Neutrino physics at high energy 1971-1992

History of the Neutrino

Paris Sept. 2018

Konrad Kleinknecht,

Ludwig Maximilians-Universität München (Excellence Cluster „Universe“)/ Universität Mainz

Sept.2018

First high energy accelerator Fermilab
founded 1967
First neutrino beam 1971
first neutrino interaction observed
November 1971 by exp. 21(Caltech-Fermilab)
Proposals by
Harvard-Penn-Wisconsin (exp.1A)
Caltech-Fermilab-Rochester (exp.21)
15 ft bubble chamber (CERN-Berkeley-Hawaii-Wisconsin, exp.28A)

Deep inelastic neutrino scattering

$$\underset{k}{\nu_\mu} + \underset{p}{N} \longrightarrow \underset{k'}{\mu^-} + \text{hadrons}$$

$$E_\nu = E_\mu + E_h$$

$$Q^2 = -(k-k')^2 \approx E_\nu E_\mu \Theta^2$$

$$\nu = p\cdot(k-k') \simeq M E_h$$

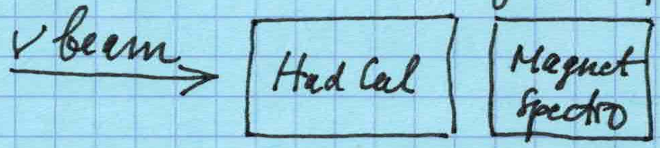
Bjorken scaling variables

$x = Q^2/2\nu$ momentum transfer

$y = \nu/(p\cdot k) = E_h/E_\nu$ inelasticity

Experiments measure $\vec{p}_\mu$ and E_h

Magnet spectrometer + Hadron calorimeter



HPW Experiment: Had Cal+Muon Spectrometer

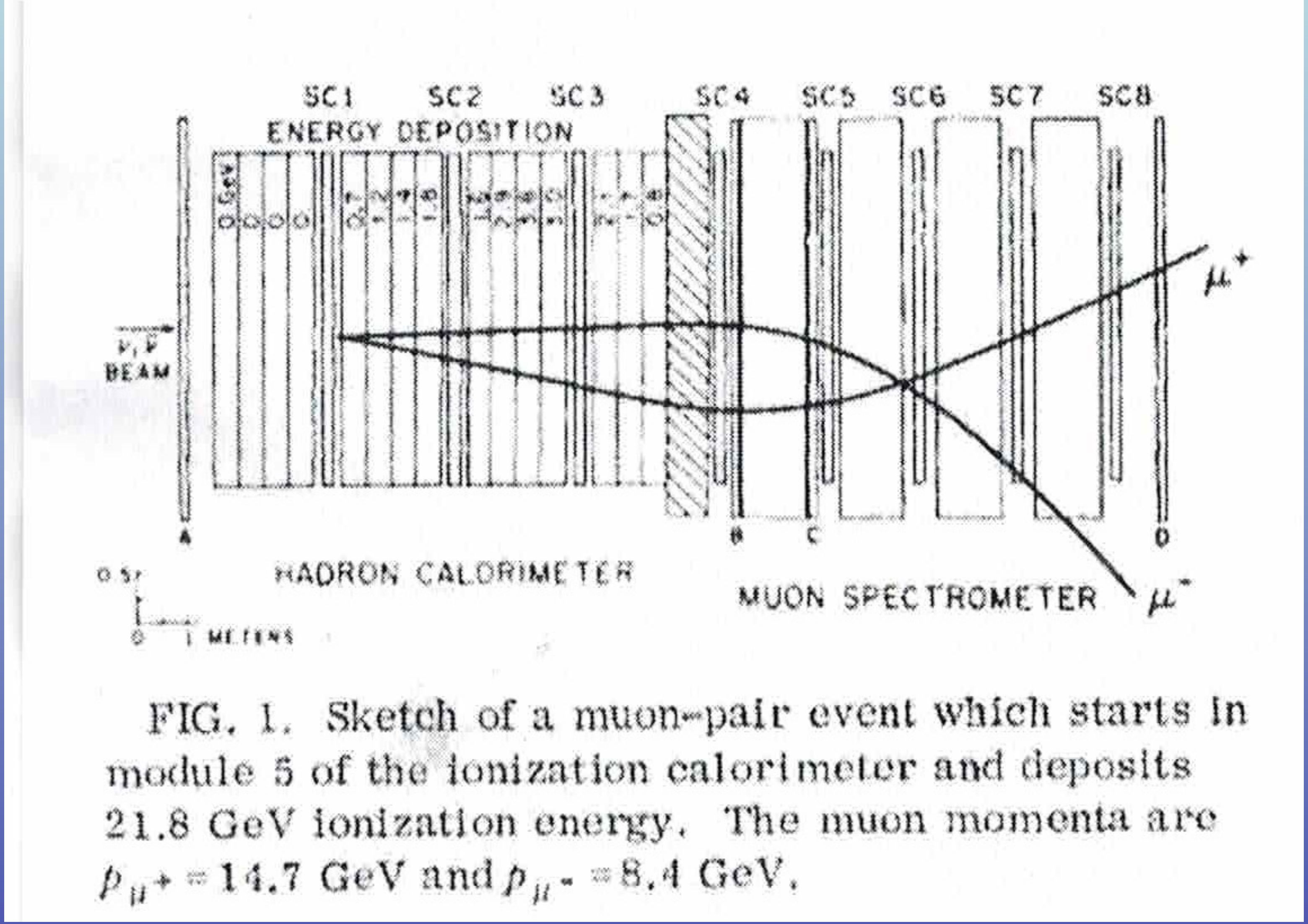
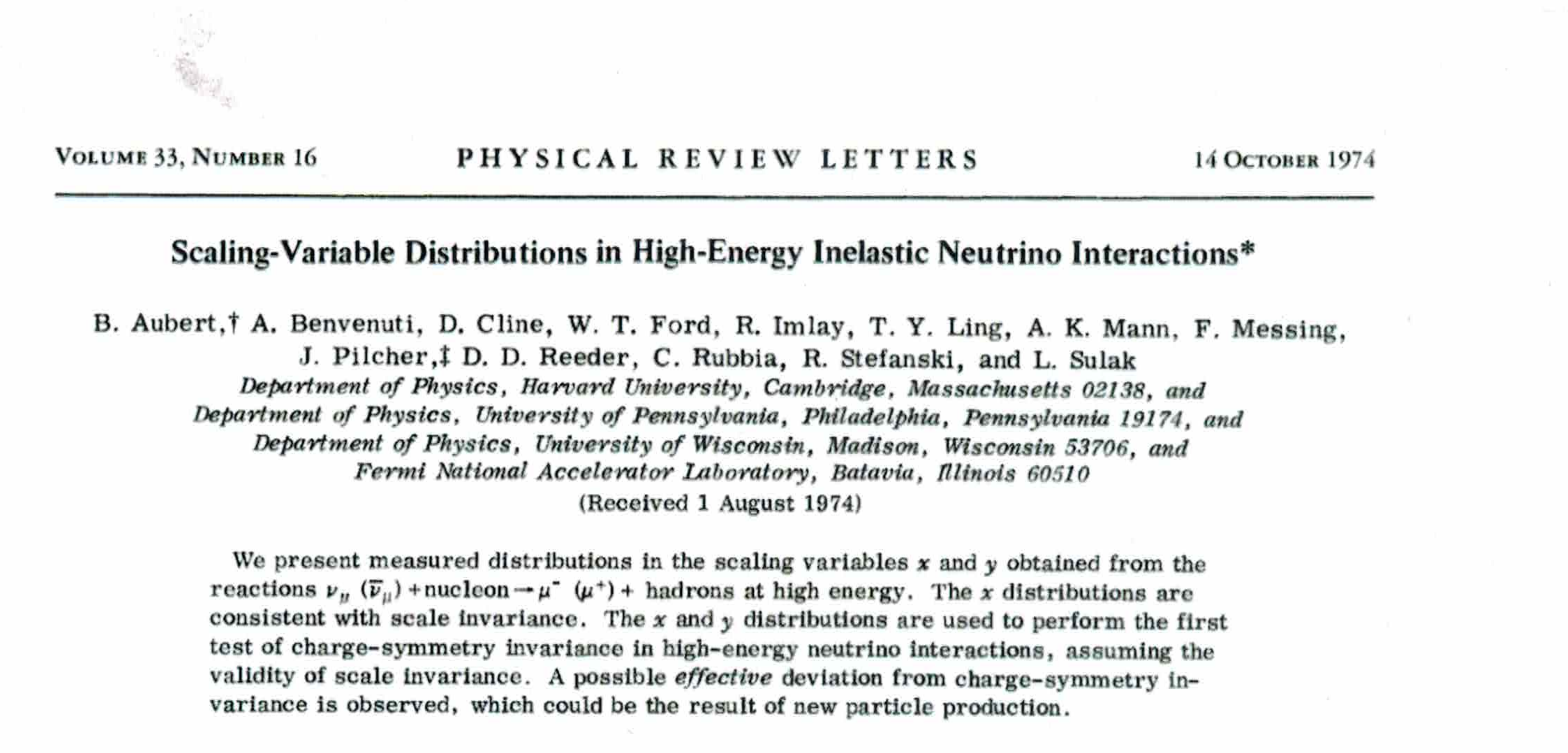


FIG. 1. Sketch of a muon-pair event which starts in module 5 of the ionization calorimeter and deposits 21.8 GeV ionization energy. The muon momenta are $p_{\mu^+} = 14.7$ GeV and $p_{\mu^-} = 8.4$ GeV.

HPW : deviation from charge symmetry ; October 1974



VOLUME 33, NUMBER 16 PHYSICAL REVIEW LETTERS 14 OCTOBER 1974

Scaling-Variable Distributions in High-Energy Inelastic Neutrino Interactions*

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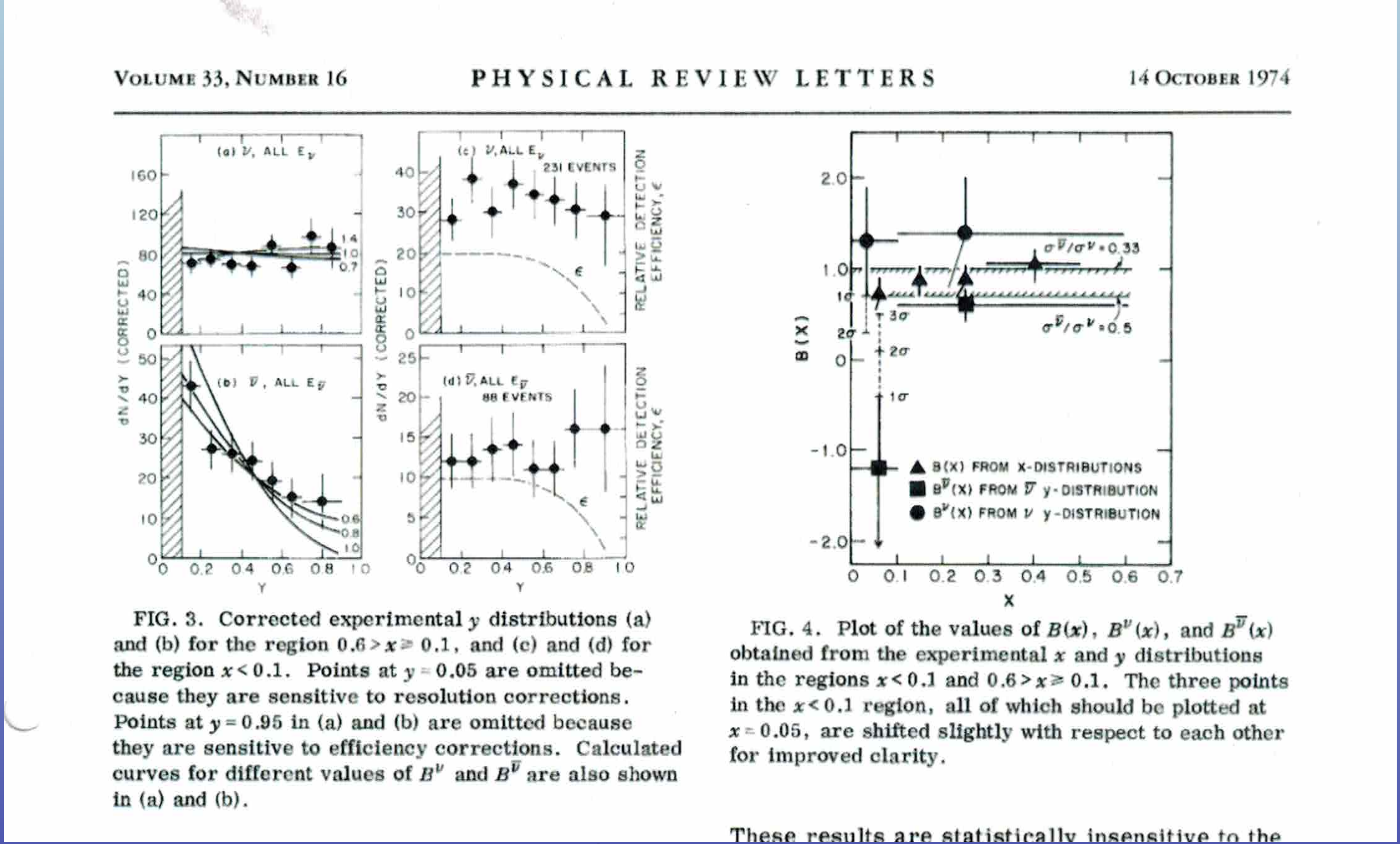
(Received 1 August 1974)

We present measured distributions in the scaling variables x and y obtained from the reactions ν_μ $(\bar{\nu}_\mu)$ + nucleon $\rightarrow \mu^-$ (μ^+) + hadrons at high energy. The x distributions are consistent with scale invariance. The x and y distributions are used to perform the first test of charge-symmetry invariance in high-energy neutrino interactions, assuming the validity of scale invariance. A possible *effective* deviation from charge-symmetry invariance is observed, which could be the result of new particle production.

HPW y anomaly October 1974



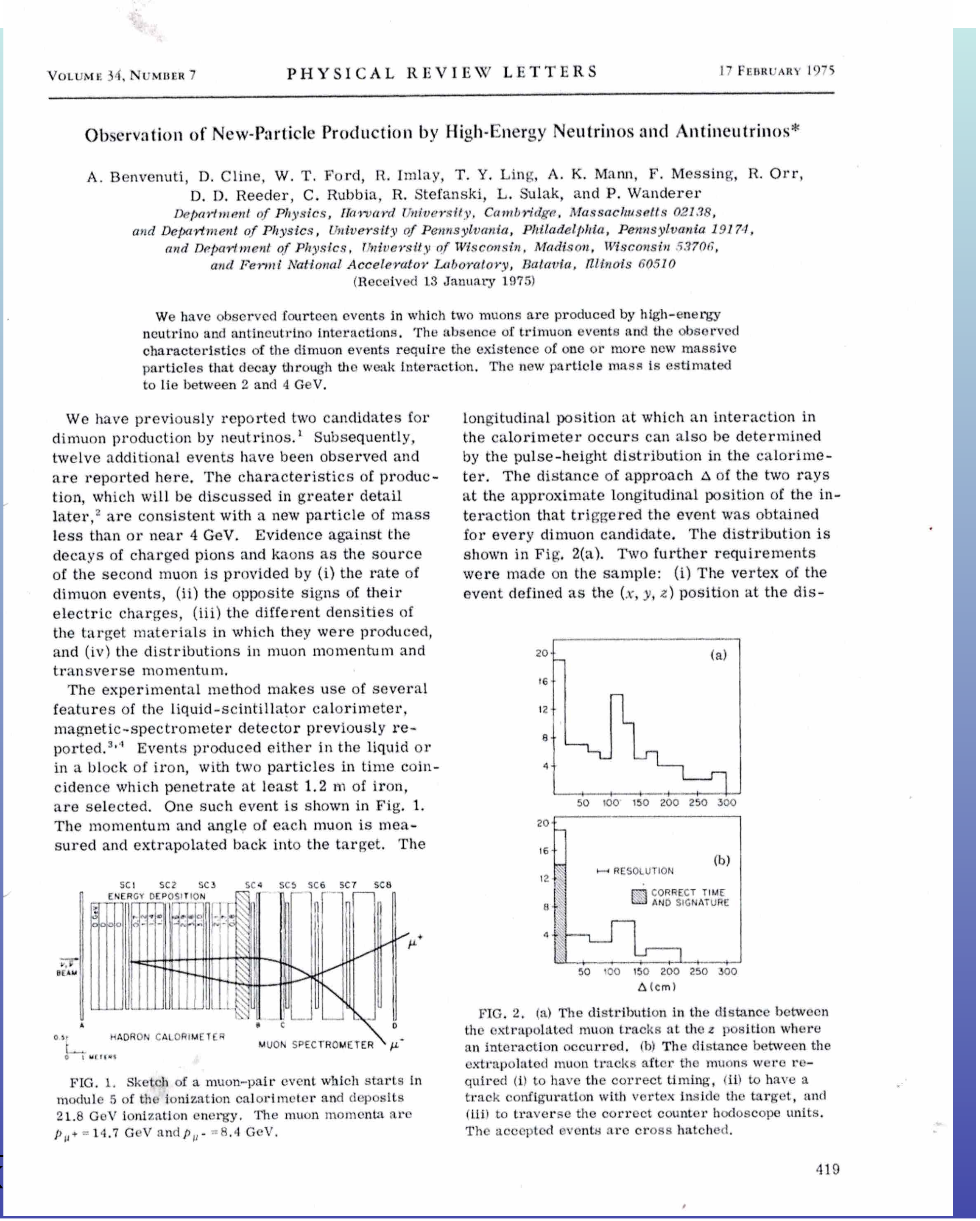
VOLUME 33, NUMBER 16 PHYSICAL REVIEW LETTERS 14 OCTOBER 1974

FIG. 3. Corrected experimental y distributions (a) and (b) for the region $0.6 > x \geq 0.1$, and (c) and (d) for the region $x < 0.1$. Points at $y = 0.05$ are omitted because they are sensitive to resolution corrections. Points at $y = 0.95$ in (a) and (b) are omitted because they are sensitive to efficiency corrections. Calculated curves for different values of B^{ν} and $B^{\bar{\nu}}$ are also shown in (a) and (b).

FIG. 4. Plot of the values of $B(x)$, $B^{\nu}(x)$, and $B^{\bar{\nu}}(x)$ obtained from the experimental x and y distributions in the regions $x < 0.1$ and $0.6 > x \geq 0.1$. The three points in the $x < 0.1$ region, all of which should be plotted at $x = 0.05$, are shifted slightly with respect to each other for improved clarity.

These results are statistically insensitive to the

HPW: Observation of neutrino-induced dimuon events
Febr. 1975



VOLUME 34, NUMBER 7 PHYSICAL REVIEW LETTERS 17 FEBRUARY 1975

Observation of New-Particle Production by High-Energy Neutrinos and Antineutrinos*

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(Received 13 January 1975)

We have observed fourteen events in which two muons are produced by high-energy neutrino and antineutrino interactions. The absence of trimuon events and the observed characteristics of the dimuon events require the existence of one or more new massive particles that decay through the weak interaction. The new particle mass is estimated to lie between 2 and 4 GeV.

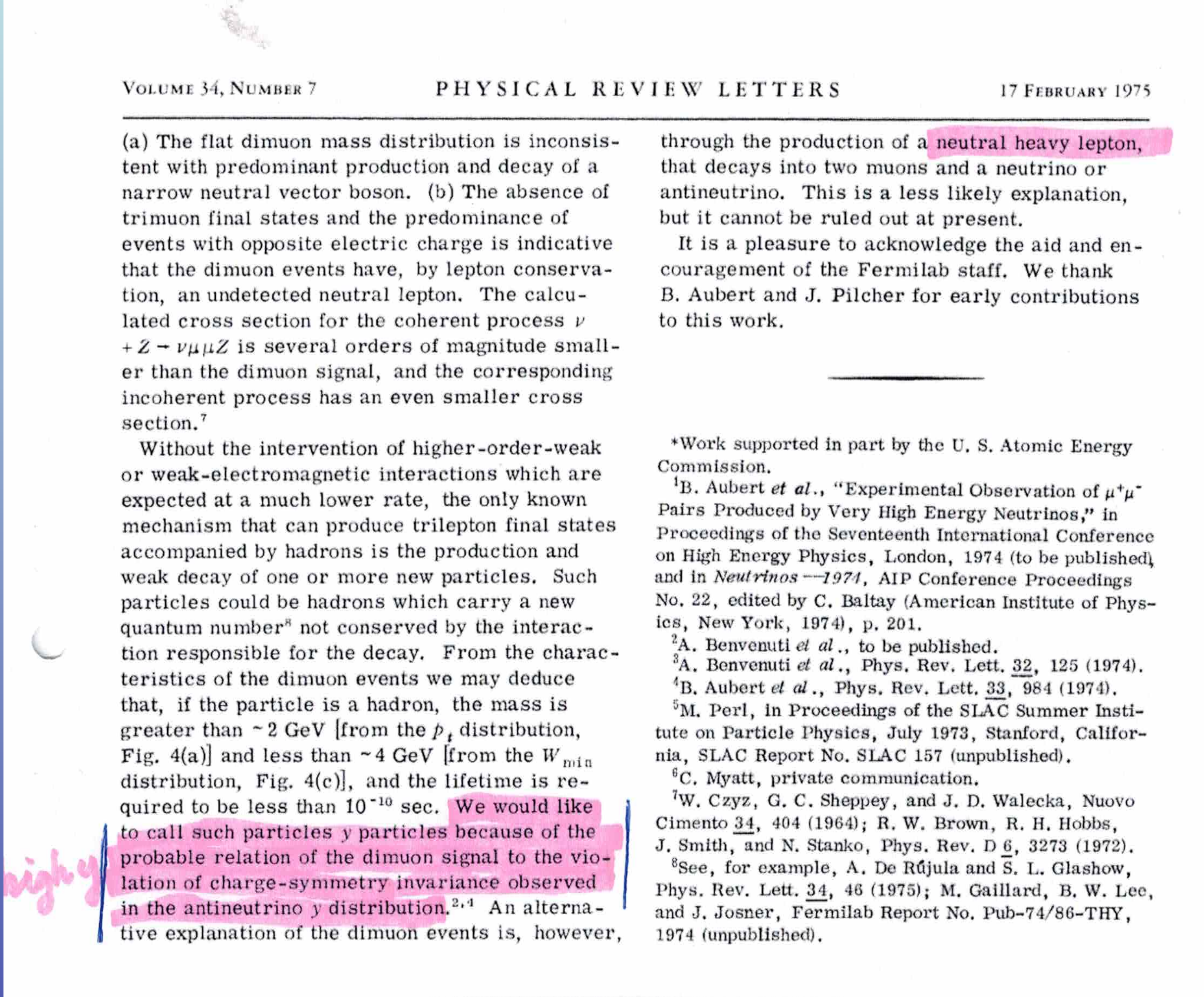
We have previously reported two candidates for dimuon production by neutrinos.[1] Subsequently, twelve additional events have been observed and are reported here. The characteristics of production, which will be discussed in greater detail later,[2] are consistent with a new particle of mass less than or near 4 GeV. Evidence against the decays of charged pions and kaons as the source of the second muon is provided by (i) the rate of dimuon events, (ii) the opposite signs of their electric charges, (iii) the different densities of the target materials in which they were produced, and (iv) the distributions in muon momentum and transverse momentum.

The experimental method makes use of several features of the liquid-scintillator calorimeter, magnetic-spectrometer detector previously reported.[3,4] Events produced either in the liquid or in a block of iron, with two particles in time coincidence which penetrate at least 1.2 m of iron, are selected. One such event is shown in Fig. 1. The momentum and angle of each muon is measured and extrapolated back into the target. The longitudinal position at which an interaction in the calorimeter occurs can also be determined by the pulse-height distribution in the calorimeter. The distance of approach Δ of the two rays at the approximate longitudinal position of the interaction that triggered the event was obtained for every dimuon candidate. The distribution is shown in Fig. 2(a). Two further requirements were made on the sample: (i) The vertex of the event defined as the (x, y, z) position at the dis-

FIG. 1. Sketch of a muon-pair event which starts in module 5 of the ionization calorimeter and deposits 21.8 GeV ionization energy. The muon momenta are $p_{\mu^+} = 14.7$ GeV and $p_{\mu^-} = 8.4$ GeV.

FIG. 2. (a) The distribution in the distance between the extrapolated muon tracks at the z position where an interaction occurred. (b) The distance between the extrapolated muon tracks after the muons were required (i) to have the correct timing, (ii) to have a track configuration with vertex inside the target, and (iii) to traverse the correct counter hodoscope units. The accepted events are cross hatched.

HPW Dimuon events: either it is a hadron „y“ , then mass betw. 2 and 4 GeV, related to high y anomaly; or heavy lepton. Feb. 1975



(a) The flat dimuon mass distribution is inconsistent with predominant production and decay of a narrow neutral vector boson. (b) The absence of trimuon final states and the predominance of events with opposite electric charge is indicative that the dimuon events have, by lepton conservation, an undetected neutral lepton. The calculated cross section for the coherent process $\nu + Z \rightarrow \nu\mu\mu Z$ is several orders of magnitude smaller than the dimuon signal, and the corresponding incoherent process has an even smaller cross section.[7]

Without the intervention of higher-order-weak or weak-electromagnetic interactions which are expected at a much lower rate, the only known mechanism that can produce trilepton final states accompanied by hadrons is the production and weak decay of one or more new particles. Such particles could be hadrons which carry a new quantum number[8] not conserved by the interaction responsible for the decay. From the characteristics of the dimuon events we may deduce that, if the particle is a hadron, the mass is greater than ~2 GeV [from the p_t distribution, Fig. 4(a)] and less than ~4 GeV [from the $W_{\min}$ distribution, Fig. 4(c)], and the lifetime is required to be less than 10^{-10} sec. We would like to call such particles y particles because of the probable relation of the dimuon signal to the violation of charge-symmetry invariance observed in the antineutrino y distribution.[2,4] An alternative explanation of the dimuon events is, however, through the production of a neutral heavy lepton, that decays into two muons and a neutrino or antineutrino. This is a less likely explanation, but it cannot be ruled out at present.

high y

It is a pleasure to acknowledge the aid and encouragement of the Fermilab staff. We thank B. Aubert and J. Pilcher for early contributions to this work.

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*Work supported in part by the U. S. Atomic Energy Commission.

[1] B. Aubert *et al*., "Experimental Observation of $\mu^+\mu^-$ Pairs Produced by Very High Energy Neutrinos," in Proceedings of the Seventeenth International Conference on High Energy Physics, London, 1974 (to be published), and in *Neutrinos—1974*, AIP Conference Proceedings No. 22, edited by C. Baltay (American Institute of Physics, New York, 1974), p. 201.

[2] A. Benvenuti *et al*., to be published.

[3] A. Benvenuti *et al*., Phys. Rev. Lett. 32, 125 (1974).

[4] B. Aubert *et al*., Phys. Rev. Lett. 33, 984 (1974).

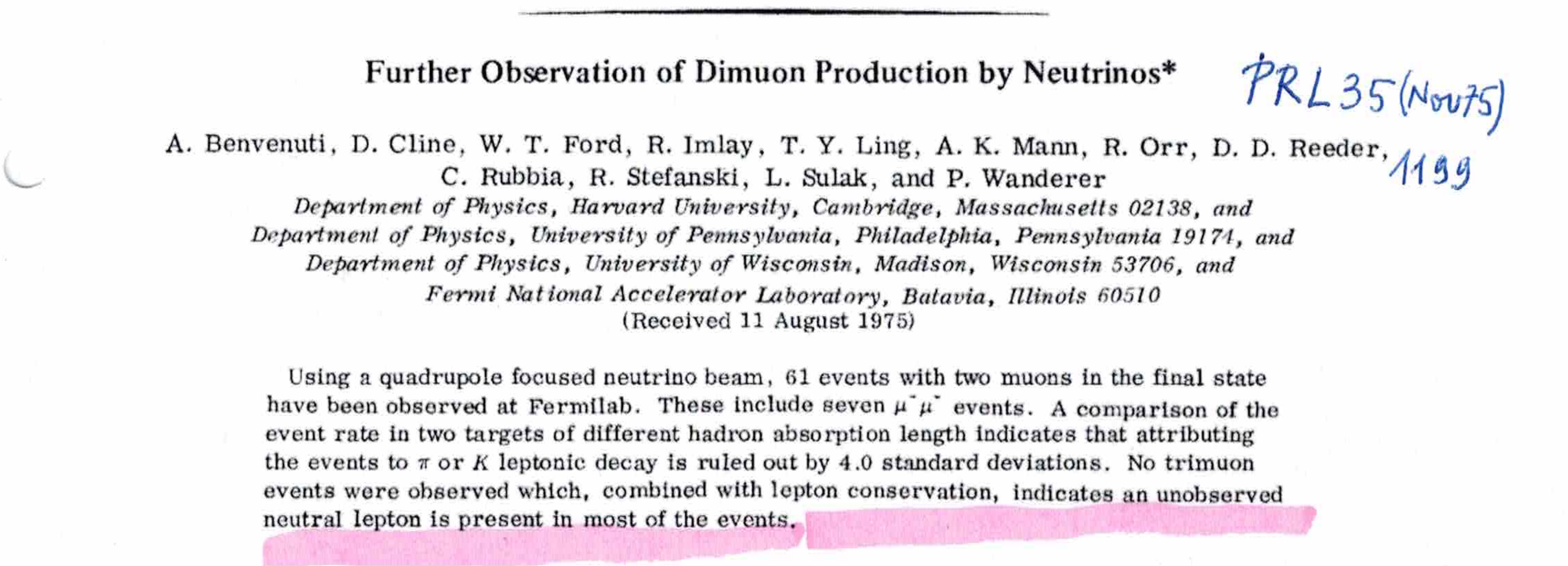
[5] M. Perl, in Proceedings of the SLAC Summer Institute on Particle Physics, July 1973, Stanford, California, SLAC Report No. SLAC 157 (unpublished).

[6] C. Myatt, private communication.

[7] W. Czyz, G. C. Sheppey, and J. D. Walecka, Nuovo Cimento 34, 404 (1964); R. W. Brown, R. H. Hobbs, J. Smith, and N. Stanko, Phys. Rev. D 6, 3273 (1972).

[8] See, for example, A. De Rújula and S. L. Glashow, Phys. Rev. Lett. 34, 46 (1975); M. Gaillard, B. W. Lee, and J. Josner, Fermilab Report No. Pub-74/86-THY, 1974 (unpublished).

HPW Dimuon production, Nov. 1975: new neutral lepton



Further Observation of Dimuon Production by Neutrinos*

PRL 35 (Nov75) 1199

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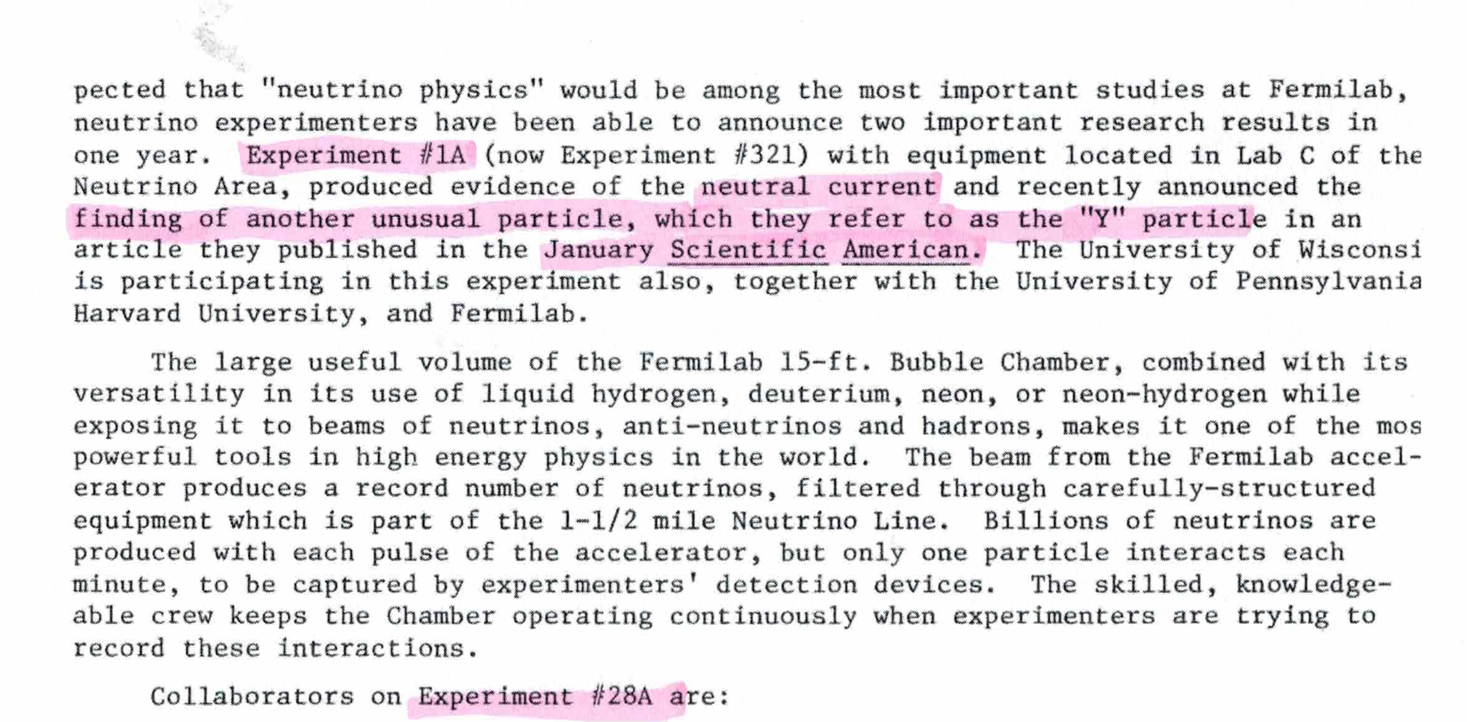
(Received 11 August 1975)

Using a quadrupole focused neutrino beam, 61 events with two muons in the final state have been observed at Fermilab. These include seven $\mu^-\mu^-$ events. A comparison of the event rate in two targets of different hadron absorption length indicates that attributing the events to π or K leptonic decay is ruled out by 4.0 standard deviations. No trimuon events were observed which, combined with lepton conservation, indicates an unobserved neutral lepton is present in most of the events.

HPW Experiment #1A
Village Crier Jan. 1976:
two important research results
--evidence of the neutral current
-- finding of an unusual particle , the Y particle



pected that "neutrino physics" would be among the most important studies at Fermilab, neutrino experimenters have been able to announce two important research results in one year. Experiment #1A (now Experiment #321) with equipment located in Lab C of the Neutrino Area, produced evidence of the neutral current and recently announced the finding of another unusual particle, which they refer to as the "Y" particle in an article they published in the January Scientific American. The University of Wisconsi is participating in this experiment also, together with the University of Pennsylvania Harvard University, and Fermilab.

The large useful volume of the Fermilab 15-ft. Bubble Chamber, combined with its versatility in its use of liquid hydrogen, deuterium, neon, or neon-hydrogen while exposing it to beams of neutrinos, anti-neutrinos and hadrons, makes it one of the mos powerful tools in high energy physics in the world. The beam from the Fermilab accelerator produces a record number of neutrinos, filtered through carefully-structured equipment which is part of the 1-1/2 mile Neutrino Line. Billions of neutrinos are produced with each pulse of the accelerator, but only one particle interacts each minute, to be captured by experimenters' detection devices. The skilled, knowledgeable crew keeps the Chamber operating continuously when experimenters are trying to record these interactions.

Collaborators on Experiment #28A are:

Fermilab Village Crier
January 1976:
Major Discovery Announced by Experimenters at Fermilab:

four neutrino events detected
in 15ft bubble chamber of type
K0+mu- +e+
evidence for production and
decay of charmed hadron

The Village Crier
fermi national accelerator laboratory
Operated by Universities Research Associatio
Under Contract with the Energy Research & Development Administr
Vol. No. 8 No. 1
January 8, 1

MAJOR DISCOVERY ANNOUNCED BY EXPERIMENTERS AT FERMILAB

CHARM 1976

An experimental group working at Fermilab has announced that their experimental results produce evidence of the existence of a new particle with an entirely new physical property. This new property may correspond to one that was predicted by theoretical physicists several years ago.

The experimenters -- representing the University of Wisconsin, the CERN Laboratory at Geneva, Switzerland, the University of California Lawrence Berkeley Laboratory, and the University of Hawaii collaborating as Experiment #28A, a study of neutrino interactions -- made their observations in pictures taken by the 15-ft. Bubble Chamber filled with a mixture of liquid hydrogen and neon. The 97,000 pictures taken for Experiment #28A were taken between April and June, 1975.

Neutrinos are elusive, massless, chargeless particles first discovered through the study of radioactivity. They are used at Fermilab as powerful probes of the structure of matter. In the usual interactions of neutrinos with protons or neutrons the neutrino is transmuted into a negatively charged muon, a particle belonging to the "lepton" family, a family which also includes electrons and neutrinos. In such an interaction the proton or neutron, both members of another family of particles called hadrons, is fragmented into other particles which are also members of the hadron family.

The experiment performed at Fermilab has so far revealed four events of special interest among about 1,000 neutrino interactions. These results were reported at a conference held in Irvine, California on December 5, 1975. Since then, additional work has been done to confirm the analysis.

All four events exhibit a negatively-charged muon, a positively charged electron (called a positron), and a neutral K meson. In two of the four events, the muon hit a special detector designed to differentiate muons from pi mesons, the most common subatomic particles observed in the fragments of protons and neutrons.

This is the first time that two leptons, (a positron and a firmly identified negative muon) have been observed together with a neutral K meson, a particle that carried a property known as "strangeness."

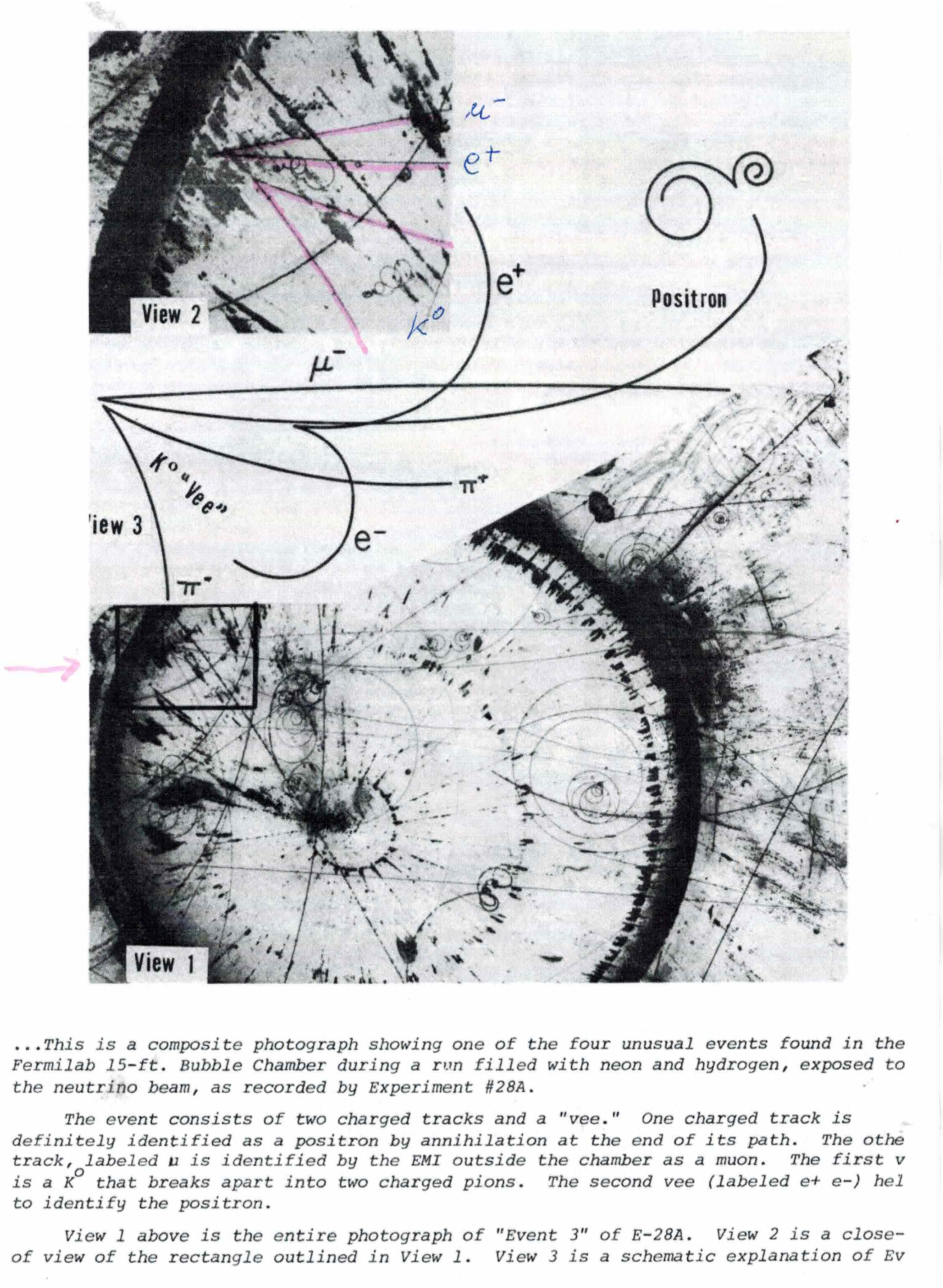
The mass of the new particle seems to be about twice the mass of a proton. Since

...15 ft. Bubble Chamber yields new experimental results...

...New data verified by External Muon Identifier...

Continued...

Observation of Charm production and decay in 15 ft bubble chamber at Fermilab Jan. 1976

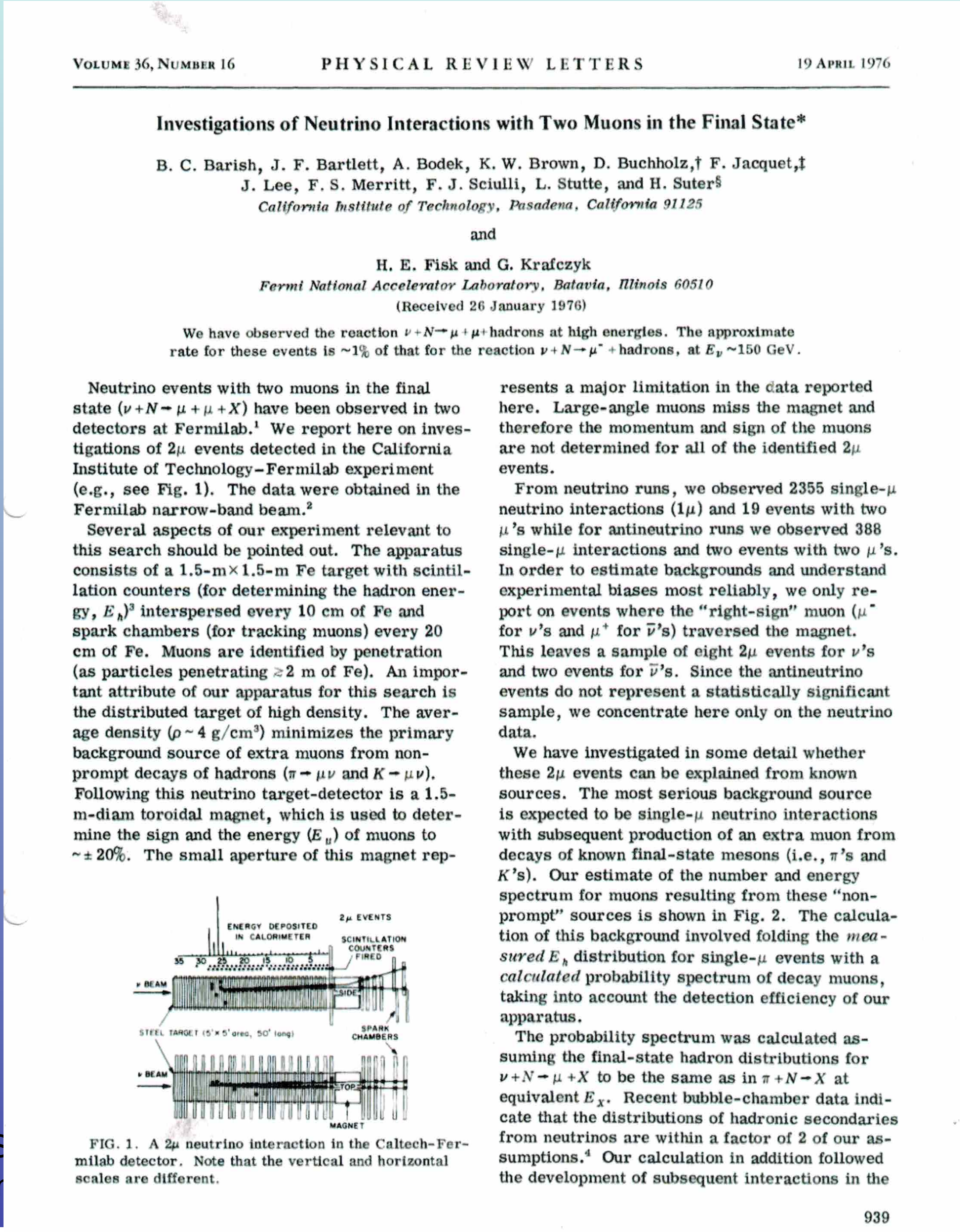


...This is a composite photograph showing one of the four unusual events found in the Fermilab 15-ft. Bubble Chamber during a run filled with neon and hydrogen, exposed to the neutrino beam, as recorded by Experiment #28A.

The event consists of two charged tracks and a "vee." One charged track is definitely identified as a positron by annihilation at the end of its path. The othe track, labeled μ is identified by the EMI outside the chamber as a muon. The first v is a K^o that breaks apart into two charged pions. The second vee (labeled e+ e-) hel to identify the positron.

View 1 above is the entire photograph of "Event 3" of E-28A. View 2 is a close- of view of the rectangle outlined in View 1. View 3 is a schematic explanation of Ev

Observation of neutrino-induced dimuon events April 1976



Investigations of Neutrino Interactions with Two Muons in the Final State*

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(Received 26 January 1976)

We have observed the reaction $\nu+N\rightarrow\mu+\mu+$hadrons at high energies. The approximate rate for these events is ~1% of that for the reaction $\nu+N\rightarrow\mu^-+$hadrons, at E_ν ~150 GeV.

Neutrino events with two muons in the final state ($\nu+N\rightarrow\mu+\mu+X$) have been observed in two detectors at Fermilab.[1] We report here on investigations of 2μ events detected in the California Institute of Technology–Fermilab experiment (e.g., see Fig. 1). The data were obtained in the Fermilab narrow-band beam.[2]

Several aspects of our experiment relevant to this search should be pointed out. The apparatus consists of a 1.5-m×1.5-m Fe target with scintillation counters (for determining the hadron energy, E_h)[3] interspersed every 10 cm of Fe and spark chambers (for tracking muons) every 20 cm of Fe. Muons are identified by penetration (as particles penetrating $\gtrsim 2$ m of Fe). An important attribute of our apparatus for this search is the distributed target of high density. The average density ($\rho \sim 4$ g/cm^3) minimizes the primary background source of extra muons from nonprompt decays of hadrons ($\pi\rightarrow\mu\nu$ and $K\rightarrow\mu\nu$). Following this neutrino target-detector is a 1.5-m-diam toroidal magnet, which is used to determine the sign and the energy (E_μ) of muons to ~±20%. The small aperture of this magnet represents a major limitation in the data reported here. Large-angle muons miss the magnet and therefore the momentum and sign of the muons are not determined for all of the identified 2μ events.

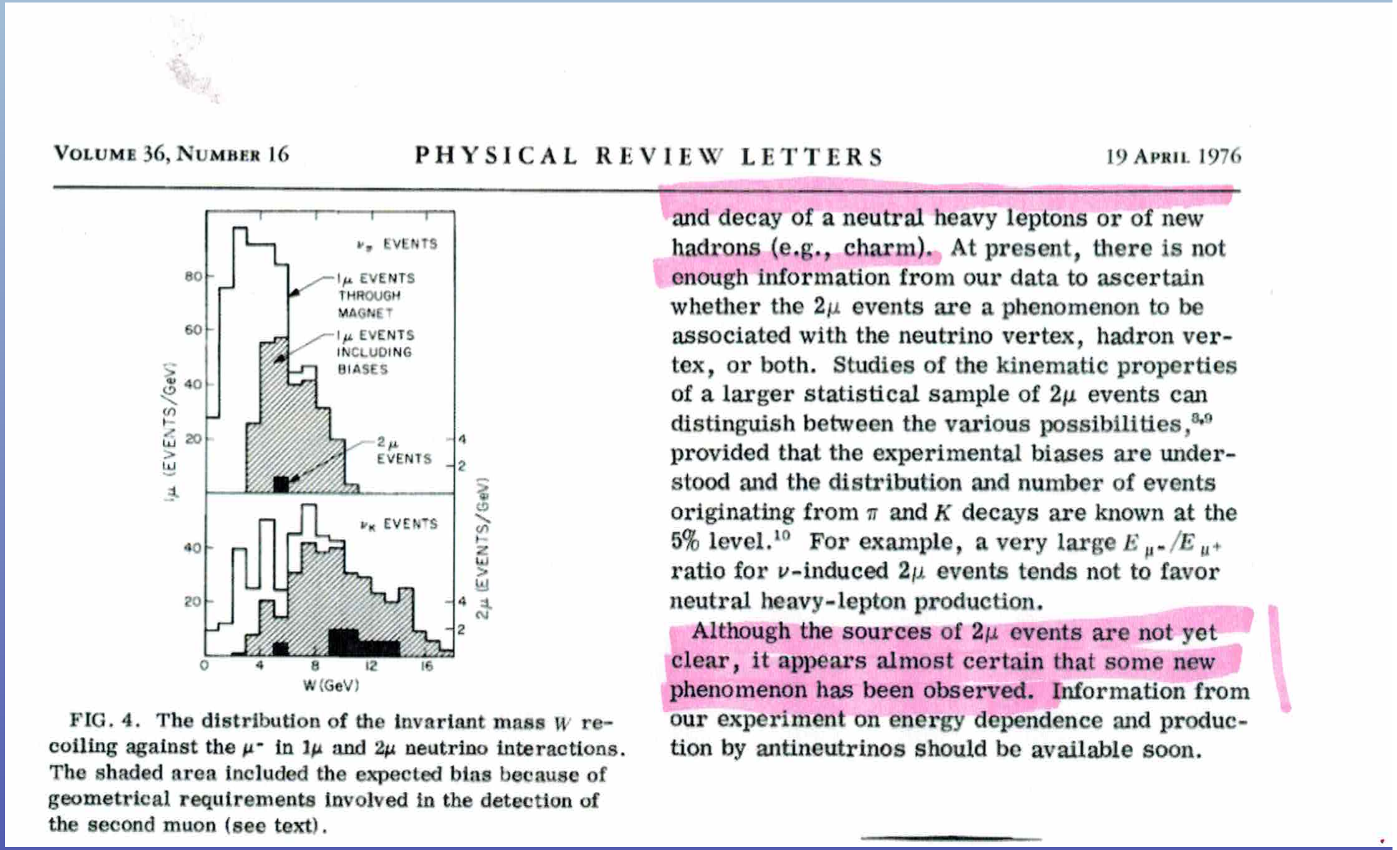
FIG. 1. A 2μ neutrino interaction in the Caltech-Fermilab detector. Note that the vertical and horizontal scales are different.

From neutrino runs, we observed 2355 single-μ neutrino interactions (1μ) and 19 events with two μ's while for antineutrino runs we observed 388 single-μ interactions and two events with two μ's. In order to estimate backgrounds and understand experimental biases most reliably, we only report on events where the "right-sign" muon (μ^- for ν's and μ^+ for $\bar{\nu}$'s) traversed the magnet. This leaves a sample of eight 2μ events for ν's and two events for $\bar{\nu}$'s. Since the antineutrino events do not represent a statistically significant sample, we concentrate here only on the neutrino data.

We have investigated in some detail whether these 2μ events can be explained from known sources. The most serious background source is expected to be single-μ neutrino interactions with subsequent production of an extra muon from decays of known final-state mesons (i.e., π's and K's). Our estimate of the number and energy spectrum for muons resulting from these "nonprompt" sources is shown in Fig. 2. The calculation of this background involved folding the *measured* E_h distribution for single-μ events with a *calculated* probability spectrum of decay muons, taking into account the detection efficiency of our apparatus.

The probability spectrum was calculated assuming the final-state hadron distributions for $\nu+N\rightarrow\mu+X$ to be the same as in $\pi+N\rightarrow X$ at equivalent E_X. Recent bubble-chamber data indicate that the distributions of hadronic secondaries from neutrinos are within a factor of 2 of our assumptions.[4] Our calculation in addition followed the development of subsequent interactions in the

Dimuon events Caltech-Fermilab: source uncertain either decay of neutral heavy lepton or of new hadrons (e.g. charm); April 1976



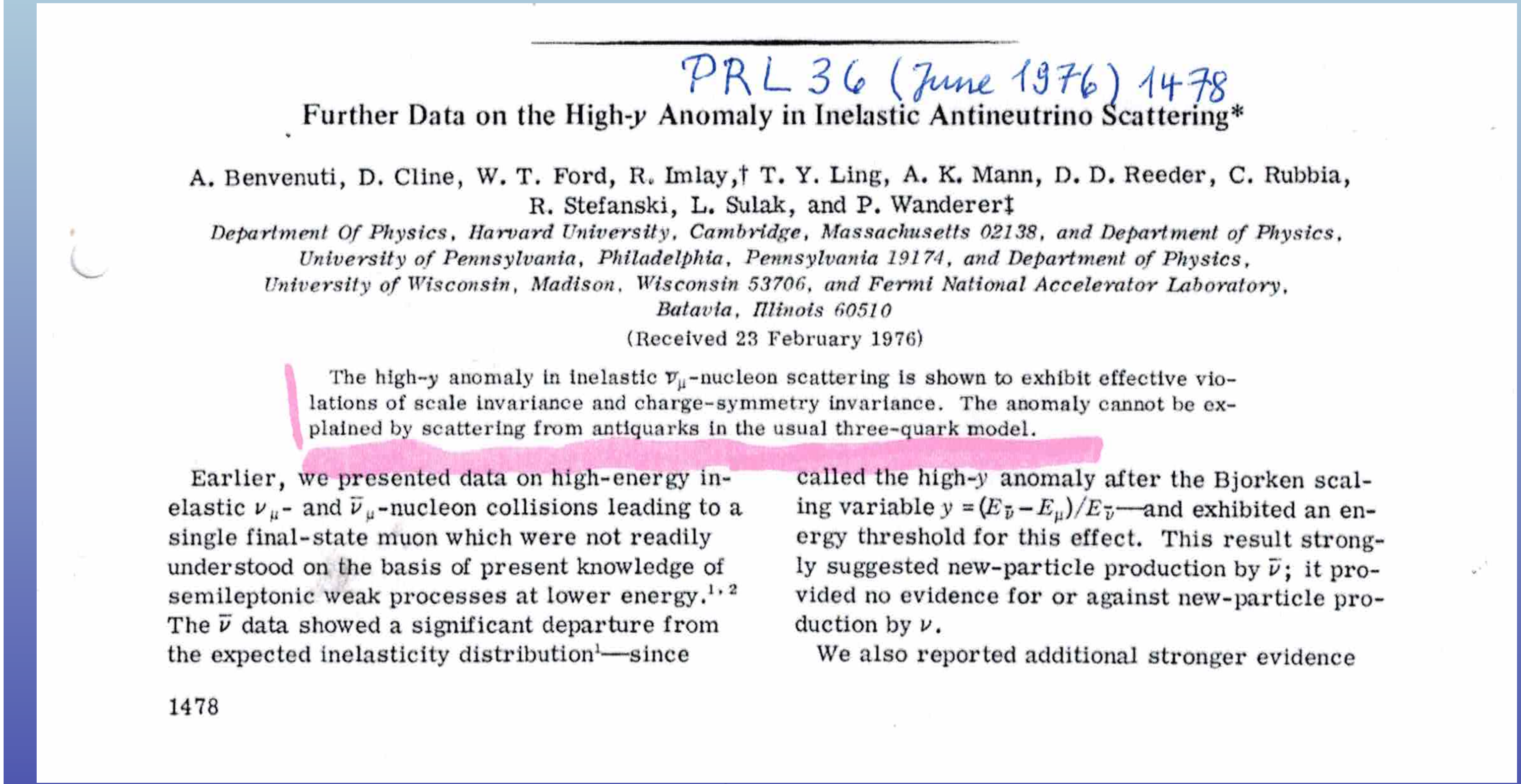
VOLUME 36, NUMBER 16 PHYSICAL REVIEW LETTERS 19 APRIL 1976

FIG. 4. The distribution of the invariant mass W recoiling against the μ^- in 1μ and 2μ neutrino interactions. The shaded area included the expected bias because of geometrical requirements involved in the detection of the second muon (see text).

and decay of a neutral heavy leptons or of new hadrons (e.g., charm). At present, there is not enough information from our data to ascertain whether the 2μ events are a phenomenon to be associated with the neutrino vertex, hadron vertex, or both. Studies of the kinematic properties of a larger statistical sample of 2μ events can distinguish between the various possibilities,[8,9] provided that the experimental biases are understood and the distribution and number of events originating from π and K decays are known at the 5% level.[10] For example, a very large E_{μ^-}/E_{μ^+} ratio for ν-induced 2μ events tends not to favor neutral heavy-lepton production.

Although the sources of 2μ events are not yet clear, it appears almost certain that some new phenomenon has been observed. Information from our experiment on energy dependence and production by antineutrinos should be available soon.

HPW High-y Anomaly June 1976



PRL 36 (June 1976) 1478

Further Data on the High-y Anomaly in Inelastic Antineutrino Scattering*

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(Received 23 February 1976)

The high-y anomaly in inelastic $\bar{\nu}_\mu$-nucleon scattering is shown to exhibit effective violations of scale invariance and charge-symmetry invariance. The anomaly cannot be explained by scattering from antiquarks in the usual three-quark model.

Earlier, we presented data on high-energy inelastic ν_μ- and $\bar{\nu}_\mu$-nucleon collisions leading to a single final-state muon which were not readily understood on the basis of present knowledge of semileptonic weak processes at lower energy.[1,2] The $\bar{\nu}$ data showed a significant departure from the expected inelasticity distribution[1]—since called the high-y anomaly after the Bjorken scaling variable $y = (E_{\bar{\nu}} - E_\mu)/E_{\bar{\nu}}$—and exhibited an energy threshold for this effect. This result strongly suggested new-particle production by $\bar{\nu}$; it provided no evidence for or against new-particle production by ν.

We also reported additional stronger evidence

HPW High-y Anomaly June 1976

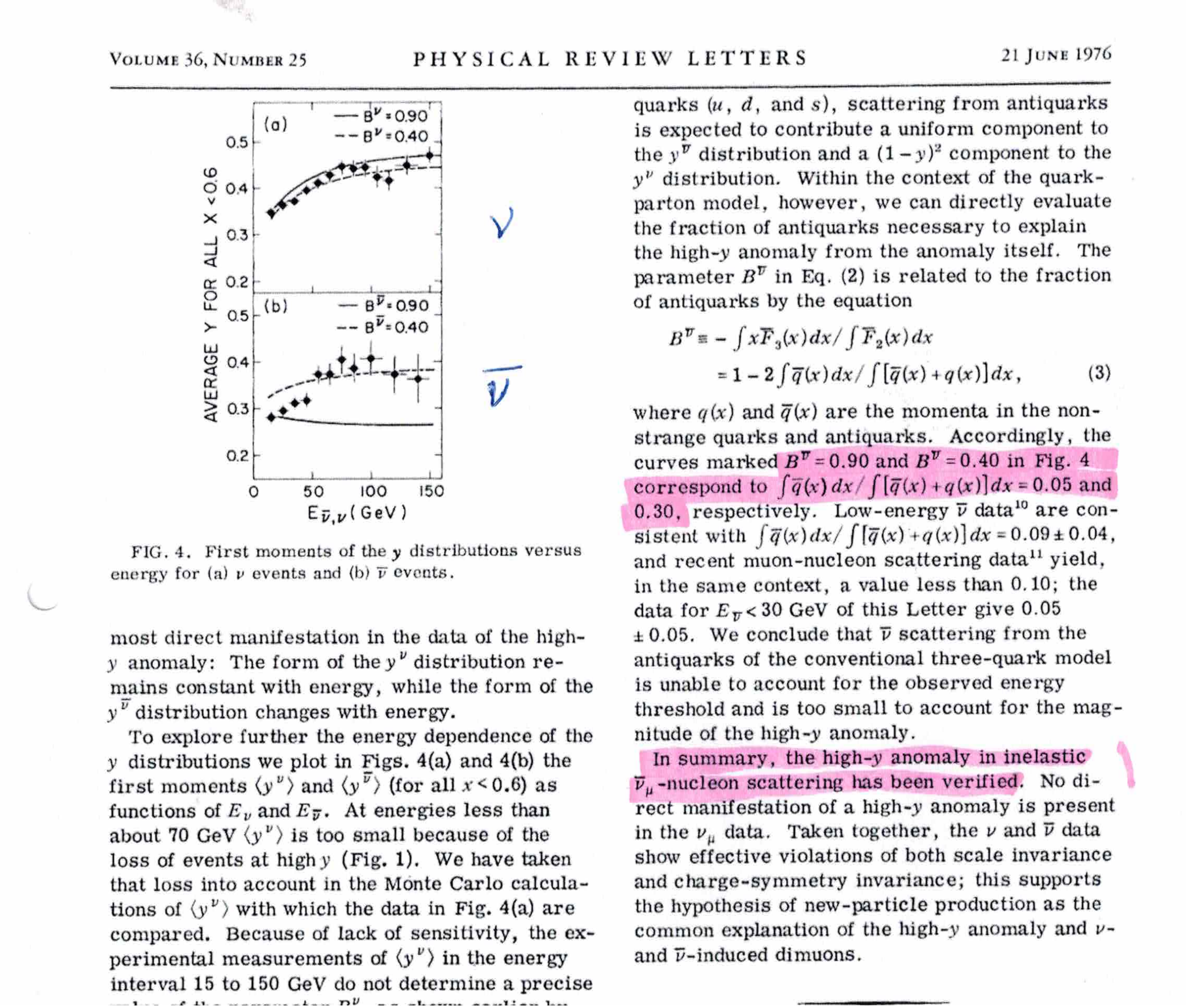


FIG. 4. First moments of the y distributions versus energy for (a) ν events and (b) $\bar\nu$ events.

most direct manifestation in the data of the high-y anomaly: The form of the y^{ν} distribution remains constant with energy, while the form of the $y^{\bar\nu}$ distribution changes with energy.

To explore further the energy dependence of the y distributions we plot in Figs. 4(a) and 4(b) the first moments $\langle y^{\nu}\rangle$ and $\langle y^{\bar\nu}\rangle$ (for all $x < 0.6$) as functions of E_{ν} and $E_{\bar\nu}$. At energies less than about 70 GeV $\langle y^{\nu}\rangle$ is too small because of the loss of events at high y (Fig. 1). We have taken that loss into account in the Monte Carlo calculations of $\langle y^{\nu}\rangle$ with which the data in Fig. 4(a) are compared. Because of lack of sensitivity, the experimental measurements of $\langle y^{\nu}\rangle$ in the energy interval 15 to 150 GeV do not determine a precise

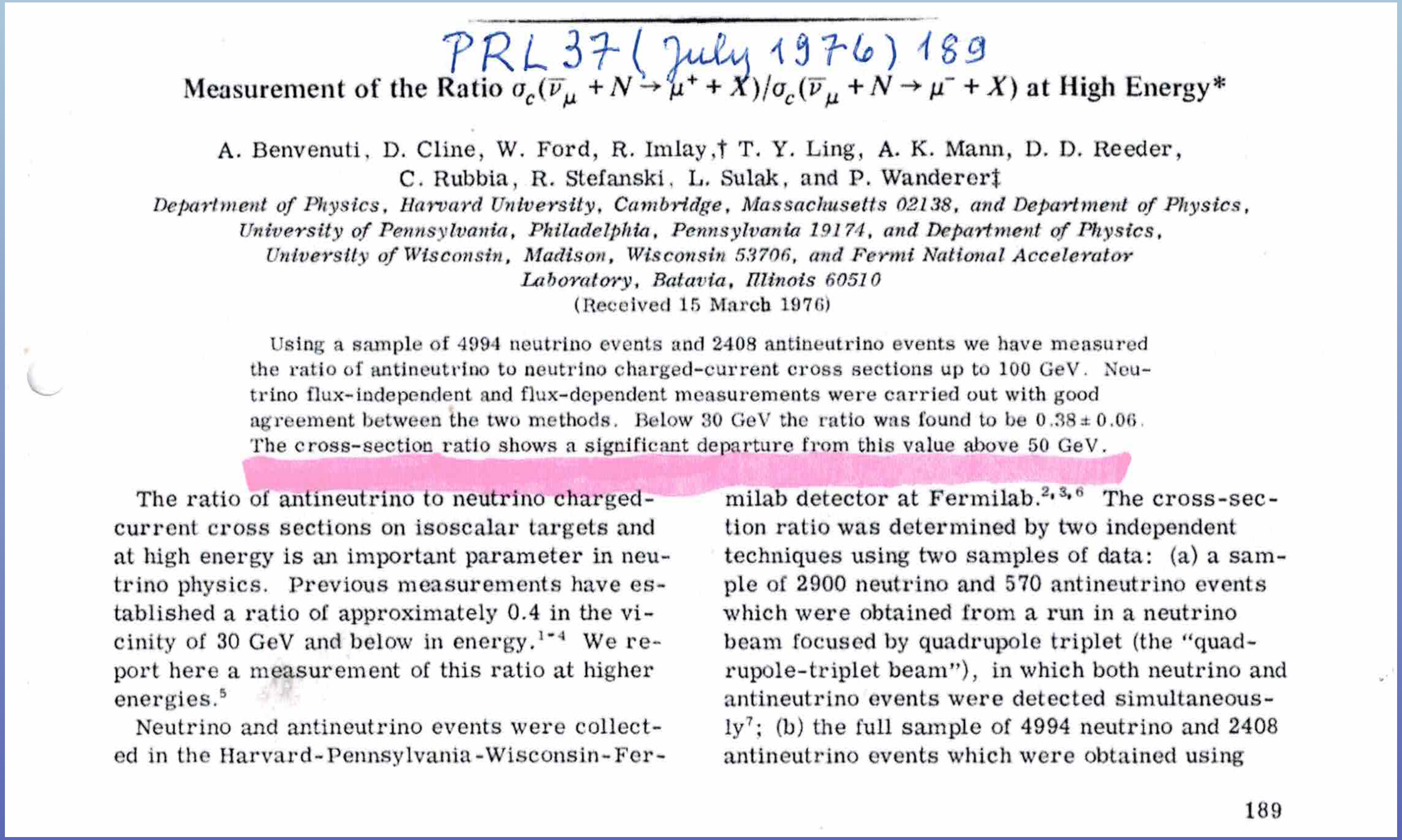
quarks (u, d, and s), scattering from antiquarks is expected to contribute a uniform component to the $y^{\bar\nu}$ distribution and a $(1-y)^2$ component to the y^{ν} distribution. Within the context of the quark-parton model, however, we can directly evaluate the fraction of antiquarks necessary to explain the high-y anomaly from the anomaly itself. The parameter $B^{\bar\nu}$ in Eq. (2) is related to the fraction of antiquarks by the equation

$$B^{\bar\nu} \equiv -\int x\bar F_3(x)\,dx \Big/ \int \bar F_2(x)\,dx = 1 - 2\int \bar q(x)\,dx \Big/ \int[\bar q(x)+q(x)]\,dx, \qquad (3)$$

where $q(x)$ and $\bar q(x)$ are the momenta in the nonstrange quarks and antiquarks. Accordingly, the curves marked $B^{\bar\nu}=0.90$ and $B^{\bar\nu}=0.40$ in Fig. 4 correspond to $\int \bar q(x)\,dx / \int[\bar q(x)+q(x)]\,dx = 0.05$ and 0.30, respectively. Low-energy $\bar\nu$ data[10] are consistent with $\int \bar q(x)\,dx / \int[\bar q(x)+q(x)]\,dx = 0.09 \pm 0.04$, and recent muon-nucleon scattering data[11] yield, in the same context, a value less than 0.10; the data for $E_{\bar\nu} < 30$ GeV of this Letter give 0.05 ± 0.05. We conclude that $\bar\nu$ scattering from the antiquarks of the conventional three-quark model is unable to account for the observed energy threshold and is too small to account for the magnitude of the high-y anomaly.

In summary, the high-y anomaly in inelastic $\bar\nu_{\mu}$-nucleon scattering has been verified. No direct manifestation of a high-y anomaly is present in the ν_{μ} data. Taken together, the ν and $\bar\nu$ data show effective violations of both scale invariance and charge-symmetry invariance; this supports the hypothesis of new-particle production as the common explanation of the high-y anomaly and ν- and $\bar\nu$-induced dimuons.

HPW cross-section ratio nubar/nu shows threshold at 50 GeV, July 1976



PRL 37 (July 1976) 189

Measurement of the Ratio $\sigma_c(\bar{\nu}_\mu + N \to \mu^+ + X)/\sigma_c(\bar{\nu}_\mu + N \to \mu^- + X)$ at High Energy*

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(Received 15 March 1976)

Using a sample of 4994 neutrino events and 2408 antineutrino events we have measured the ratio of antineutrino to neutrino charged-current cross sections up to 100 GeV. Neutrino flux-independent and flux-dependent measurements were carried out with good agreement between the two methods. Below 30 GeV the ratio was found to be 0.38 ± 0.06. The cross-section ratio shows a significant departure from this value above 50 GeV.

The ratio of antineutrino to neutrino charged-current cross sections on isoscalar targets and at high energy is an important parameter in neutrino physics. Previous measurements have established a ratio of approximately 0.4 in the vicinity of 30 GeV and below in energy.[1-4] We report here a measurement of this ratio at higher energies.[5]

Neutrino and antineutrino events were collected in the Harvard-Pennsylvania-Wisconsin-Fermilab detector at Fermilab.[2,3,6] The cross-section ratio was determined by two independent techniques using two samples of data: (a) a sample of 2900 neutrino and 570 antineutrino events which were obtained from a run in a neutrino beam focused by quadrupole triplet (the "quadrupole-triplet beam"), in which both neutrino and antineutrino events were detected simultaneously[7]; (b) the full sample of 4994 neutrino and 2408 antineutrino events which were obtained using

HPW cross-section ratio nubar/nu agrees below 30 GeV with bubble chamber value 0.38+-0.06 but increases above 30 GeV to 0.6+-0.1 July 1976

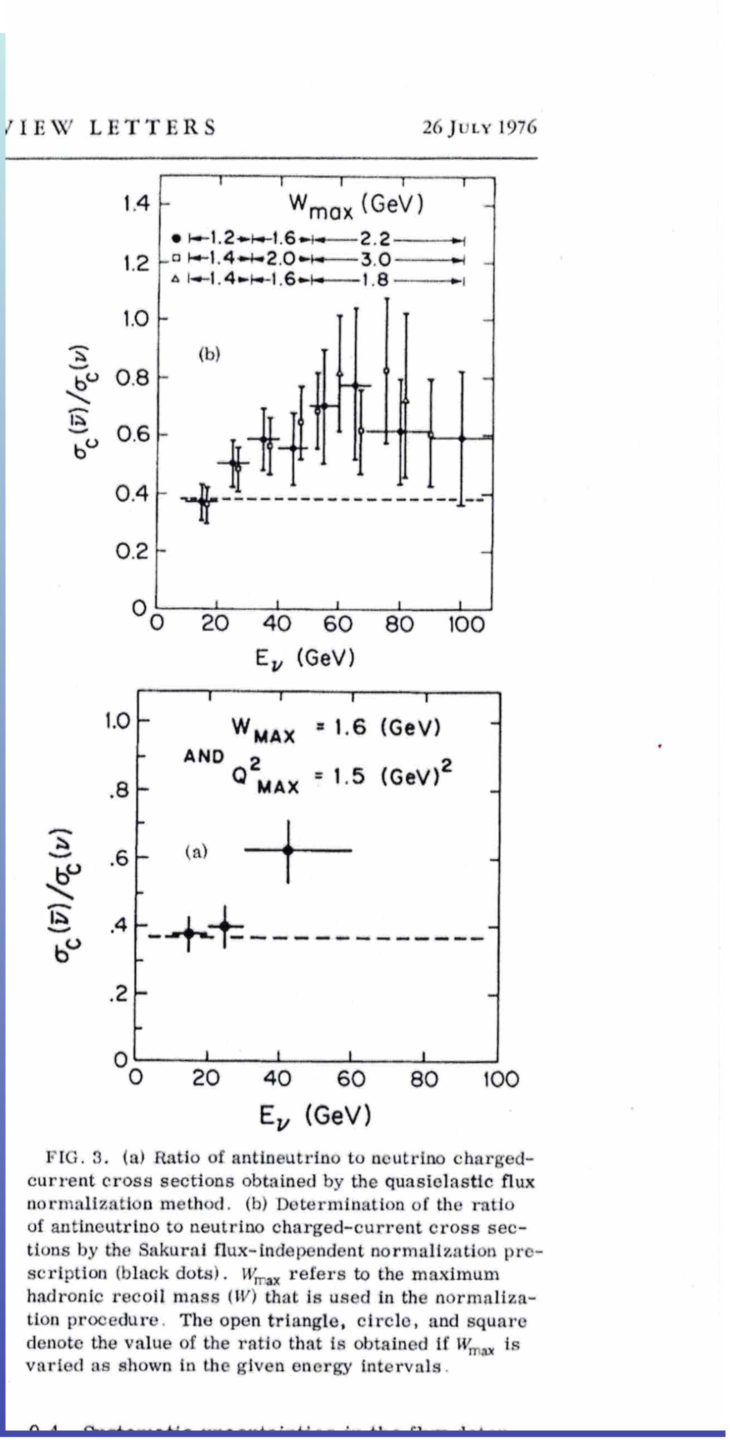


FIG. 3. (a) Ratio of antineutrino to neutrino charged-current cross sections obtained by the quasielastic flux normalization method. (b) Determination of the ratio of antineutrino to neutrino charged-current cross sections by the Sakurai flux-independent normalization prescription (black dots). W_{max} refers to the maximum hadronic recoil mass (W) that is used in the normalization procedure. The open triangle, circle, and square denote the value of the ratio that is obtained if W_{max} is varied as shown in the given energy intervals.

State of the art end of 1976

--Dimuon and mu- e+ events observed, origin either hadron (charm) or heavy lepton

--scaling works for neutrinos, but not for antineutrinos

--hadronic neutral weak currents observed

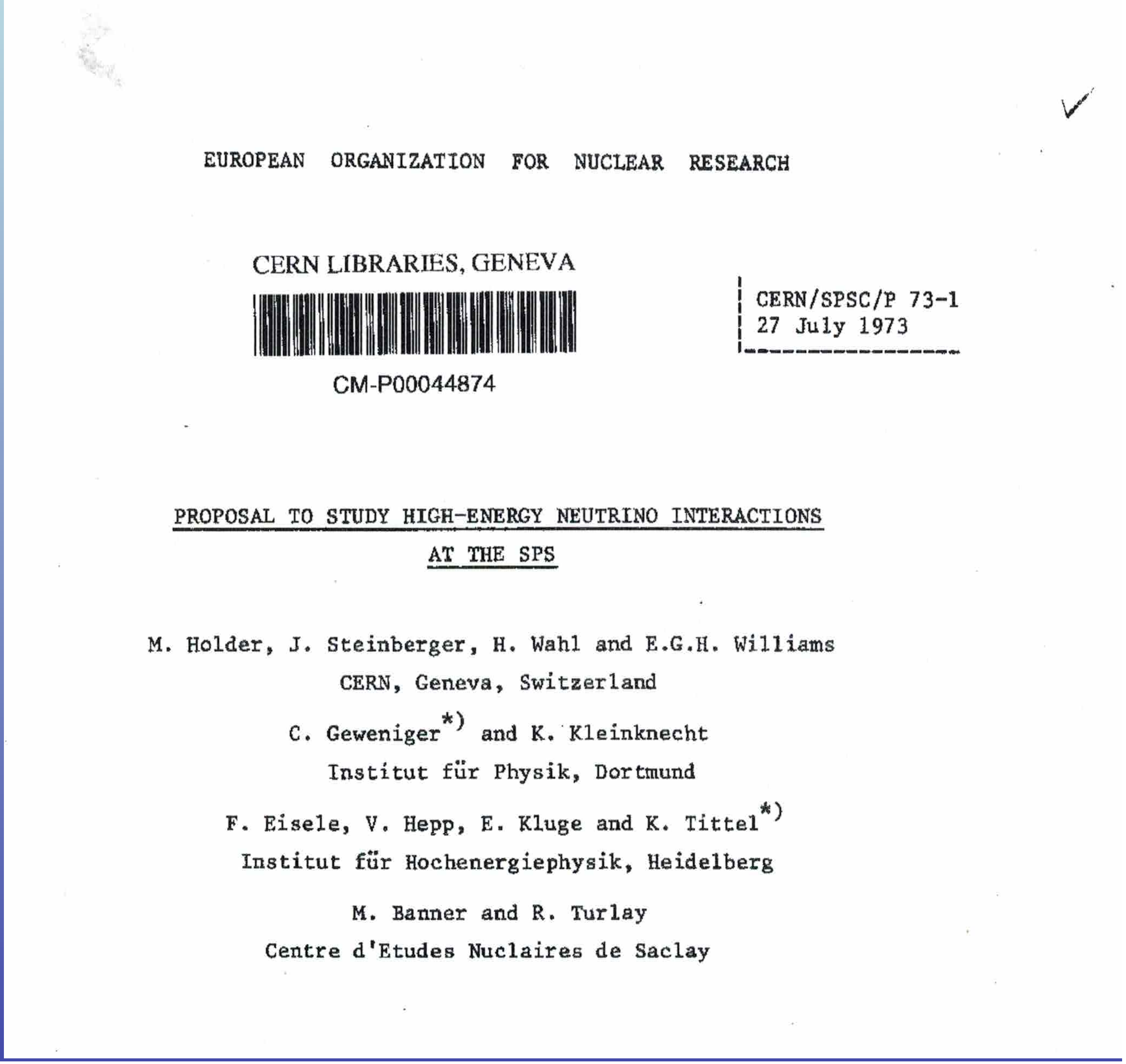
CERN SPS

Construction started 1971, 4 years after Fermilab

First beams in 1976

Proposals P1 and P3 (1973), and BEBC designed for West Area NBB and WBB neutrino beams

Proposal CDHS collaboration (P1) July 1973



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/SPSC/P 73-1
27 July 1973

PROPOSAL TO STUDY HIGH-ENERGY NEUTRINO INTERACTIONS AT THE SPS

M. Holder, J. Steinberger, H. Wahl and E.G.H. Williams
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Institut für Hochenergiephysik, Heidelberg

M. Banner and R. Turlay
Centre d'Etudes Nuclaires de Saclay

CDHS Proposal Had.Cal.+ Mu Spectrometer

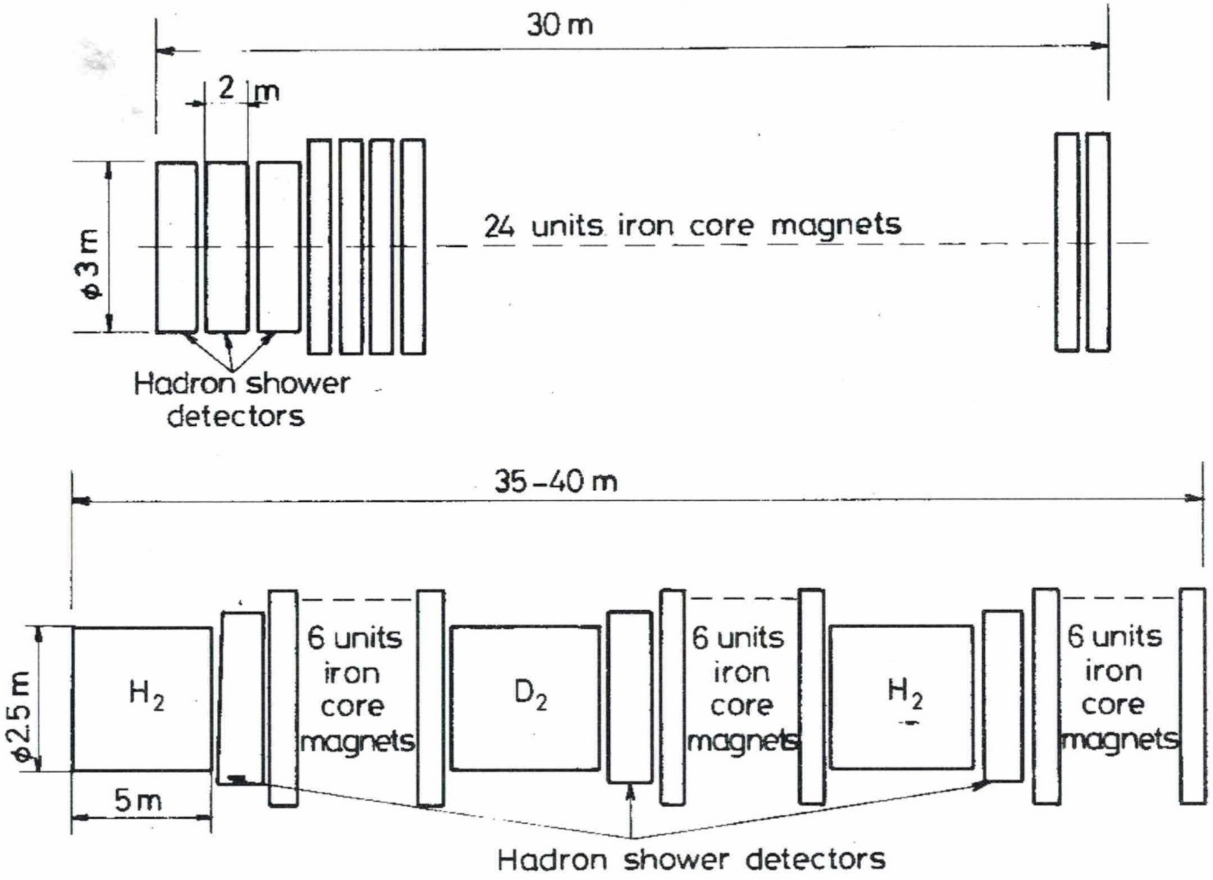


Fig. 7

CDHS original proposal 1973

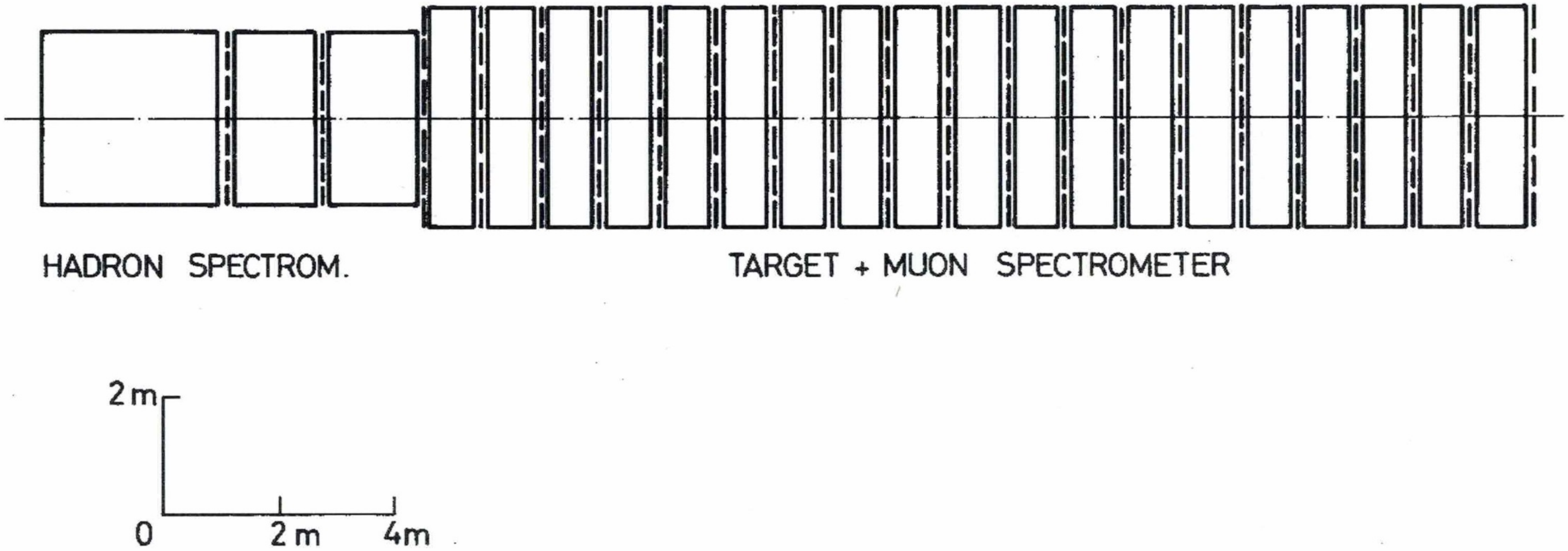


Fig. 3 Layout of the detector

CDHS proposal: Iron Core Magnet 1973

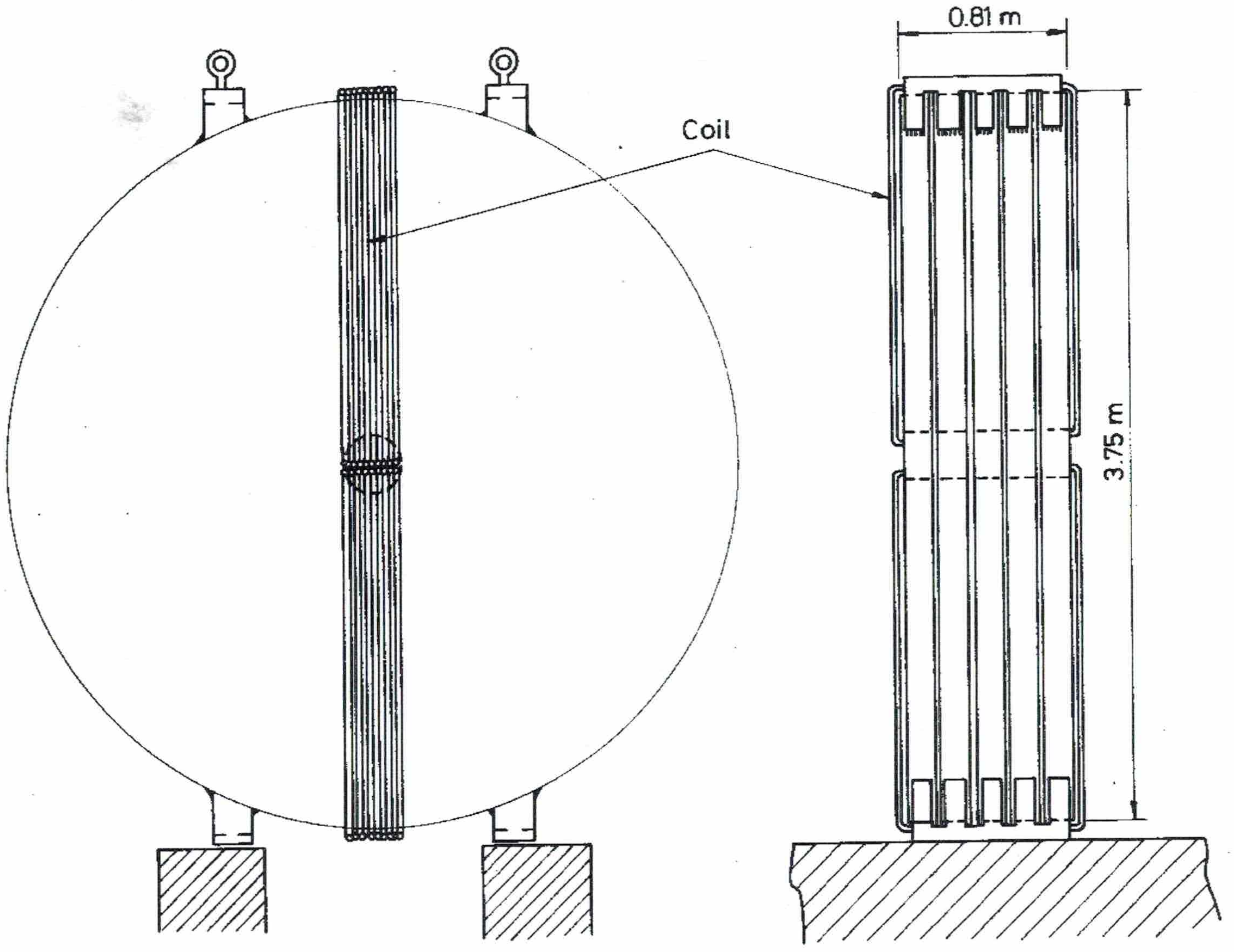
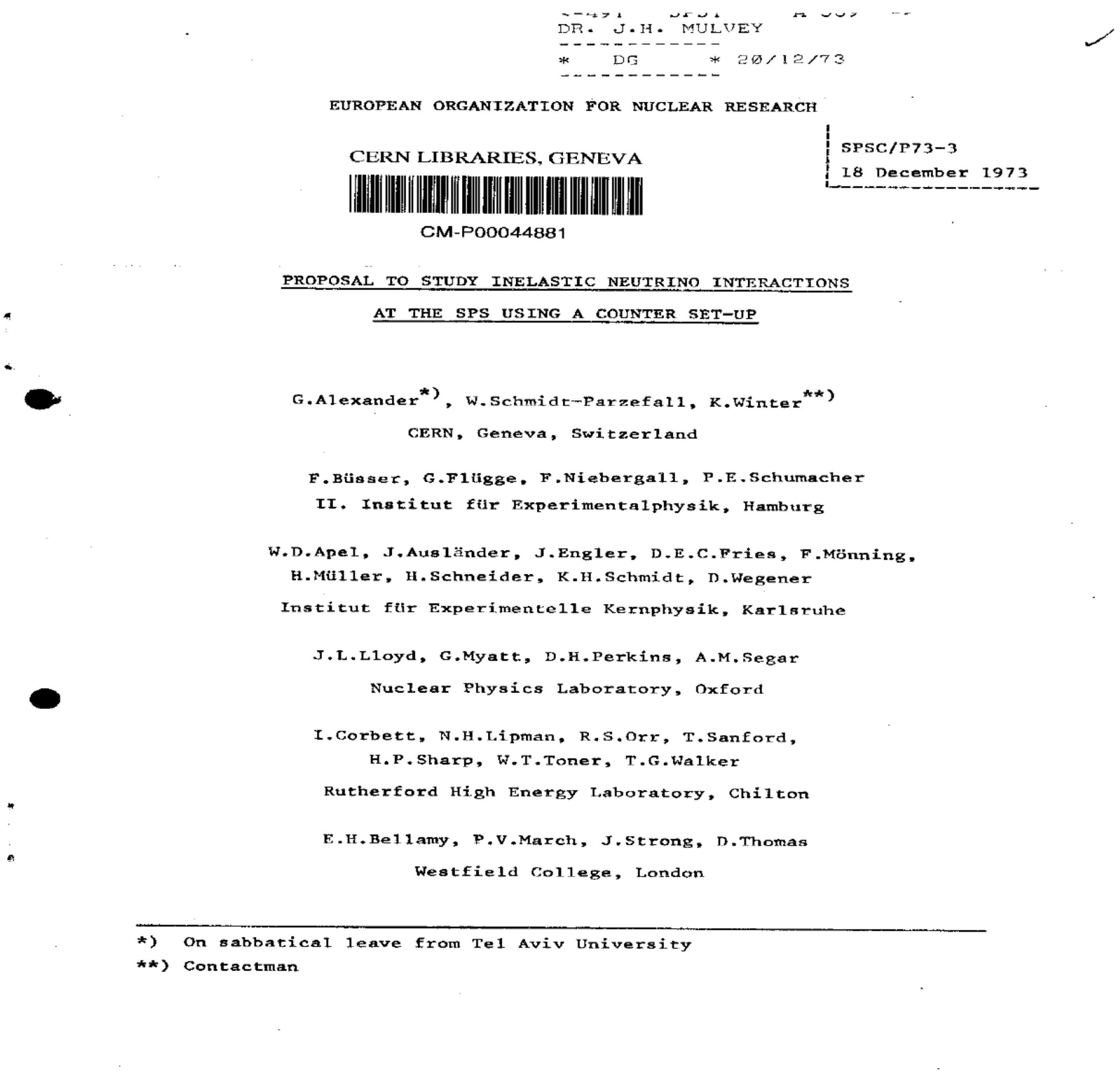


Fig. 5

Proposal P3
CERN-Hamburg-Karlsruhe-Oxford-Rutherford-Westfield



DR. J.H. MULVEY

* DG * 20/12/73

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

SPSC/P73-3
18 December 1973

PROPOSAL TO STUDY INELASTIC NEUTRINO INTERACTIONS AT THE SPS USING A COUNTER SET-UP

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II. Institut für Experimentalphysik, Hamburg

W.D.Apel, J.Ausländer, J.Engler, D.E.C.Fries, F.Mönning,
H.Müller, H.Schneider, K.H.Schmidt, D.Wegener
Institut für Experimentelle Kernphysik, Karlsruhe

J.L.Lloyd, G.Myatt, D.H.Perkins, A.M.Segar
Nuclear Physics Laboratory, Oxford

I.Corbett, N.H.Lipman, R.S.Orr, T.Sanford,
H.P.Sharp, W.T.Toner, T.G.Walker
Rutherford High Energy Laboratory, Chilton

E.H.Bellamy, P.V.March, J.Strong, D.Thomas
Westfield College, London

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*) On sabbatical leave from Tel Aviv University
**) Contactman

2018

Setup Proposal P3 for SPSC
LArgon/Fe-Calorimeter(340t)+ Air core solenoid magnet (820t)

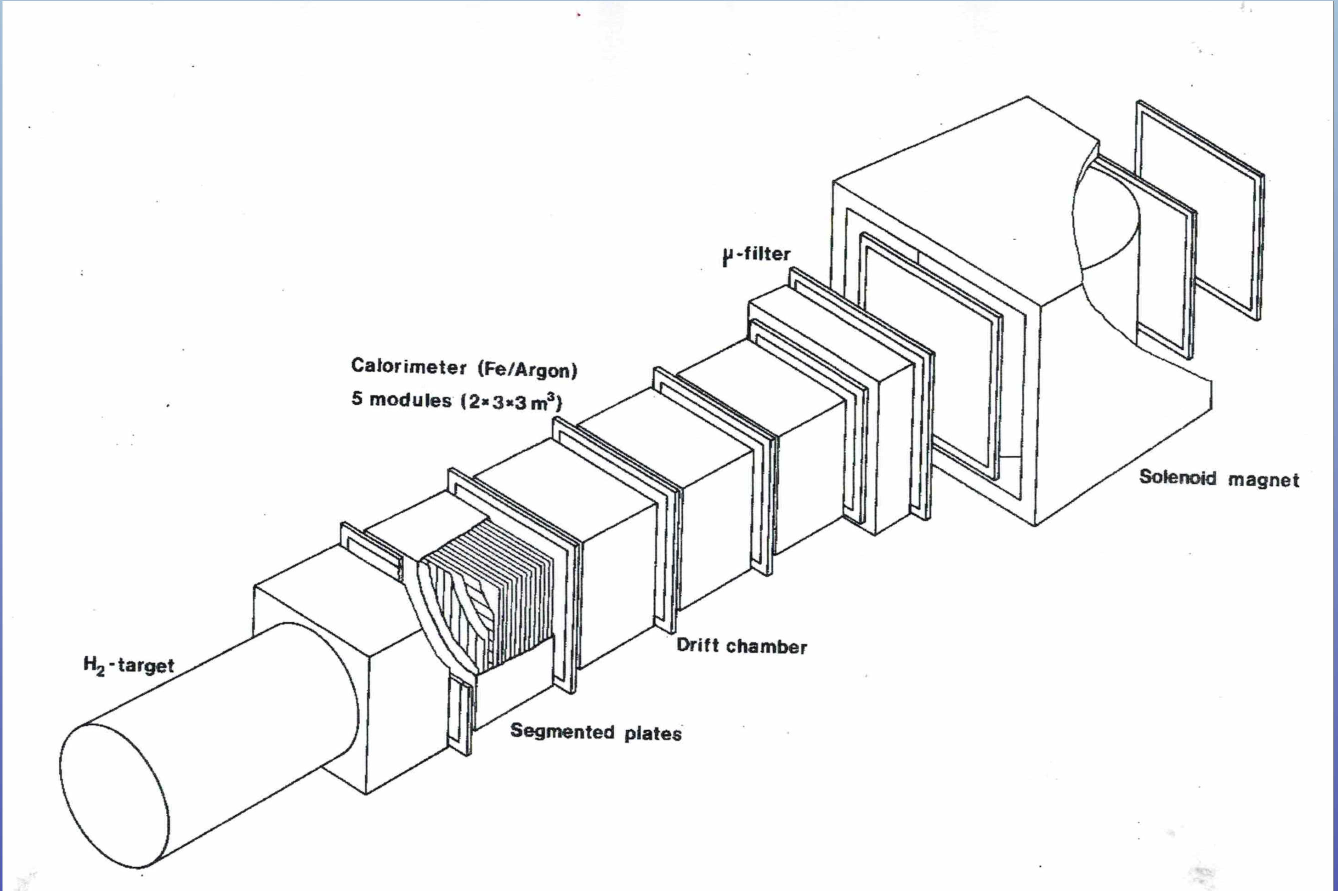

Fig. 3.6

Isometric view of the neutrino detector

SPSC Committee at CERN

not convinced by either proposal, P1 or P3,
both are a combination of Hadron Cal as target+
a magnet behind.
SPSC urges collaborations to unite –
with no success.
In february 1974 comes a new idea by Heinrich Wahl :
combine calorimeter and iron core magnet by
instrumenting ICM with scintillator (Memo M25):
SPSC and NPRC approve WA1=CDHS april 1974

P3 group made new proposal P49 (Oct. 1975) aiming at neutral current interactions approved March 1976 as WA18=CHARM experiment (CERN-Hamburg-Amsterdam-Roma-Moscow);

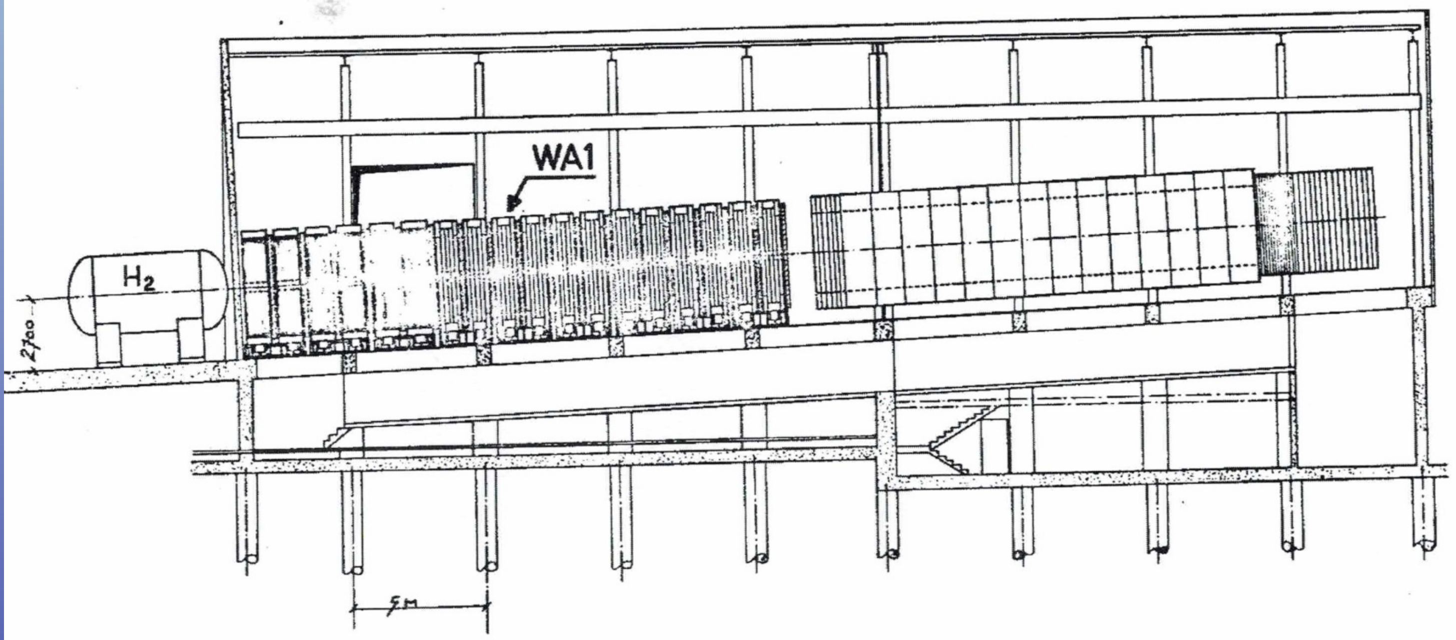

Figure 1.1

The lay-out of experiment WA1 and the proposed experiment in Hall 182.

Results CDHS from 1977:

1) Dimuons of opposite sign, PL 69B(1977) 377: 315 events show „remarkable agreement with hypothesis of charm production and decay“;“evidence against models with heavy lepton“; „evidence against bottom quark production by antineutrinos“

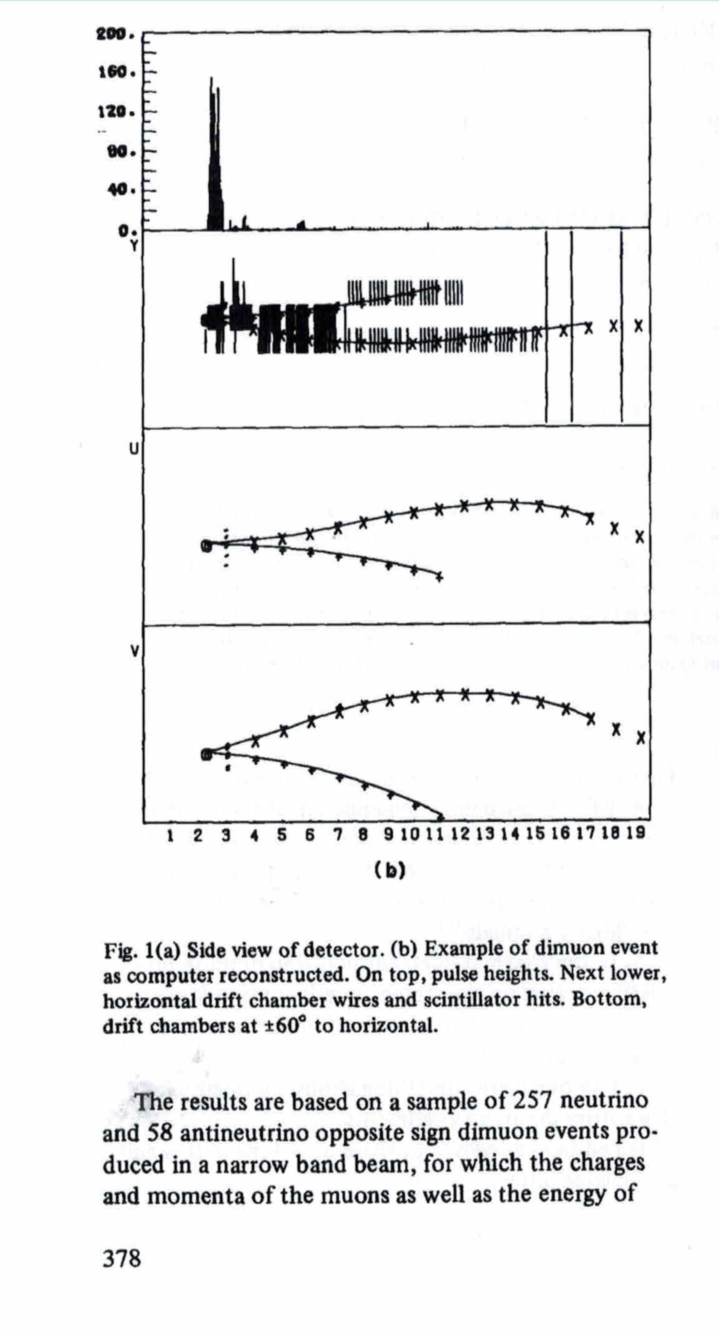

Fig. 1(a) Side view of detector. (b) Example of dimuon event as computer reconstructed. On top, pulse heights. Next lower, horizontal drift chamber wires and scintillator hits. Bottom, drift chambers at ±60° to horizontal.

The results are based on a sample of 257 neutrino and 58 antineutrino opposite sign dimuon events produced in a narrow band beam, for which the charges and momenta of the muons as well as the energy of

378

CDHS results

2) dimuons with like sign , PL 70B (1977) 396:
47 events , mostly background from pion decays of the hadron shower; excess is (3+-2)x 10-4 of CC, may well be due to hadronic production of c-cbar pair;
no evidence for cascading heavy leptons

CDHS: no High y Anomaly
PRL 39 (1977) 433: perfect agreement with scaling in y distribution

VOLUME 39, NUMBER 8 PHYSICAL REVIEW LETTERS 22 AUGUST 1977

Is There a High-*y* Anomaly in Antineutrino Interactions?

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and

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and

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and

P. Bloch, B. Devaux, M. Grimm, J. Maillard, B. Peyaud,
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(Received 12 July 1977)

Accepted without review at the request of E. Picasso under policy announced 26 April 1976

We have analyzed data taken in the CERN narrow-band neutrino and antineutrino beams with regard to the "high-*y* anomaly" observed by previous experiments at Fermilab. At neutrino energies between 30 and 200 GeV, the $\bar{\nu}$ and ν charged-current cross-section ratios and muon-inelasticity distributions disagree with the earlier results. In particular, there is no evidence for energy-dependent effects in the antineutrino data which constitute an important aspect of the alleged anomaly.

In recent years, low- and high-energy inelastic interactions of neutrinos with nuclei were believed to be consistent with $V-A$ coupling and Bjorken scale invariance in the framework of the spin-$\frac{1}{2}$ parton model[1-4]. In 1974 evidence was reported for a significant departure from expectation of the antineutrino-muon inelasticity distributions at higher enery[5] which was subsequently dubbed the "high-*y* anomaly" after the Bjorken scaling variable $y=(E_\nu-E_\mu)/E_\nu$. Subsequent experimental results supported an anomalous behavior of $\bar{\nu}$ total and differential cross sections.[6-9] This was considered as evidence for a deviation from charge symmetry, together with new particle production,[5] the existence of right-handed currents, and a breaking of scale invariance.[6] The experimental observations were the following[10]: An excess of events in the high-*y* region of the antineutrino *y* distribution was observed for $x < 0.1$ [5]; a strong energy dependence of the average value of *y* was found in the region $E_{\bar{\nu}}=30-70$ GeV[6]; the ratio of antineutrino to neutrino charged-current cross sections was found to increase with energy above about 30 GeV[7]; the antiquark component in the antineutrino *y* distribution was observed to increase with energy.[6,8,9]

We report here first results from an experiment which is currently running at the CERN 400-GeV proton synchrotron. The present analysis is addressed to the specific question of a high-*y* anomaly in antineutrino interactions, and follows, therefore, in part the guidelines set out by the advocates of this anomaly. The experimental conditions, on the other hand, are quite different.

In this experiment, neutrinos and antineutrinos of known energy between 10 and 200 GeV are produced by selecting 200-GeV parents, pions and kaons of the appropriate charge, in 400-GeV proton-beryllium interactions. The parent beam with 0.2-mrad divergence and ± 5% momentum spread is directed towards the detector, passing through a 300-m decay tunnel, and about 350-m

CDHS: scaling, no high y anomaly

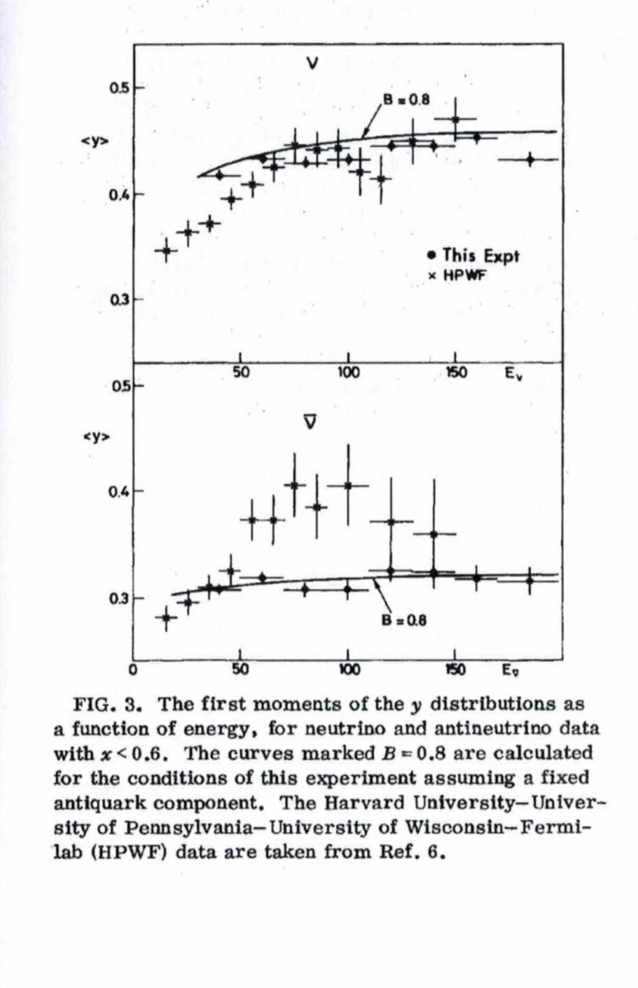


FIG. 3. The first moments of the y distributions as a function of energy, for neutrino and antineutrino data with $x < 0.6$. The curves marked $B = 0.8$ are calculated for the conditions of this experiment assuming a fixed antiquark component. The Harvard University–University of Pennsylvania–University of Wisconsin–Fermilab (HPWF) data are taken from Ref. 6.

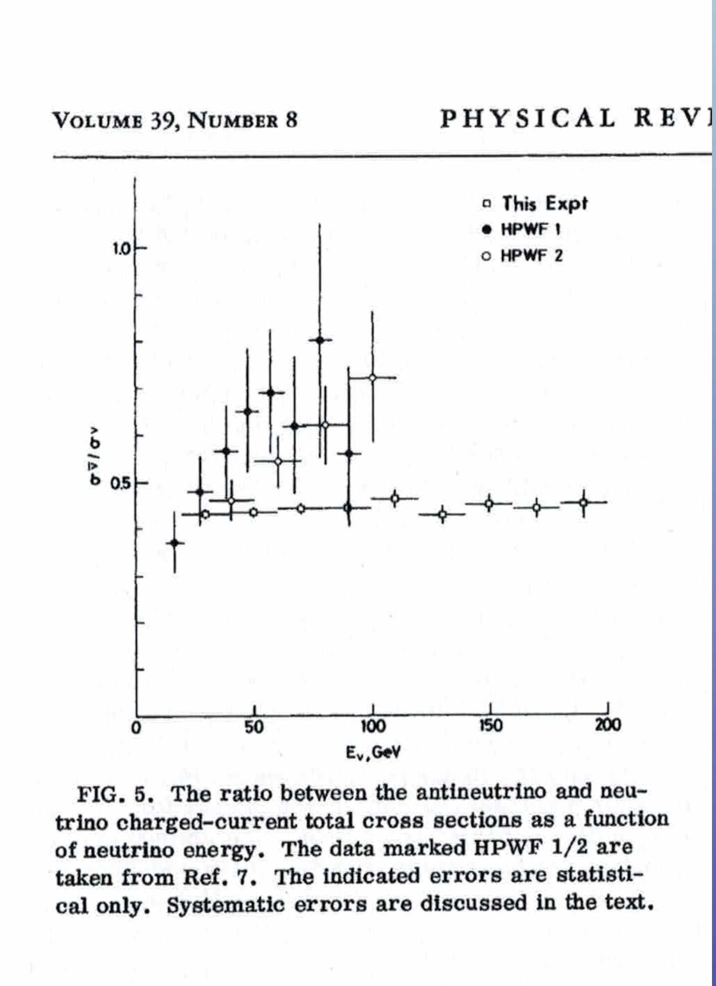

VOLUME 39, NUMBER 8 PHYSICAL REV

FIG. 5. The ratio between the antineutrino and neutrino charged-current total cross sections as a function of neutrino energy. The data marked HPWF 1/2 are taken from Ref. 7. The indicated errors are statistical only. Systematic errors are discussed in the text.

Structure functions (isoscalar target nuclei)

$$\frac{d\sigma^{\nu,\bar{\nu}}}{dx\,dy} = \frac{GME_\nu}{\pi}\left[(1-y)F_2(Q^2,\nu) + xy^2F_1(Q^2,\nu) \pm \left(y-\frac{y^2}{2}\right)xF_3(Q^2,\nu)\right]$$

Callan - Gross $2xF_1 = F_2$

Scaling Bjorken $F_i(Q^2,\nu)$ depends only on $\frac{Q^2}{\nu} = x$

Quark Parton Model $F_2^\nu(x) = F_2^{\bar{\nu}}(x) = q(x) + \bar{q}(x)$

$$xF_3(x) = q(x) - \bar{q}(x)$$

$$\frac{d\sigma^\nu}{dx\,dy} + \frac{d\sigma^{\bar{\nu}}}{dx\,dy} = \frac{GME_\nu}{\pi}\left[1+(1-y)^2\right]\left(q(x)+\bar{q}(x)\right)$$

$$\frac{d\sigma^\nu}{dx\,dy} - \frac{d\sigma^{\bar{\nu}}}{dx\,dy} = \frac{GME_\nu}{\pi}\left[1-(1-y)^2\right]\left(q(x)-\bar{q}(x)\right)$$

Total cross sections proportional to neutrino energy: scaling
ratio nu/nubar=0.48+-0.02 for Enu 30 to 190 GeV

150

J. G. H. de Groot et al.: Inclusive Interactions of High-Energy Neutrinos

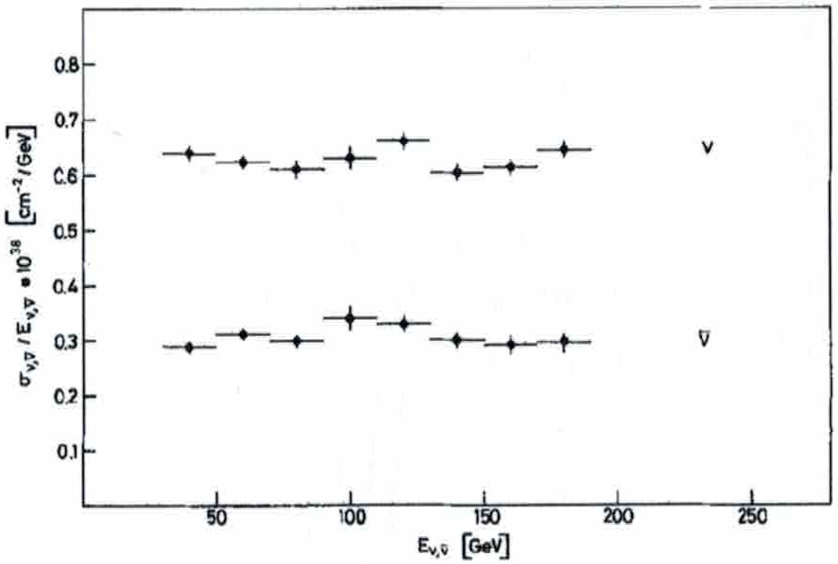


Fig. 8. Neutrino and antineutrino total cross-sections as a function of the neutrino energy

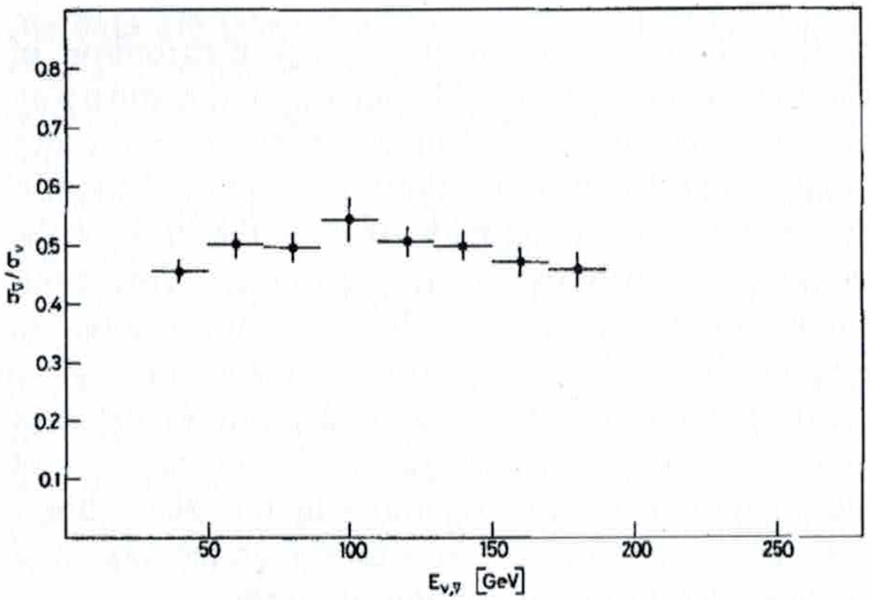


Fig. 9. Ratio of antineutrino to neutrino total cross-sections as a function of the neutrino energy

Total cross sections - all experiments

151

nos

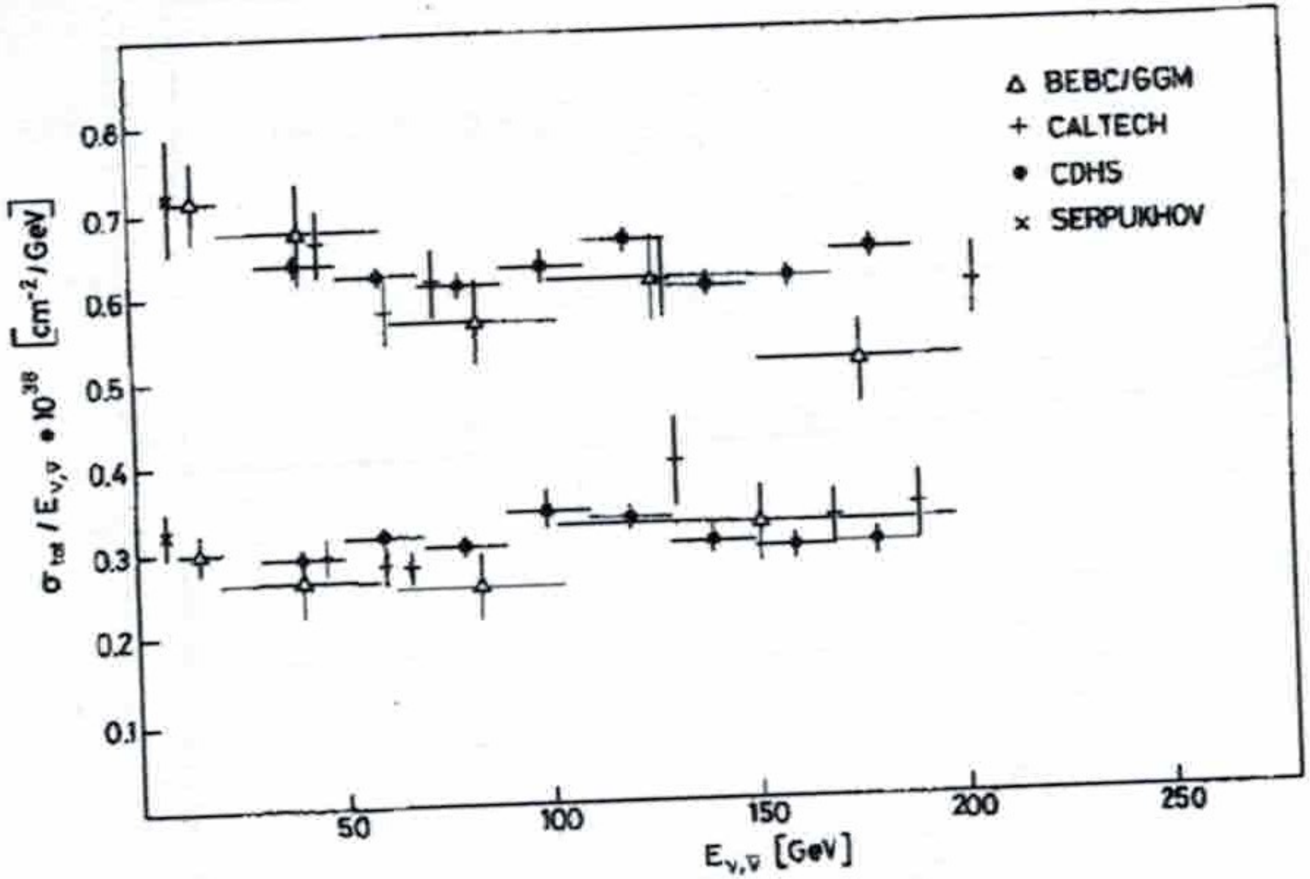
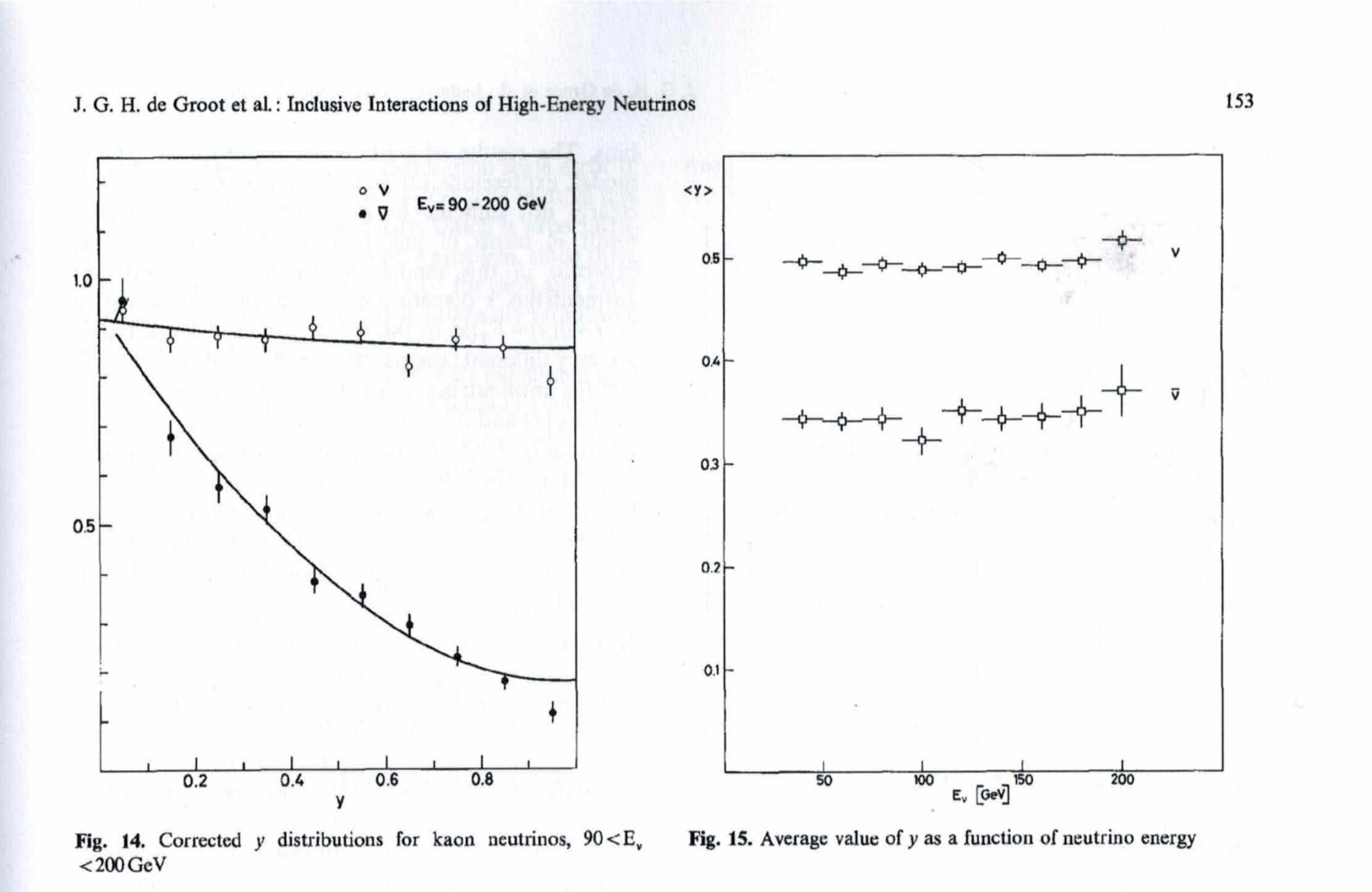


Fig. 10. Comparison of the results of this experiment for the total cross-section with previous results

Y distribution for nu and nubar ; average y: perfect scaling



J. G. H. de Groot et al.: Inclusive Interactions of High-Energy Neutrinos 153

Fig. 14. Corrected y distributions for kaon neutrinos, $90 < E_\nu < 200$ GeV

Fig. 15. Average value of y as a function of neutrino energy

Scaling violations in x- or Q^2 distributions observed in agreement with QCD predictions

Preference for vector gluons from moments of valence structure function F3

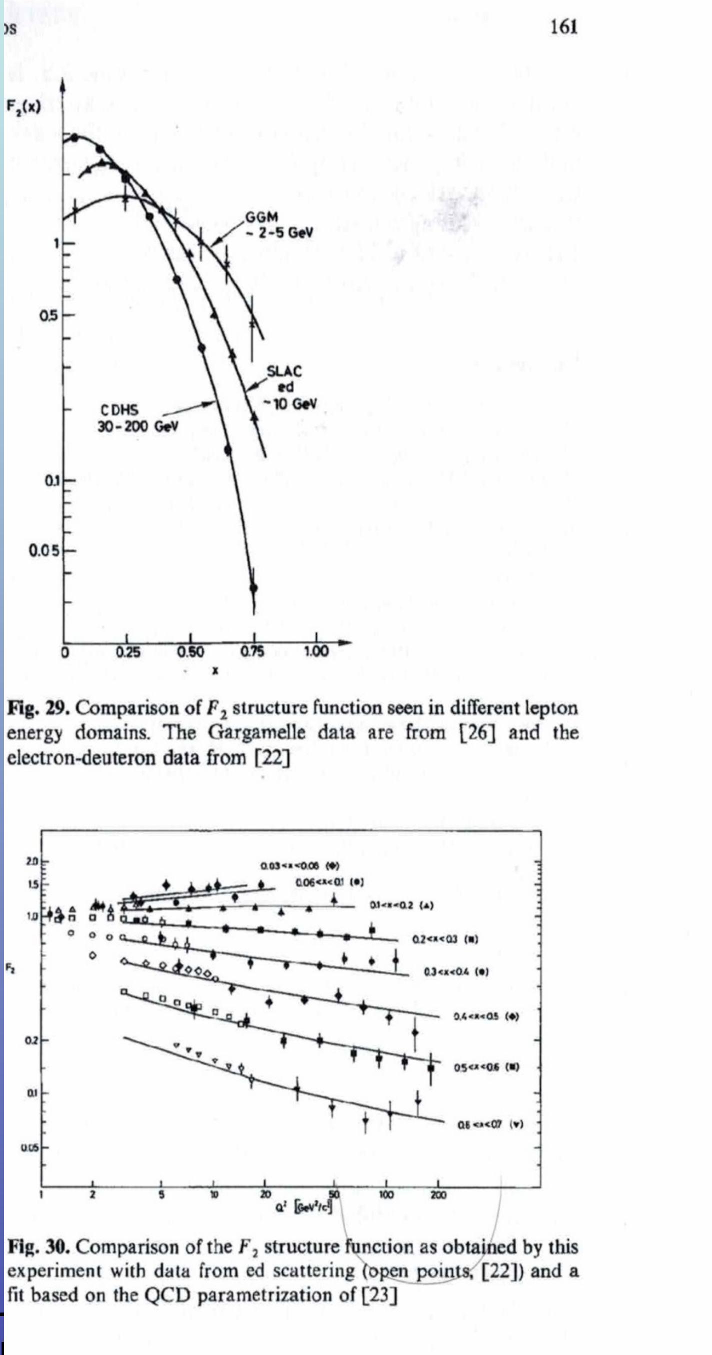


Fig. 29. Comparison of F_2 structure function seen in different lepton energy domains. The Gargamelle data are from [26] and the electron-deuteron data from [22]

Fig. 30. Comparison of the F_2 structure function as obtained by this experiment with data from ed scattering (open points, [22]) and a fit based on the QCD parametrization of [23]

QCD analysis
(with DGLAP equations)

of contributions from gluon bremsstrahlung and quark pair production to the structure function F2 and quark sea structure function qbar (nubar);

alternative field theories are excluded by data
(Abelian vector gluons, Abelian scalar gluons, Non-Abelian scalar gluons)

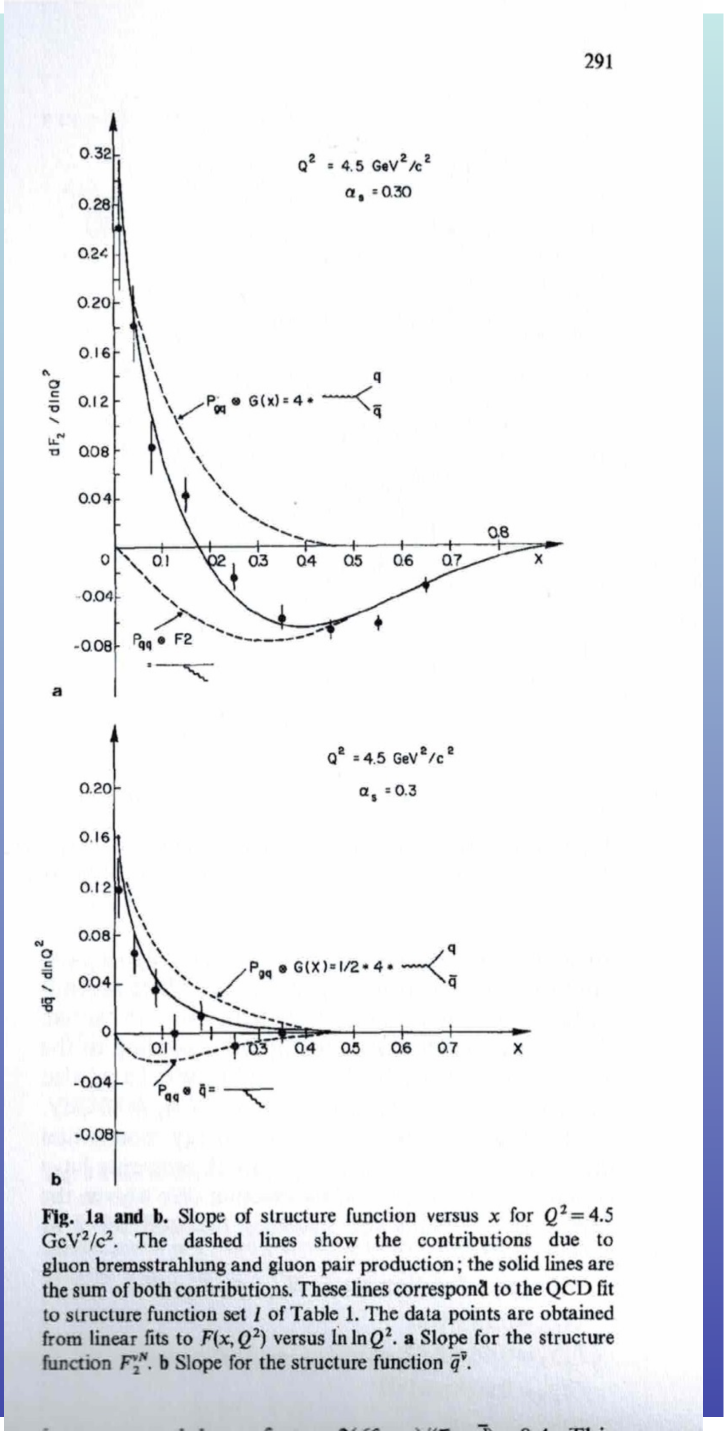


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Fig. 1a and b. Slope of structure function versus x for $Q^2 = 4.5$ GeV^2/c^2. The dashed lines show the contributions due to gluon bremsstrahlung and gluon pair production; the solid lines are the sum of both contributions. These lines correspond to the QCD fit to structure function set I of Table 1. The data points are obtained from linear fits to $F(x, Q^2)$ versus $\ln \ln Q^2$. **a** Slope for the structure function $F_2^{\nu N}$. b Slope for the structure function $\bar{q}^{\bar{\nu}}$.

Structure functions F2 and xF3

Experiments:

CCFR Z.Phys.C26 (1984)1

CHARM PL 123B (1983) 269

CDHSW Z.Phys. C49 (1991)187

EMC Aubert et al., Nucl.Phys. B272(1986) 158

BCDMS Benvenuti et al., Phys. Lett. 195B (1987) 91

Status 1991

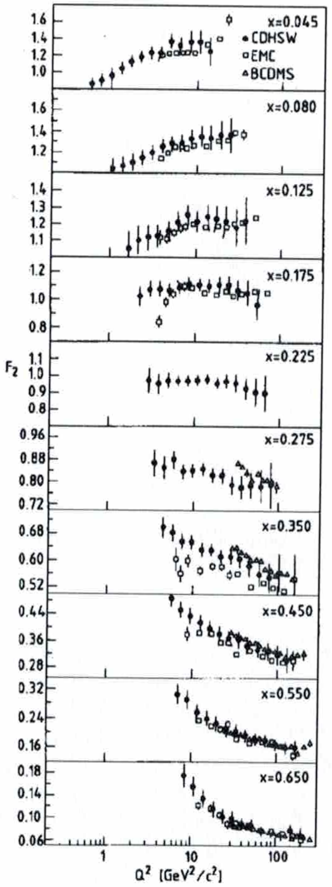

Fig. 42. Comparison of the structure function $F_2(x, Q^2)$ with t results of muon experiments multiplied by 18/5

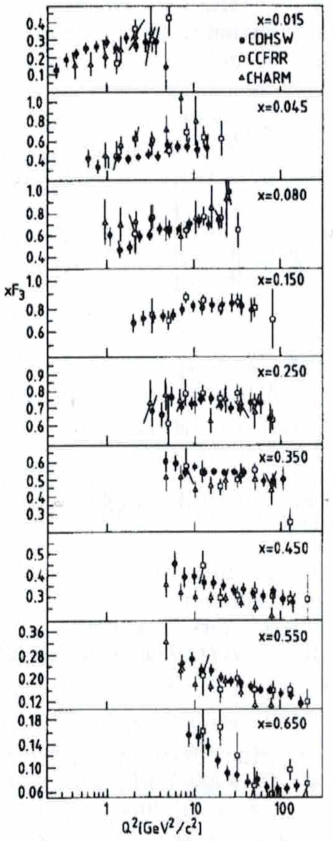

Fig. 41. Comparison of the structure function $xF_3(x, Q^2)$ with the results of other neutrino experiments

Neutral current measurements: ratios NC/CC Rnu and Rnubar and sin^2 th$_W$

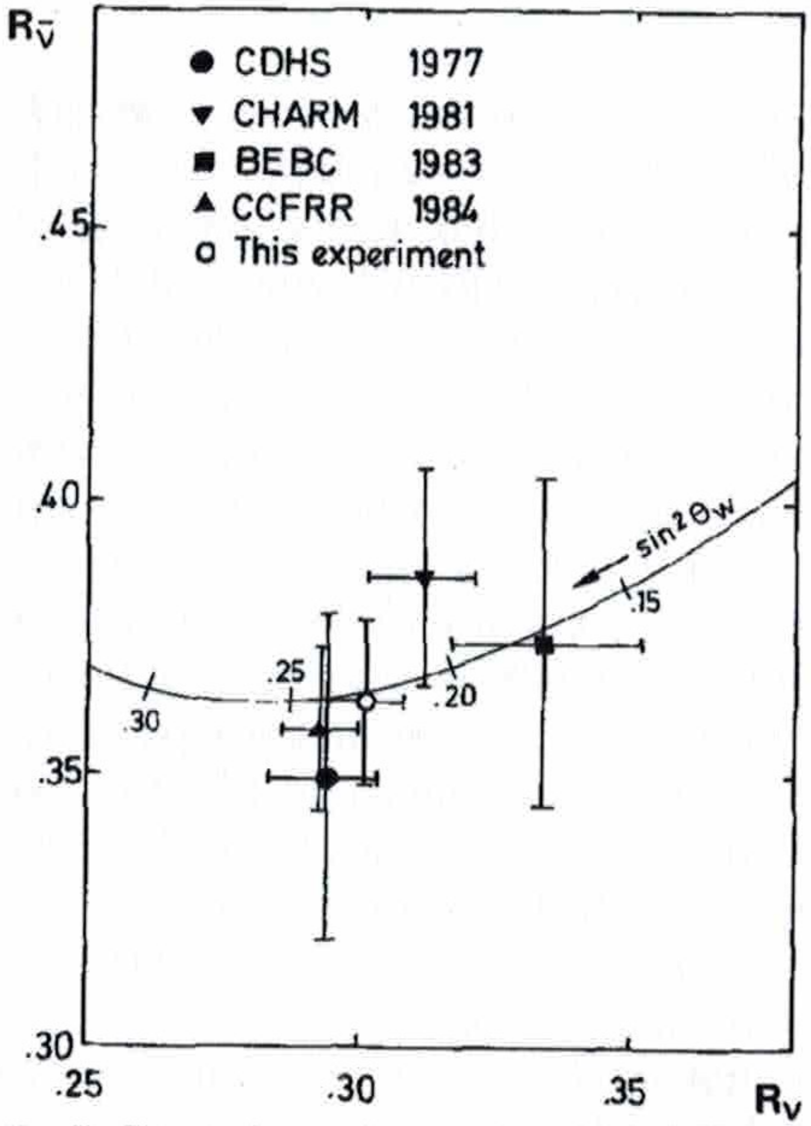

Fig. 3. Comparison of measurements of R_ν and $R_{\bar{\nu}}$ with the prediction of a model calculation described in the text. The curve is valid for the conditions of this experiment, other data are scaled to these conditions

Neutral currents 1990
Measure ratio NC/CC for neutrinos and antineutrinos

1) **HPW 1977, P. Wanderer et al.,** $\sin^2 th_W$ =0.23+-0.06
2) **CFR coll. 1977, F.S. Merritt et al.,** $\sin^2 th_W$ = 0.33+-0.07
3) **CDHS 1977, M. Holder et al.:**$\sin^2 th_W$ **=0.24+-0.02**
4) **CHARM 1981, M. Jonker et al., Phys. Lett. 99B,265 (1981)**
5) **BEBC 1983, P.C.Bosetti et al., Nucl. Phys. B217,1(1983)**
6) **CCFR 1985, P.G. Reutens et al. Phys.Lett. 152B,404**
7) **CDHS 1985, Abramowicz et al.,** $\sin^2 th_W$ **=0.226+-0.012**
8) **CHARM 1987, J.V. Allaby et al., Z.Phys.C 36 (1987) 611,**$\sin^2 th_W$=0.236+-0.006
9) **CDHS 1990, A. Blondel et al.,** $\sin^2 th_W$ **=0.228+-0.007**

Average of two most precise measurements: $\sin^2 th_W$=0.232+-0.006
From $\sin^2 th_W$ **predict mass of W boson 81+-2.5 GeV**
and of Z boson 92.2+-2.2 GeV
Simplest GUT theory SU(5) excluded by $\sin^2 th_W$

Conclusions from 20 years of experiments

1) Scaling in y valid

2) Scaling violations in x in agreement with QCD, but not with Abelian field theories or scalar gluons

3) Dimuon events due to charm production and decay

4) Neutral currents with Weinberg parameter

$\sin^2 th_W = 0.232 \pm 0.006$

points to W and Z masses in agreement with LEP discoveries

John Updikes poem

Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass, Like
dustmaids down a drafty hall Or photons
through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.
— John Updike