(\nu_\mu/\nu_e)_{\rm MC}$ that indicate a deficit of ν_μ with respect to Monte Carlo. Other less precise experiments (Frejus, NUSEX) do not confirm there findings. If interpreted as a real effect due to ν_μ–ν_e or ν_μ–ν_τ oscillations the data would imply $\Delta m^2 \geq 10^{-3}$ eV^2 with $\sin^2 2\theta$ large (0.5, 1).



This evidence does not appear to be really compelling so far. I will keep these results in mind, but I will put them aside waiting for a clear–cut experimental clarification.

… Large Mixing angles are "unpalatable" ….

J. R. Ellis,
“Supersymmetry and grand unification,”
In Proc. 17th International Symposium on Lepton-photon Interactions,
Beijing, China, 10 - 15 Aug 1995
hep-ph/9512335.

Abstract:
Supersymmetry and Grand Unification are the two most promising directions for physics beyond the Standard Model. They receive indirect experimental support from the apparent lightness of the Higgs boson, the values of the gauge couplings measured at LEP and elsewhere, and the persistent solar neutrino deficit.

[.....]

As reviewed here by Winter, there are other suggestions of mass and oscillations effects in atmospheric neutrinos and the LSND experiment, but I prefer to wait and see whether these claims are confirmed.

O. G. Ryazhskaya,
“Is there an excess of electron-neutrinos in the atmospheric flux?,”
JETP Lett. **60**, 617 (1994).

O. G. Ryazhskaya,
“Comment on an interpretation of measurements of the flux of atmospheric neutrinos by the Kamiokande detector,”
JETP Lett. **61**, 237 (1995).

Neutron
Background ?

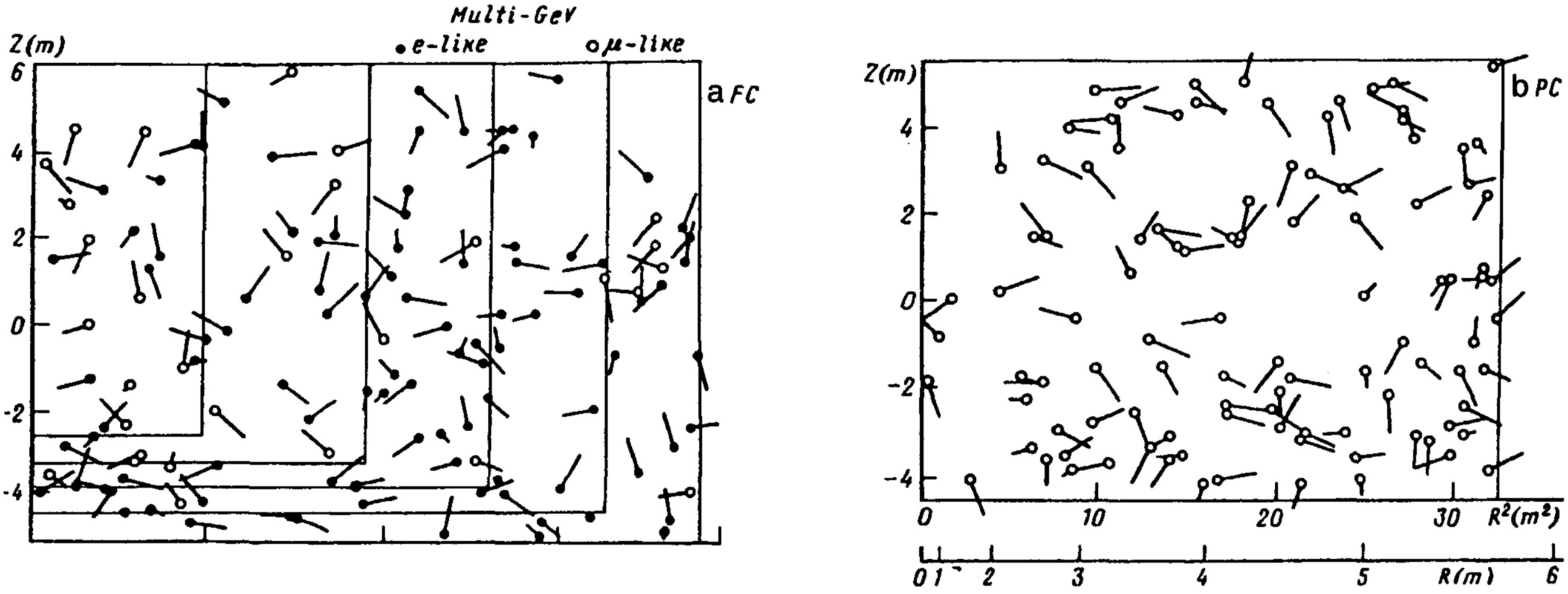
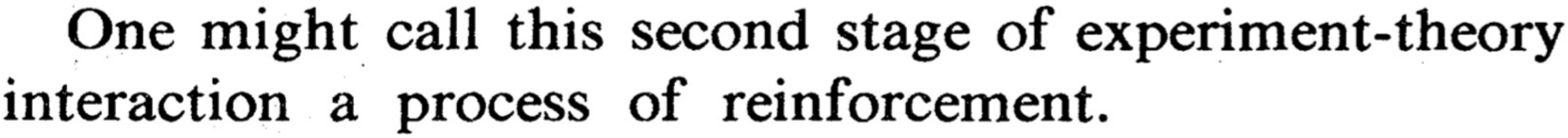


FIG. 1. Two-dimensional R^2–Z distribution of the interaction points and momentum directions for events detected by the Kamiokande detector. a) Fully contained (FC) events; b) partially contained (PC) events. Z—Vertical axis; R—distance along the radius of the cylindrical working volume; filled circles—interaction points for electron-like events; open circles—the same, for muon-like events. The vertical and horizontal lines are the boundaries of identical volumes (see the text proper).

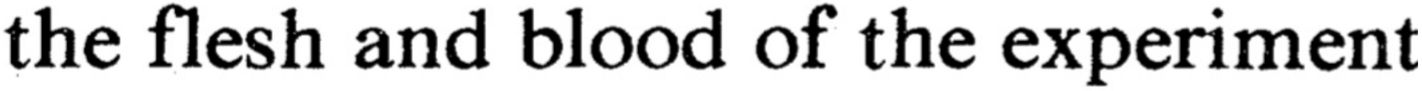
The “Flesh and Blood” of experiments

“Alternating Neutral Currents”

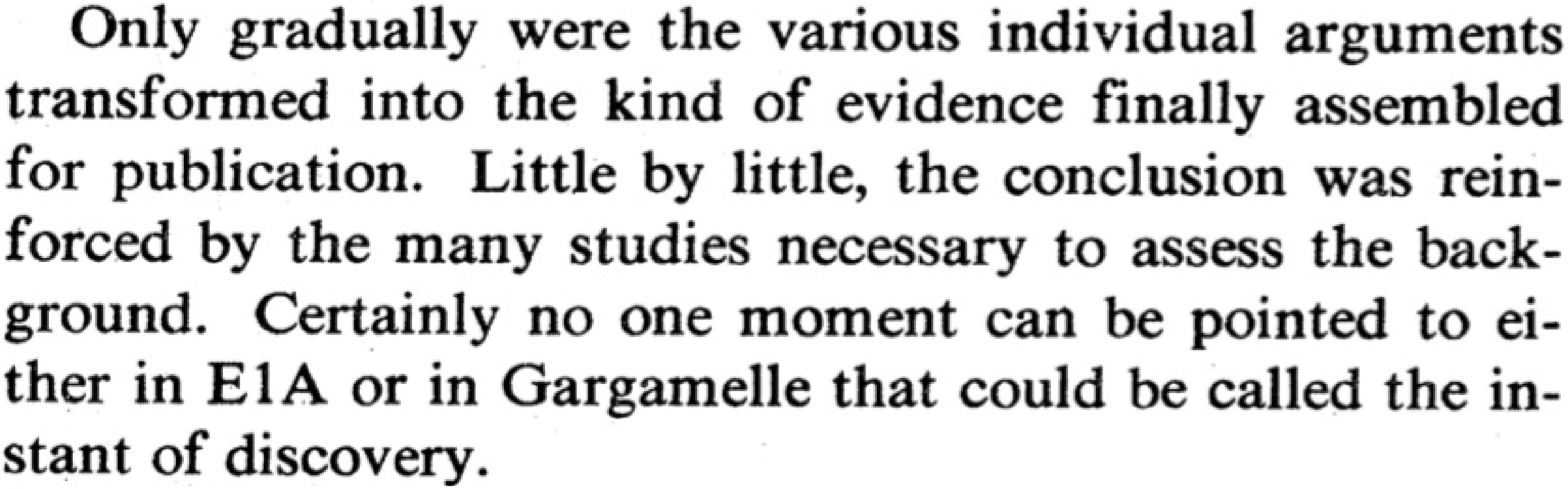
P. Galison,
“How the First Neutral Current Experiments Ended,”
Rev. Mod. Phys. **55**, 477 (1983).



One might call this second stage of experiment-theory interaction a process of reinforcement.



the flesh and blood of the experiment



Only gradually were the various individual arguments transformed into the kind of evidence finally assembled for publication. Little by little, the conclusion was reinforced by the many studies necessary to assess the background. Certainly no one moment can be pointed to either in E1A or in Gargamelle that could be called the instant of discovery.

The resolution of the "Anomaly" into "Evidence"

What was necessary was the extension
of the domain in L and E of the observations

What emerged was an *ensemble of deviations*
from the "standard" prediction,
With a "structure" (in energy, zenith angle)
could reveal the properties of the new physics.

The results had a consistent interpretation
in terms of a new physical concept
[Neutrino Oscillations]

Witnessing this "process" in real time has reinforced
my confidence in the *"scientific method"*.