Hunting Down Cosmic Neutrinos: An Extraordinary South African Particle Physics Safari

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1963-1964

Two miles underground in a gold mine near Johannesburg, South Africa, an experiment took place to study high-energy neutrinos produced by cosmic-ray collisions in the earth's atmosphere.

The unusual circumstances of that investigation are characteristic of the unusual history of this most elusive of the known elementary particles.

In 1931 Wolgang Pauli postulated the existence of the neutrino in order to explain the energy/momentum considerations manifested in β-decay.

$$n \rightarrow p + e^- + \bar{\nu}$$
$$p \rightarrow n + e^+ + \nu$$

Hans Bethe and Rudolf Peierls by studying the inverse β-decay calculated its cross-section to be of the order of **10^{-44} cm^2**!!!!

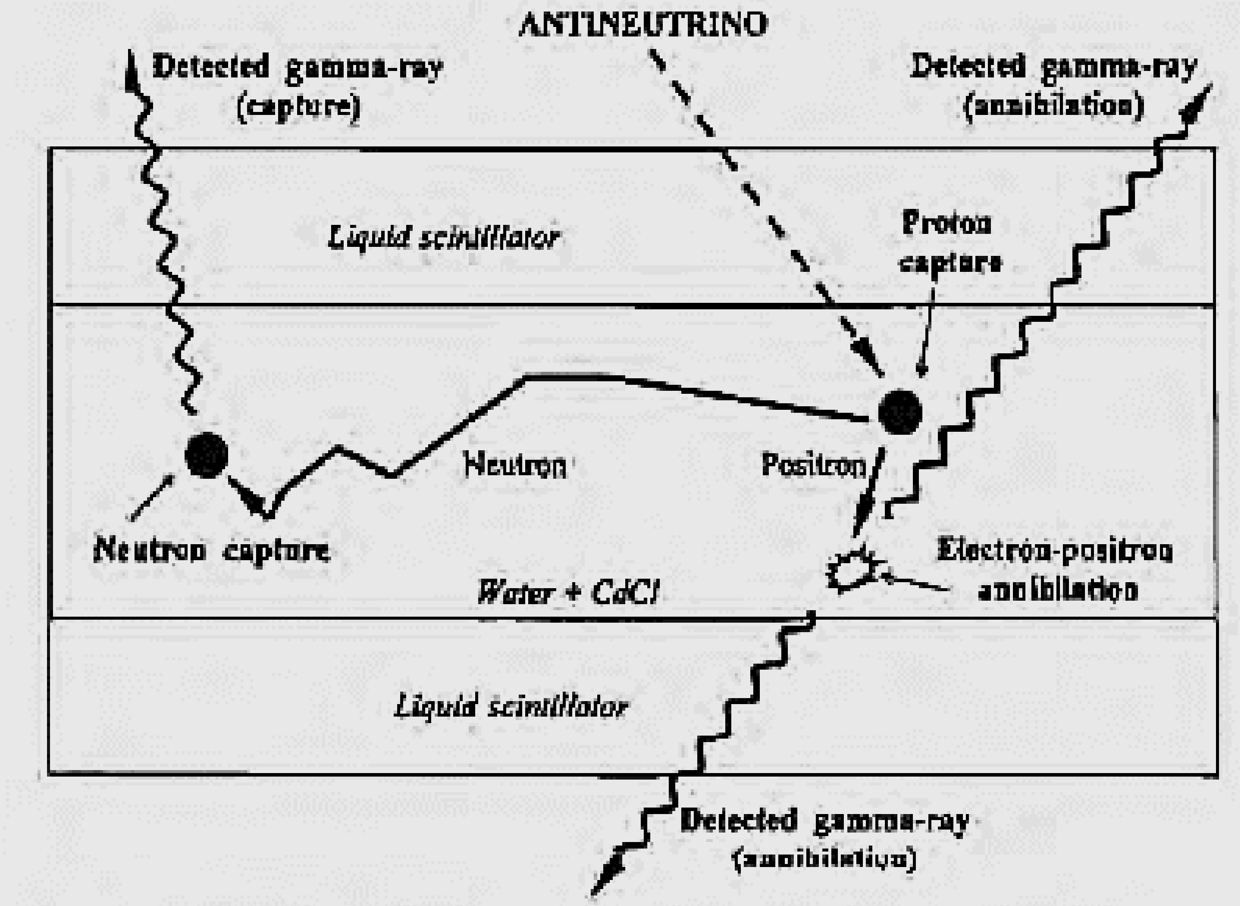
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Pauli's Statement: *I have done a terrible thing! I have postulated a particle that cannot be detected"!*

For 25 years the neutrino was little more than a figment of the theoretical physicist's imagination.

By 1956 however, with the development of nuclear reactors things started looking more promising: **Fission neutrinos**!!!

Frederick Reines



$$\overline{\nu}_e + p \rightarrow n + e^+$$

$$n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$$

$$e^+ + e^- \rightarrow \gamma + \gamma$$

Detect the reaction by detecting the 3 gamma-rays

14 June 1956, Reines's telegram to Pauli:

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta-decay of protons. Observed cross section agrees well with expected 6 x 10^{-44} cm^2 !!! "

By that time, it was found that the decay of the π-meson,

spontaneously decays to form a muon and a neutrino.

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

The muon in turn decays into an electron and two more neutrinos.

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

1962, Leon M. Lederman ***"The Two-Neutrino Experiment"***:

Neutrinos produced in meson decay were in fact not always identical with those produced in nuclear β-decay.

Thus in 30 years our understanding of the neutrino advanced to the point where four distinct forms were recognized: **electron-type neutrino, the electron-type antineutrino, the muon-type neutrino and the muon-type antineutrino .**

ORIGIN	TYPE OF NEUTRINO PRODUCED	ENERGY RANGE	(NEUTRINOS PER SQUARE CENTIMETER PER SECOND)
BETA DECAY IN EARTH	$\bar{\nu}_e$	LOW	10^5 TO 10^7
COSMIC-RAY COLLISIONS IN ATMOSPHERE	ν_μ $\bar{\nu}_\mu$ ν_e $\bar{\nu}_e$	LOW TO VERY HIGH	3×10^{-3}
NUCLEAR REACTIONS IN STARS	ν_e	LOW	10^7 TO 10^{11}
COSMIC-RAY COLLISIONS IN INTERGALACTIC SPACE	ν_μ $\bar{\nu}_\mu$ ν_e $\bar{\nu}_e$	LOW TO VERY HIGH	10^{-5} TO 10^{-7}

Certain neutrinos produced in nature may have a <u>vastly greater energy</u> than those produced by the most advanced high-energy machines!!!

Neutrino as a probe for studying the Cosmos!!!

Neutrinos Produced in Nature

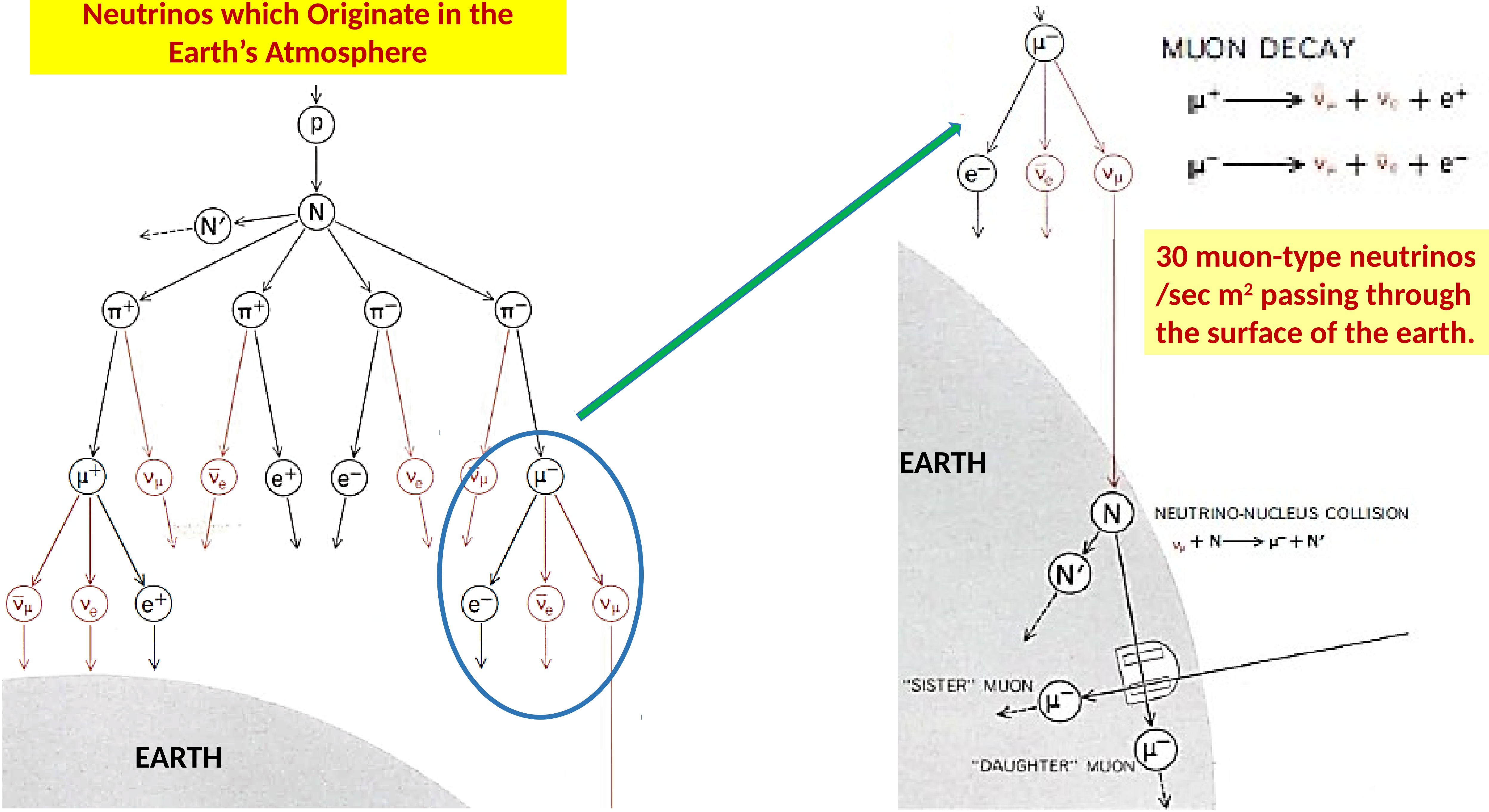
Low-energy neutrinos (up to 15 MeV): nuclear reactions that occur in the explosions of supernovae.

High-energy neutrinos (up to ~up to tens of GeV) originate from at least two sources.

a) Collision at the earth's atmosphere of primary cosmic rays (mostly protons) with atmospheric nuclei.

b) Collisions between cosmic protons and matter in the vicinity of stars and in intergalactic space - may have been produced in the reactions from the beginning of the universe.

Neutrinos which Originate in the Earth's Atmosphere



30 muon-type neutrinos /sec m² passing through the surface of the earth.

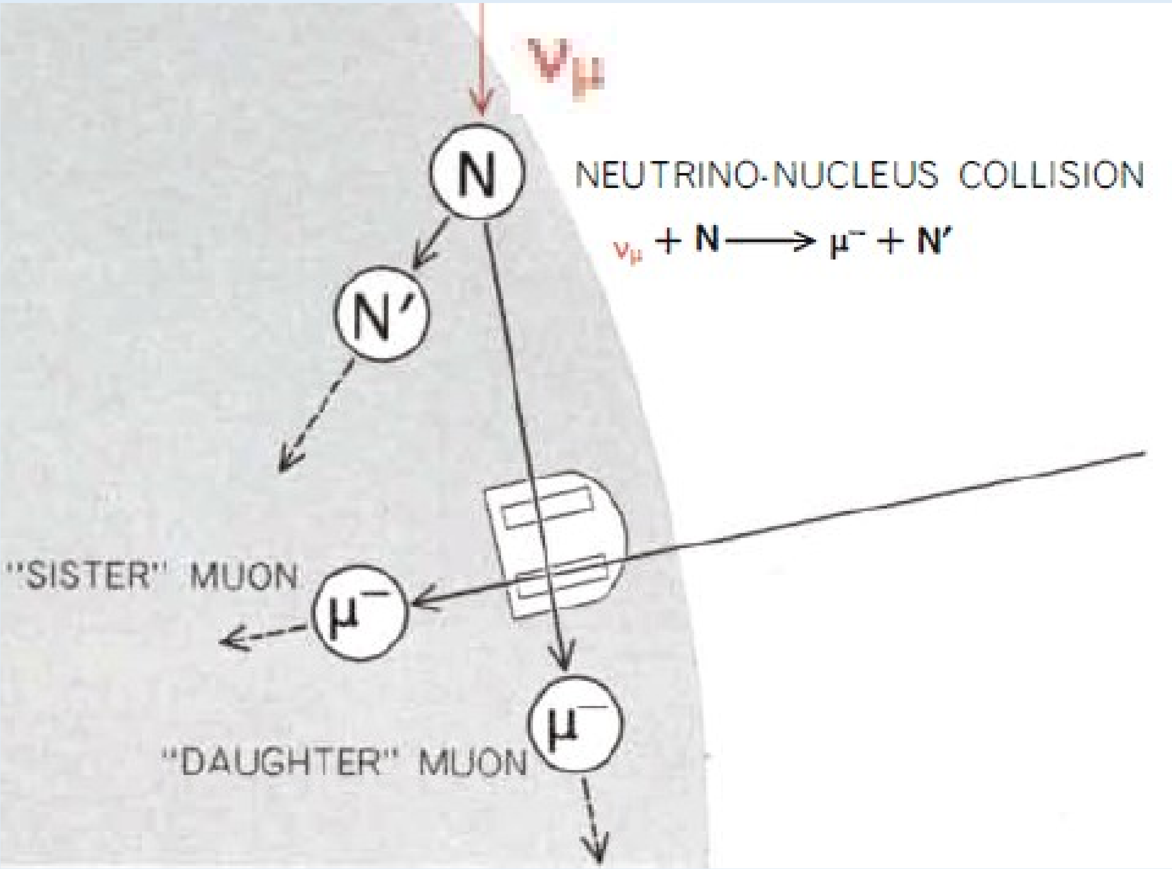
The focus of Reine's research program, given the detection capabilities at that time, was to **detect high-energy neutrinos originating in the earth's atmosphere**.

How could this be done?

Considerations:

a) **Neutrinos have by far the greatest penetrating power and most of them will pass unimpeded through the earth.**

b) **A small fraction of the muon-neutrinos do interact with matter in the earth and produce "daughter" muons which can be detected with conventional techniques.**



Design an experiment to detect atmospheric muon-type neutrinos by means of their daughter muons!

Problem:

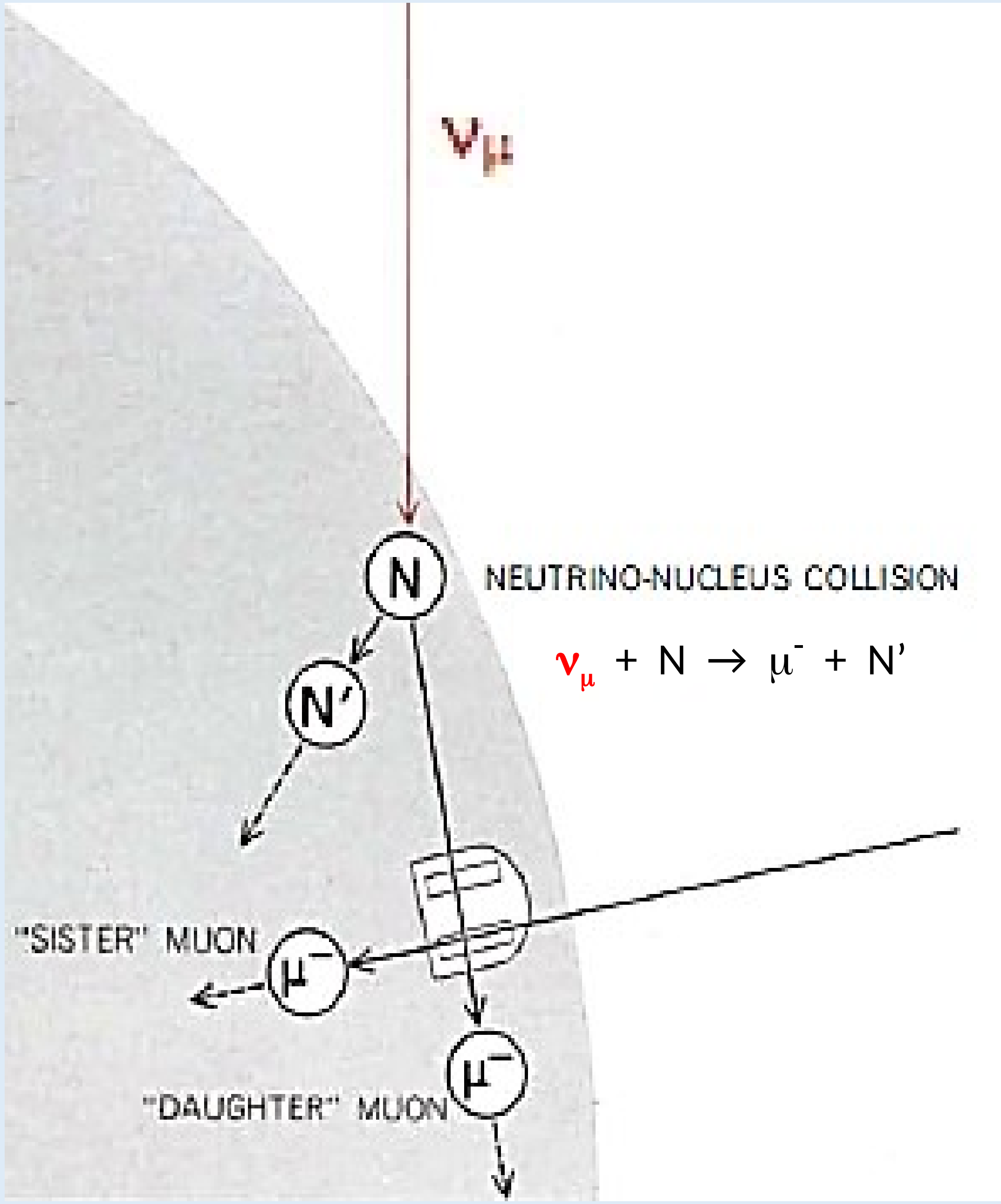
How do you distinguish a **"daughter" muon** produced by ν_μ in the earth from a **"sister" muon** produced with neutrinos in the atmosphere?

Solution:

Both daughter and sister type muons have isotropic distributions.

However the sister muons cannot penetrate matter easily and they will peak toward the local zenith (angles away from zenith imply longer paths in atmosphere).

The angular distribution of the daughter muons produced by neutrino interactions should show a slight peaking in the horizontal direction.



<u>Another Problem:</u>

At sea level there are 50 billion times more "sister" muons than the "daughter" muons produced by ν_μ in the earth.

The Solution:

Place the detectors deep underground!!!!

The larger the depth underground the better the angular sensitivity and the less the interfering sister muons.

1962: A New Kid in Town!.....Sellschop Comes to Cleveland!!!

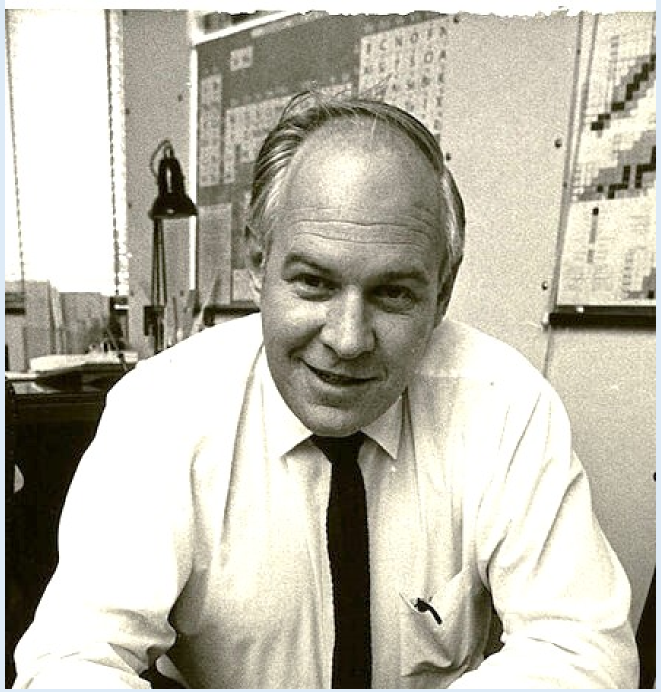
At around 1962 Sellschop at the age of 32 gave an invited lecture at the Case Institute of Technology in Cleveland, Ohio.

Reines attended the lecture and invited Friedel for dinner afterwards.

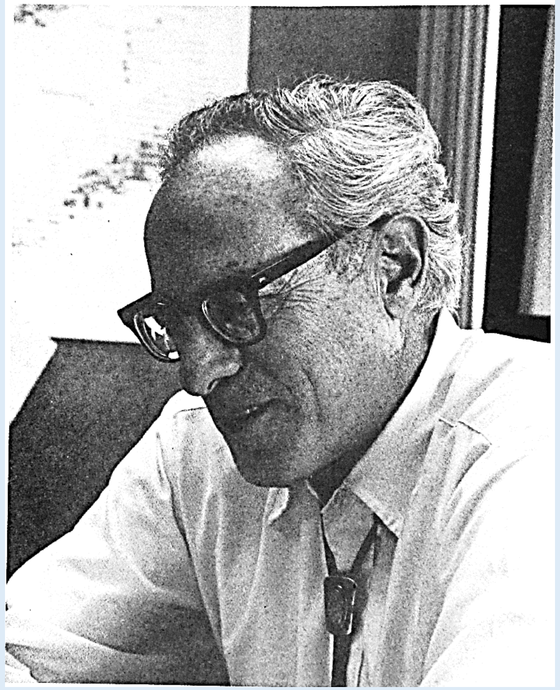
Friedel asked him about what had happened since the famous experiment with Cowan. He said that nothing much had happened because he didn't know where to do the experiment that he wanted to do.

They discussed the complexities of the experiment

and Sellschop turned and told Reines……….:



Jacques Pierre Friedel Sellschop



Frederick Reines

‘ I'll fix you up !

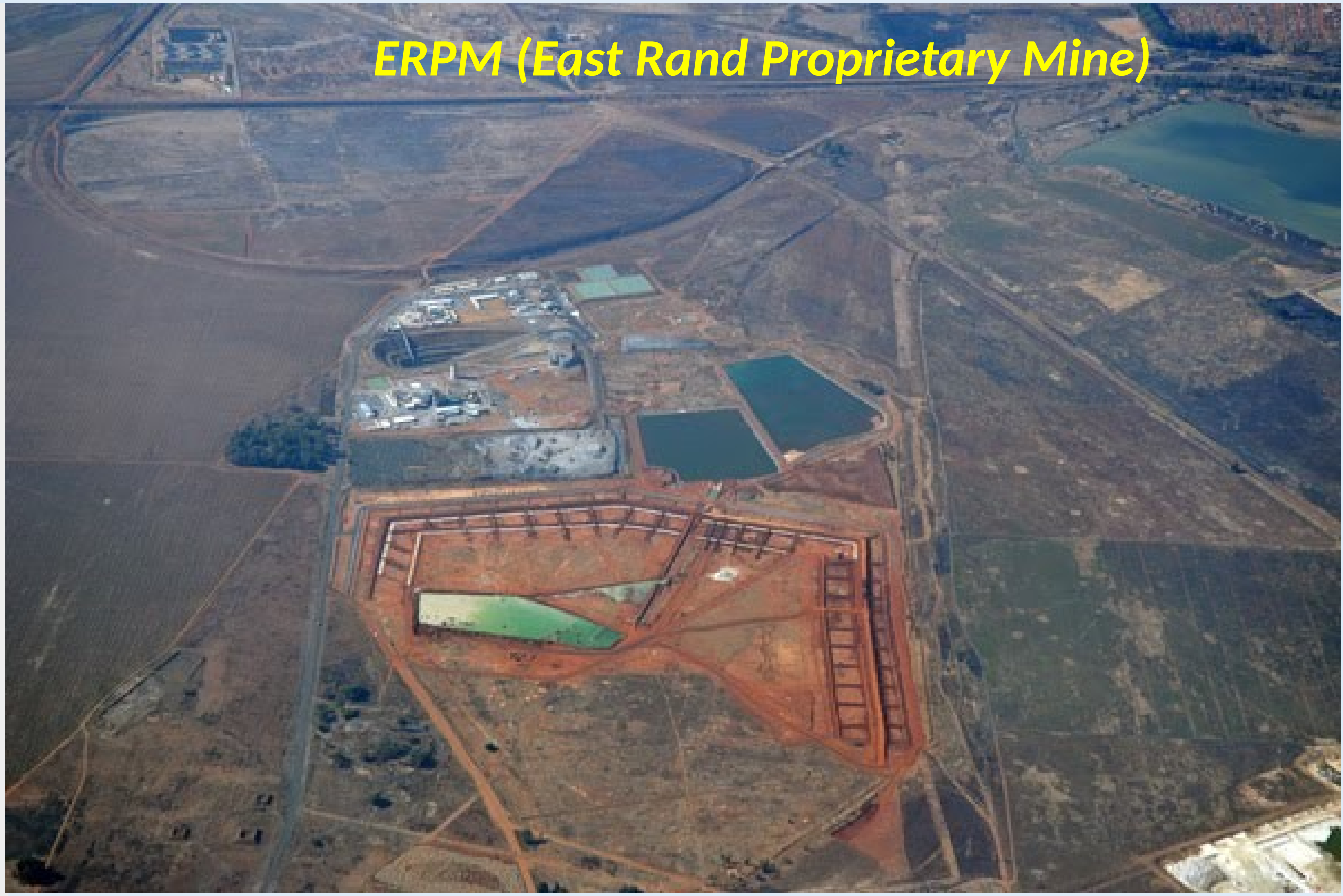
We are going Deep Underground ”

The largest detector in the world at that stage had to be installed at a depth of ~3,200 m underground!

Assistance and cooperation by the **South African Chamber of Mines**.

The ERPM (East Rand Proprietary Mine) :

- **<u>It was the deepest mine</u>** at the time
- **<u>One of the few mining groups willing to encourage good research without considering the loss of profits</u>** (the experiment was after all a perturbation on their operation)



ERPM covers an area of 12,000 acres.
The largest mine in the world: tunnels stretch for more than 5 km underground.

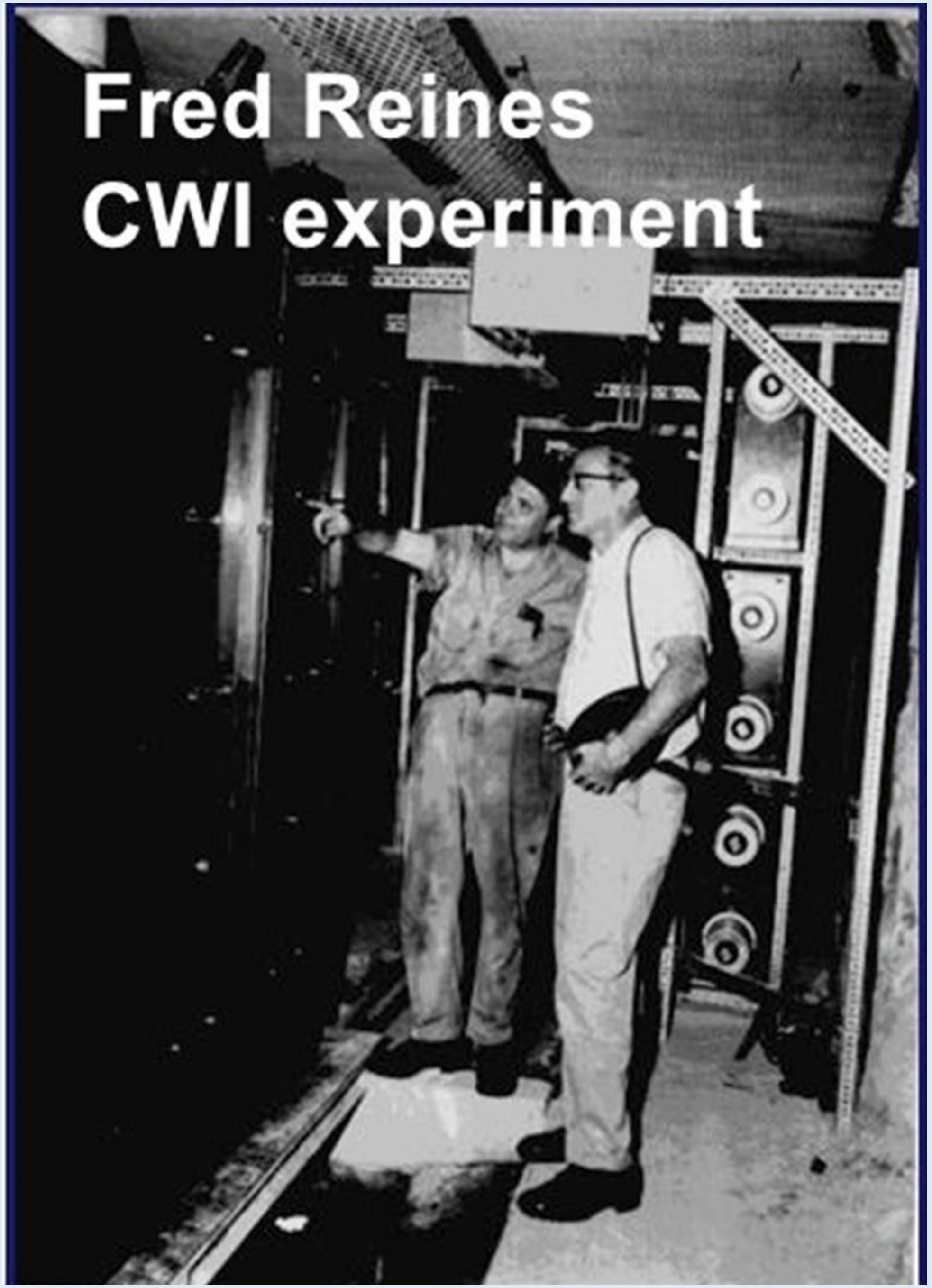
Certain logistics of such operation:

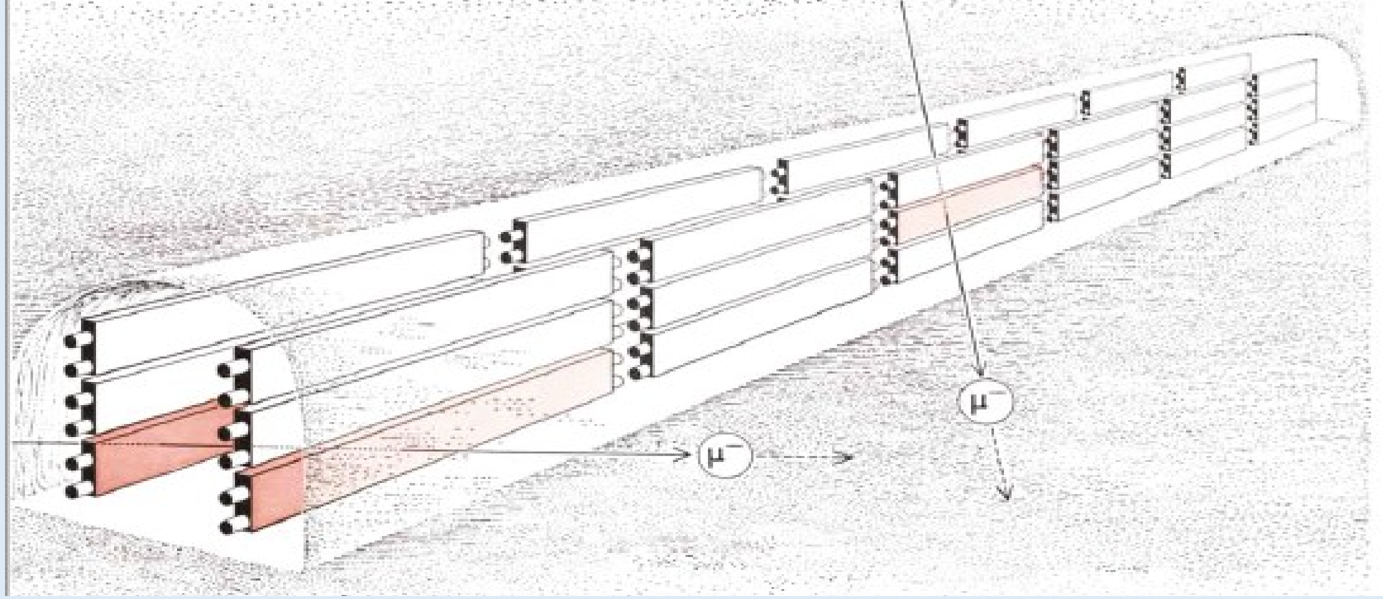
The detector equipment:

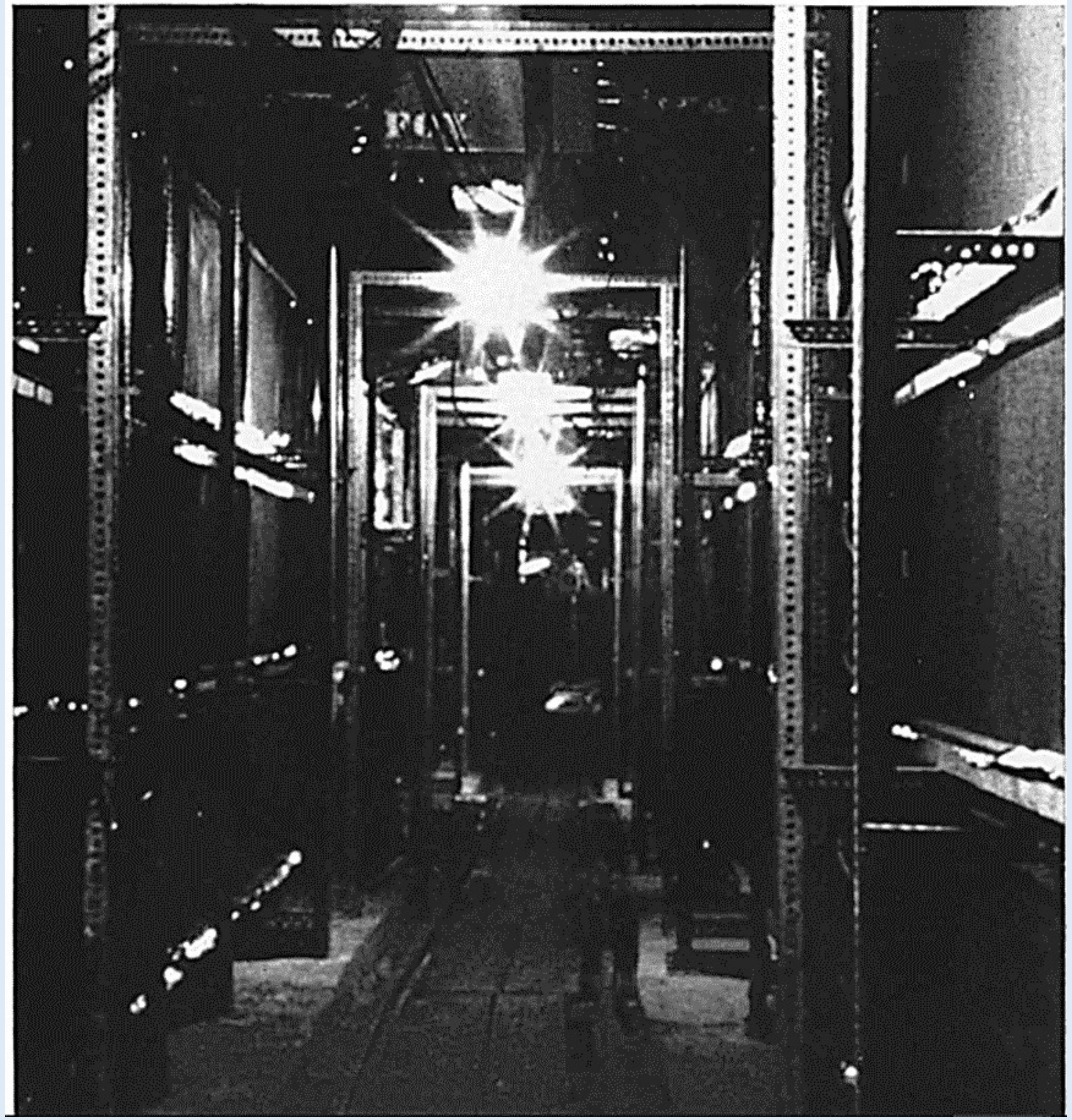
- **10 km of cable,**
- **16 tons of scintillating liquid,**
- **144 photomultiplier tubes**
- **A structural framework 40 meters long.**

- Going down **3,500 meters** takes time (more than an hour)!
- The temperature underground rises by almost 2^{o}C for every 100 meters! **About 60^{o}C at the experiment's depth**. Problematic both for researchers as well as equipment! Insulation problems….+….
- The members of the American group logged a total of 500,000 miles of travel between the U.S. and South Africa in two years.


LABORATORY
EAST RAND PROPRIETARY MINES
HERCULES SHAFT
PHYSICS DEPARTMENT CASE INSTITUTE OF TECHNOLOGY
CLEVELAND OHIO U.S.A.


Fred Reines
CWI experiment

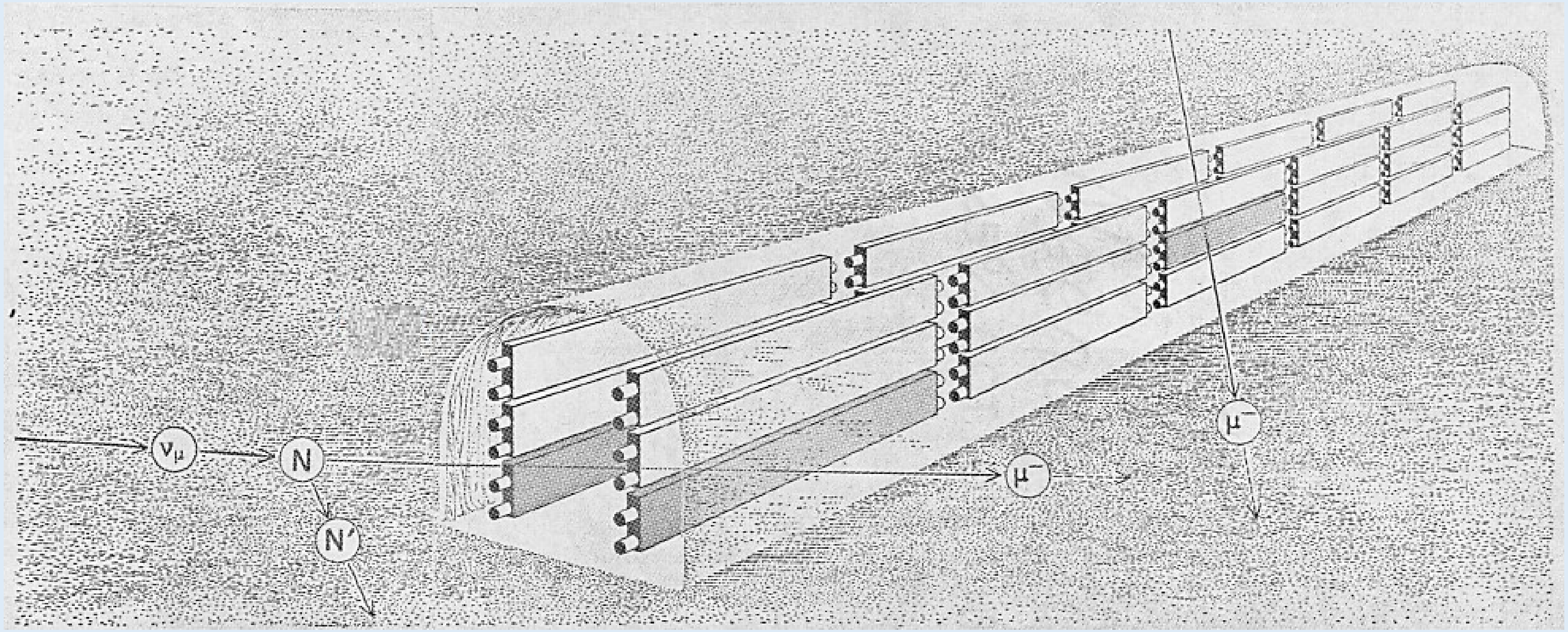




The detector array consisted of two parallel vertical walls with 36 detector elements. A total of 165 m^2 !!!!

The array was grouped into 6 "bays" of 6 elements each. Each detector element is a rectangular box of lucite containing 380 liters of a mineral-oil based liquid scintillator, with two photomultiplier tubes at each end.

In addition, the event is located along the detector axis by the ratio of the photomultiplier responses at the two ends.



The detectors are stuck three high in order to measure three different angular ranges.

Entering from the left and passing through a detector in each row is a daughter muon produced by the interaction of an atmospheric muon-type neutrino with the surrounding rock.

Entering from top and passing through just one detector is a sister muon produced by a cosmic ray interaction in the atmosphere.

October 27, 1964 - 13 months after the selection of the South African site
The detectors registered the first deep-underground observation of a sister cosmic-ray muon.

Then on February 23, 1965, the detectors recorded a muon
that had traveled in a horizontal direction!

The first "natural“ high-energy neutrino had been observed!

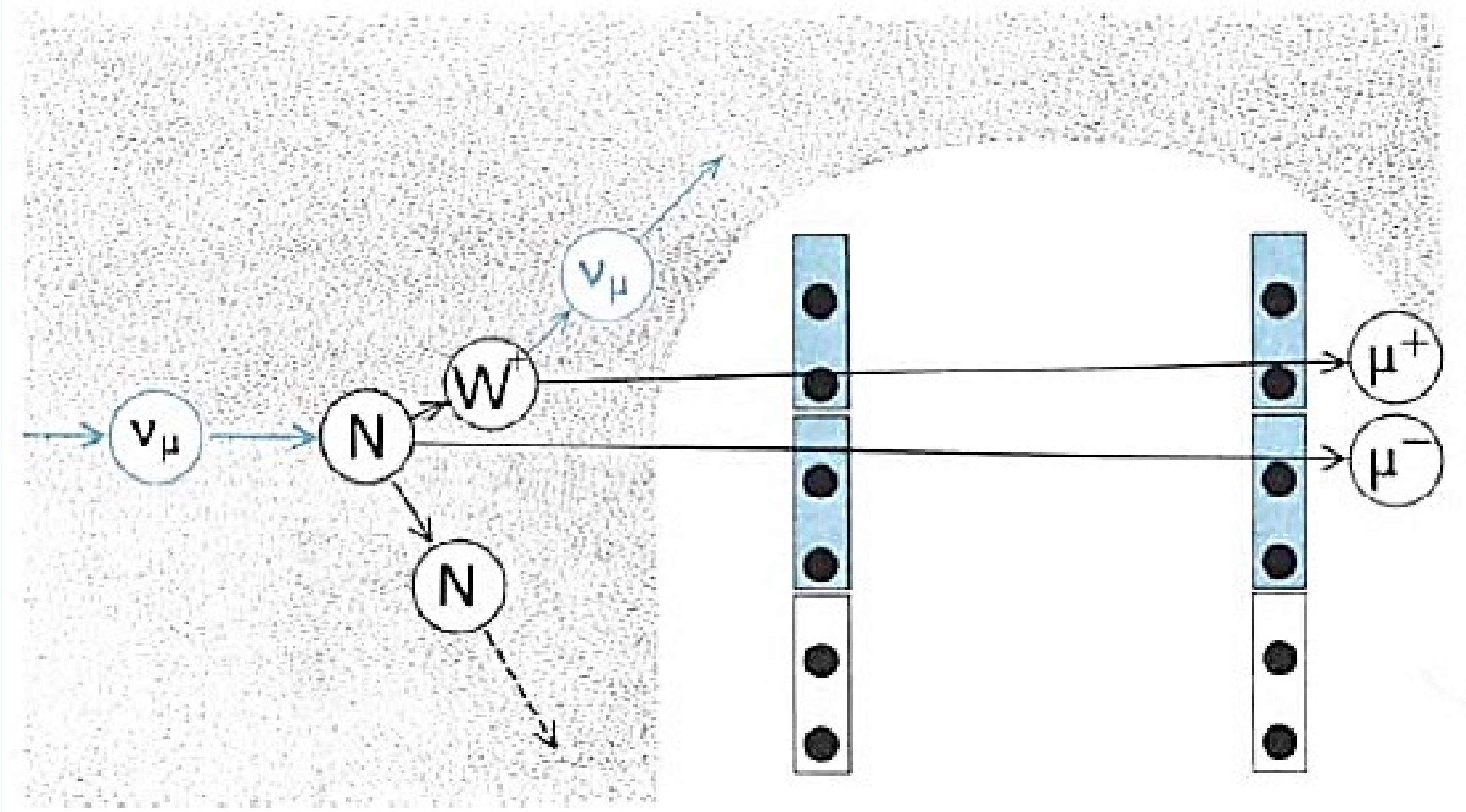
Some 80 sister muons and 10 daughter muons

were finally detected before the

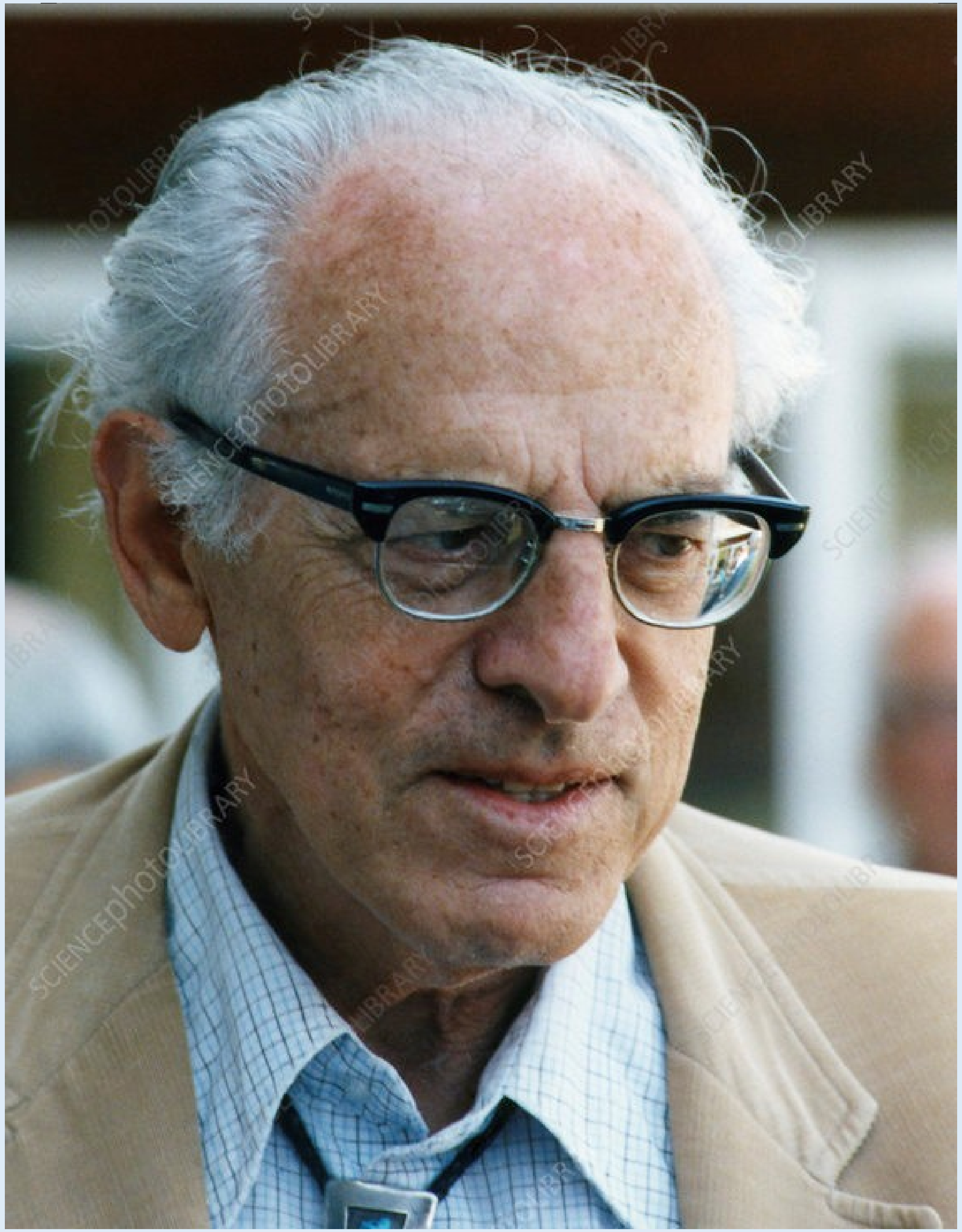
Phys Rev. Lett. Publication in 1965.

Evidence for the existence of **the intermediate vector boson W** could be provided by the observation of **two nearly parallel muon tracks**, starting from a common origin and penetrating two detector elements in each row.

Two events resulting from such a muon pair were detected!



Nobel Prize Winner 1995



Seek opportunities for your research that exploit what is unique about your local environment.