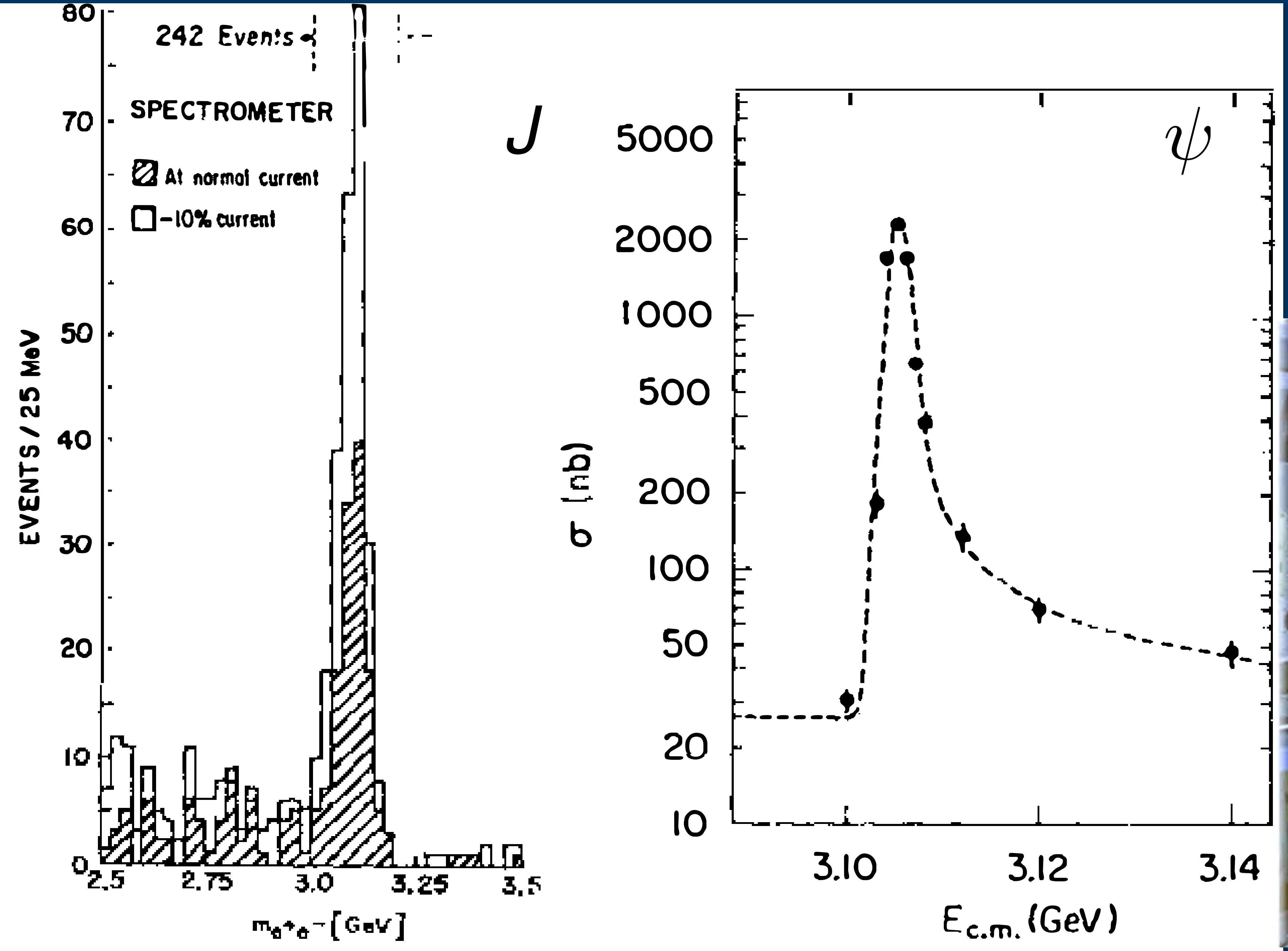
The Night Before Charmonium

Chris Quigg
Fermilab

52nd SLAC Summer Institute · November Revolution · 9 August 2024

11 November 1974



$p + \mathrm{Be} \rightarrow e^+e^- + X$ $e^+e^- \rightarrow$ hadrons

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

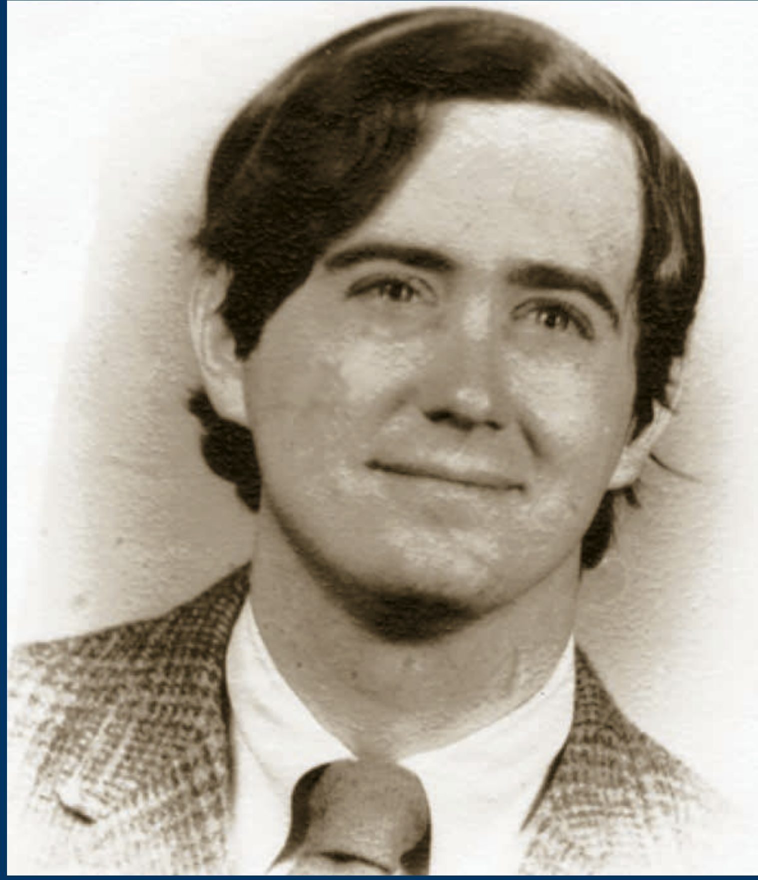
Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.



Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

J: Absence of continuum puzzling

ψ: Soon known, treating ISR and resolution à la Jackson & Scharre:

$$\Gamma_e = (4.80 \pm 0.06)\ \mathrm{keV} \rightsquigarrow (5.52 \pm 0.14)\ \mathrm{keV}$$

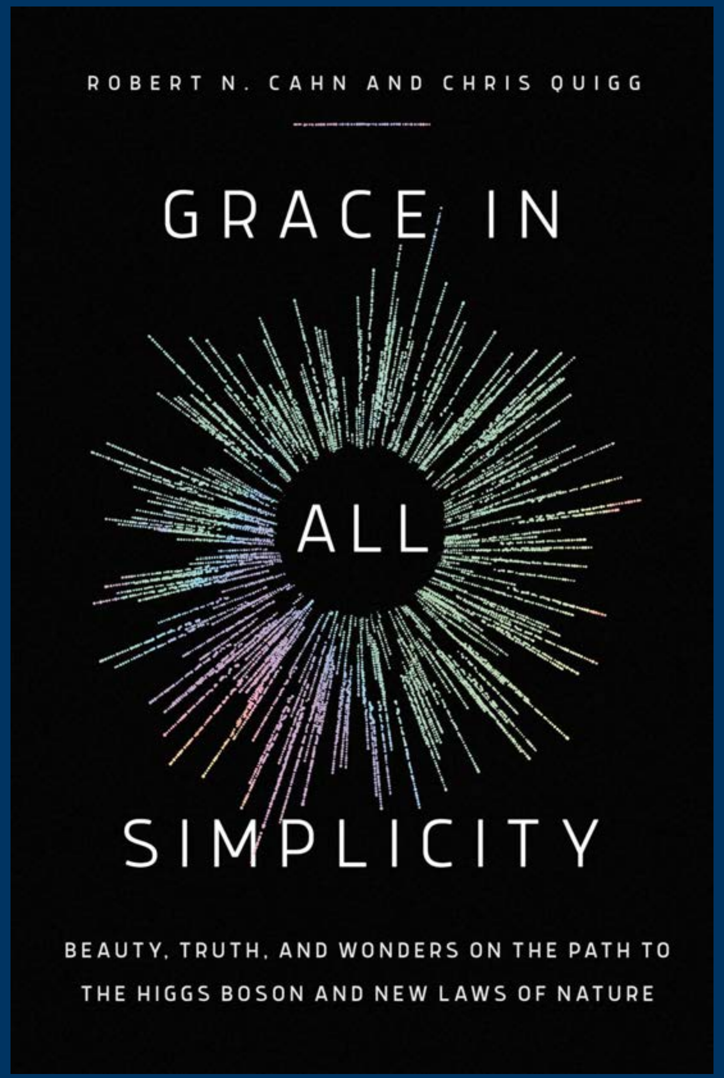
$$\Gamma = (69 \pm 15)\ \mathrm{keV} \rightsquigarrow (92.6 \pm 1.5)\ \mathrm{keV}$$

$$M = (3095 \pm 4)\ \mathrm{MeV} \rightsquigarrow (3096.900 \pm 0.006)\ \mathrm{MeV}$$

How could these results be wrong?
Most things that seem too good to be true
are too good to be true.

This was too good to be false!

Every experimenter's question: How can I get my hands on it?



Chapter 6: Revolution!

"Celebrating Quarkonium: The First Forty Years"

Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in e^+e^- Annihilation*

C. Bacci, R. Balbini Celio, M. Berna-Rodini, G. Caton, R. Del Fabbro, M. Grilli, E. Iarocci, M. Locci, C. Mencuccini, G. P. Murtas, G. Penso, G. S. M. Spinetti, M. Spano, B. Stella, and V. Valente
The Gamma-Gamma Group, Laboratori Nazionali di Frascati, Frascati, Italy

and

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzzi, G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy

and

G. Barbarino, G. Barbiellini, C. Bemporad, R. Biancastelli, F. Cevenini, M. Celvetti, F. Costantini, P. Lariccia, P. Parascandalo, E. Sassi, C. Spencer, L. Tortora, U. Troya, and S. Vitale
The Baryon-Antibaryon Group, Laboratori Nazionali di Frascati, Frascati, Italy

(Received 18 November 1974)

We report on the results at ADONE to study the properties of the newly found 3.1-BeV particle.

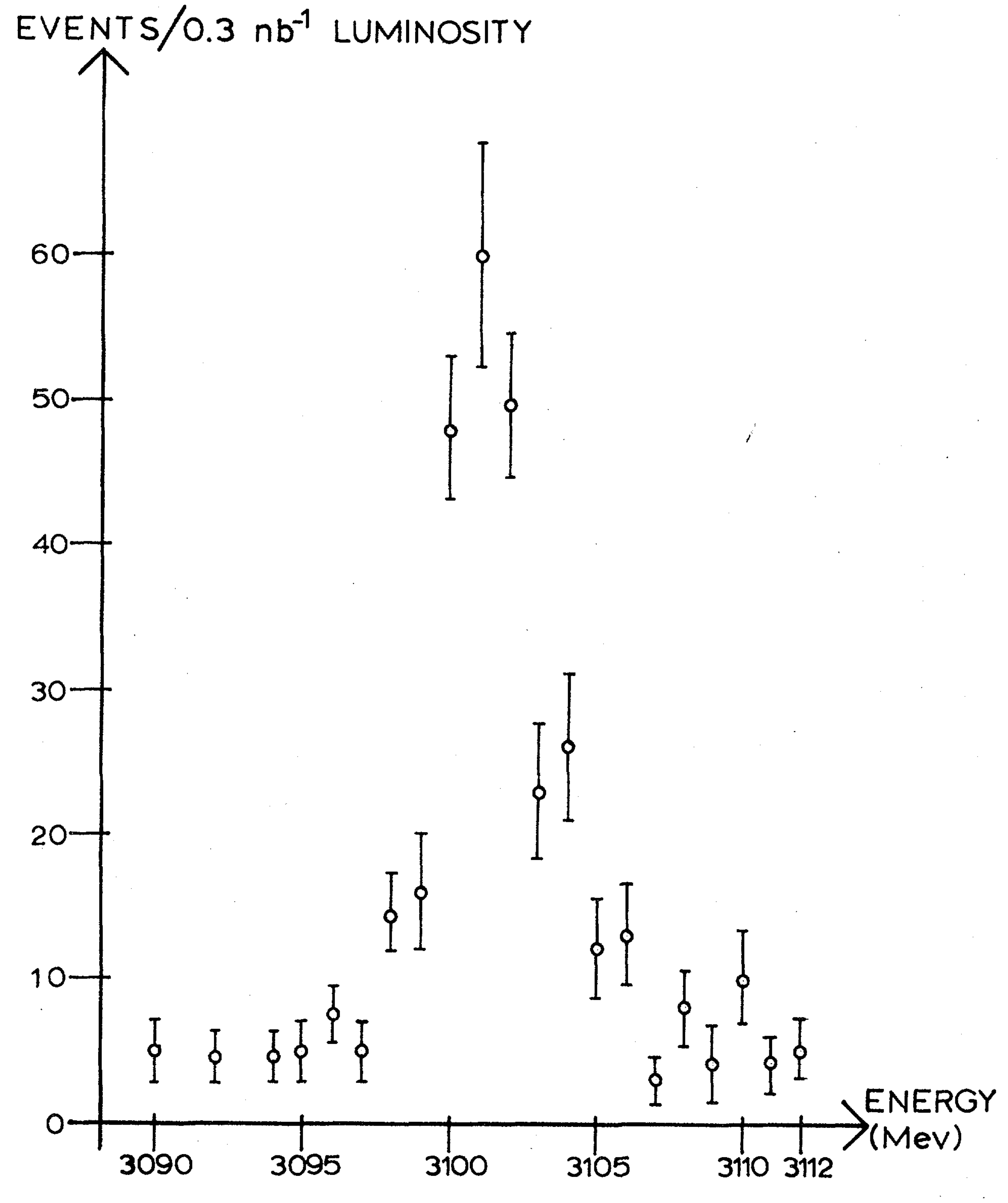


FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

Volume 53B, number 4 PHYSICS LETTERS 23 December 1974

A MEASUREMENT OF LARGE ANGLE e^+e^- SCATTERING AT THE 3100 MeV RESONANCE

DASP – Collaboration

W. BRAUNSCHWEIG, C.L. JORDAN, U. MARTYN, H.G. SANDER D. SCHMITZ, W. STURM, W. WALLRAFF
I. Physikalisches Institut der RWTH Aachen

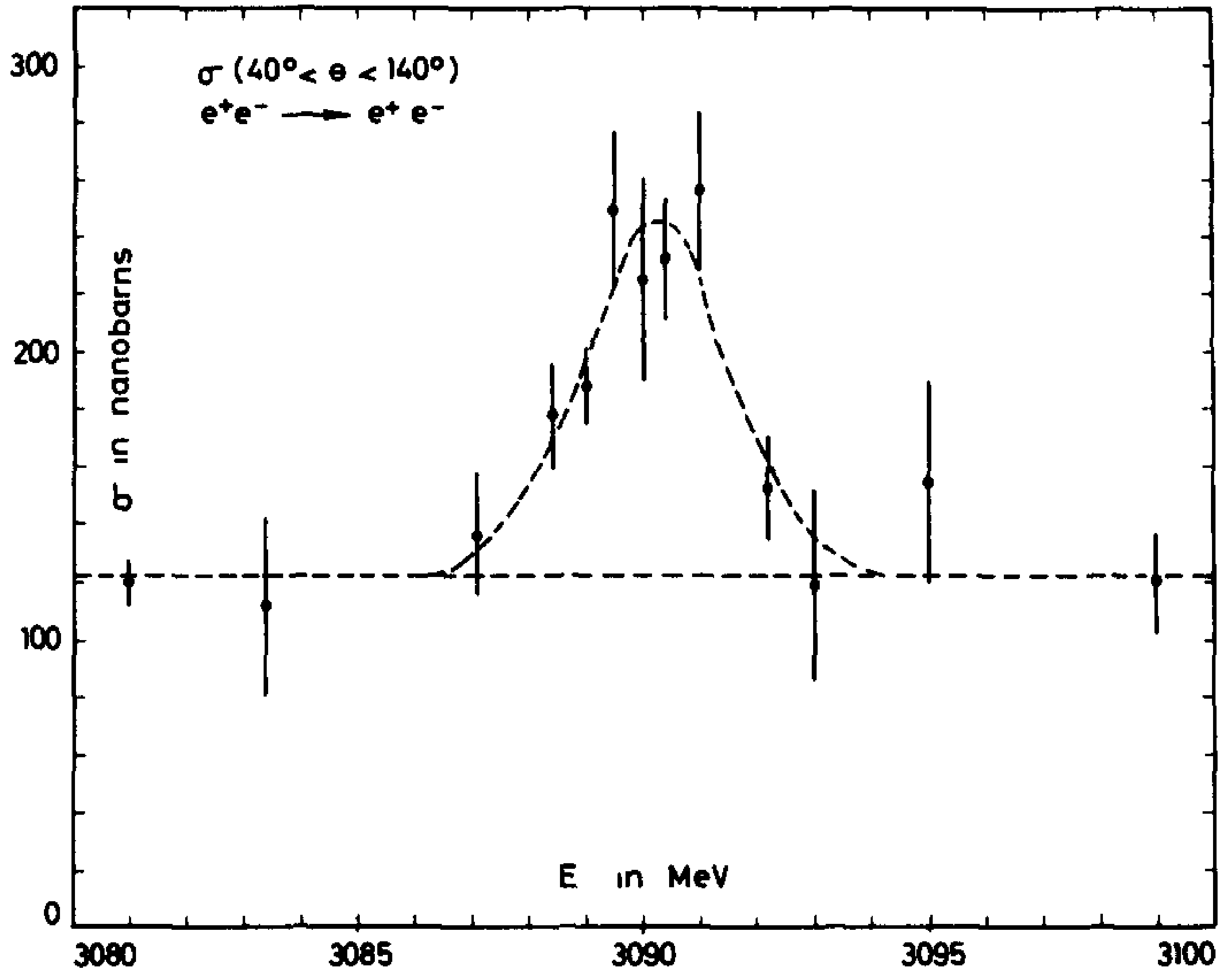
K. BERKELMAN*, D. CORDS, R. FELST, E. GADERMANN, G. GRINDHAMMER, H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KREHBIEL, D. KREINICK, J. LUDWIG, K.-H. MESS, K.C. MOFFEITT, D. NOTZ**, G. POELZ, K. SAUERBERG, P. SCHMÜSER, G. VOGEL, B.H. WIIK, G. WOLF
Deutsches Elektronen-Synchrotron DESY and II. Institut für Experimentalphysik der Universität Hamburg, Hamburg

G. BUSCHHORN, R. KOTTHAUS, U.E. KRUSE**, H. LIERL, H. OBERLACK, S. ORITO, K. PRETZL, M. SCHLIWA
Max-Planck-Institut für Physik und Astrophysik, München

T. SUDA, Y. TOTSUKA and S. YAMADA
University of Tokyo, Tokyo

Received 19 December 1974

Elastic e^+e^- scattering has been measured at total energies covering the newly found resonance at 3100 MeV. The angular distribution is consistent with spin-parity 1^-, and the cross section integrated over energy yields $\Gamma_{ee}^2/\Gamma_{tot}$ = 0.23 ± 0.05 keV for the resonance.



94   21 NOV 1974   21 ... 1974

00:30 Hours ALL SEEMS STABLE (PRAY FOR US)

MUON CHAMBERS SHOW LOW AND DECREASING EFFICIENCY

Getting 2 sparks 2 close on 13, 14, missing 1st & 2nd fids on 16. The muon chambers are not essential for the scan but are more important for peaking and dipping. Some one ought to look into this Thurs. day.

The wand signals look OK for muon chambers. All (11,12,13,14,16) have small 2nd fids. Zero X'ers are seeing the 1st fids. Trouble is, to kill all 5 chambers 2 ANNAS must go out. Assuming 11,12,13,14,16 WANDS ARE when they need to be (111,112,113,114,116) at least 11 & 12 show no serious error problems.

02:10 μ Ch. ε looks to be below 20% now. It is as if the μ chambers are never giving any sparks now and ε is steadily declining as more and more "predictions" come in.

SOMEBODY PLEASE LOOK INTO THIS ON DAY SHIFT.

02:30 WE SEE A POSSIBLY SIGNIFICANT BUMP AT 1.847-1.848 (nominal), LOOKS ~ 6 MeV fwhm (steps are 2 MeV cm). STOP RUN GO 1.845 & rescan. (cm)

WE WILL GO BACK OVER IT IN 1/4 Step Size

```
SP-17 BNL RUN 1522   1.85 GEV 3.9 KG CF-XXXXXXXX TL-2   A(2
SCALERS
  1  DS  TRUE      45378         10                        0   2
  2  DS  FLSE         29         11                        0
  3  LU  NU.SD     19229         12  EVENTS              968
  4  LU  ND.SU     26149         13  PIPE/100          58323
  5  LIVETIME      42903         14                        0
  6                    0         15  THYRTRON            968
  7                    0         16  CLCKTIME          46554
  8                    0         17                        0
  9                    0         18                        0
INTEGRATED LUMINOSITY =      .101E 34
                  PITSORT

          I        P           PI        MICROPITS
E+       2.1    .143E-08    .305E-08     15.
E-       2.3    .139E-08    .319E-08     16.

LIVETIME =  4193.40 SEC. LIVETIME FRACTION =    .921
INTEGRATED LUM =     .99CE 33 T/F  =  1537.03
EXPECTED MU PAIR PRODUCTION IS        5
E = 2.000 GEV              RUN  1522
EXPECTED MU PAIR PRODUCTION IS        23
E = 2.000 GEV              RUN  1521
```

95   21 NOV 1974   ψ'

03:00 Start (Historic?) Run 1522

Pipe Occ ~ 0.1 %   47/222 → 0.2 Evn/sec.

03:20 SON OF GLORY

Chuck Morehouse, Allen Litke, Bob Stege Do it!

NOTE: THE RESCAN (RUN 1522) WAS STARTED AT "1.845" OBTAINED BY RUNNING DOWN FROM 1.863, SO ENERGIES & DAC's DON'T CORRESPOND TOO WELL AT RUN 1522.

04:15 STOP. Dump & Refil

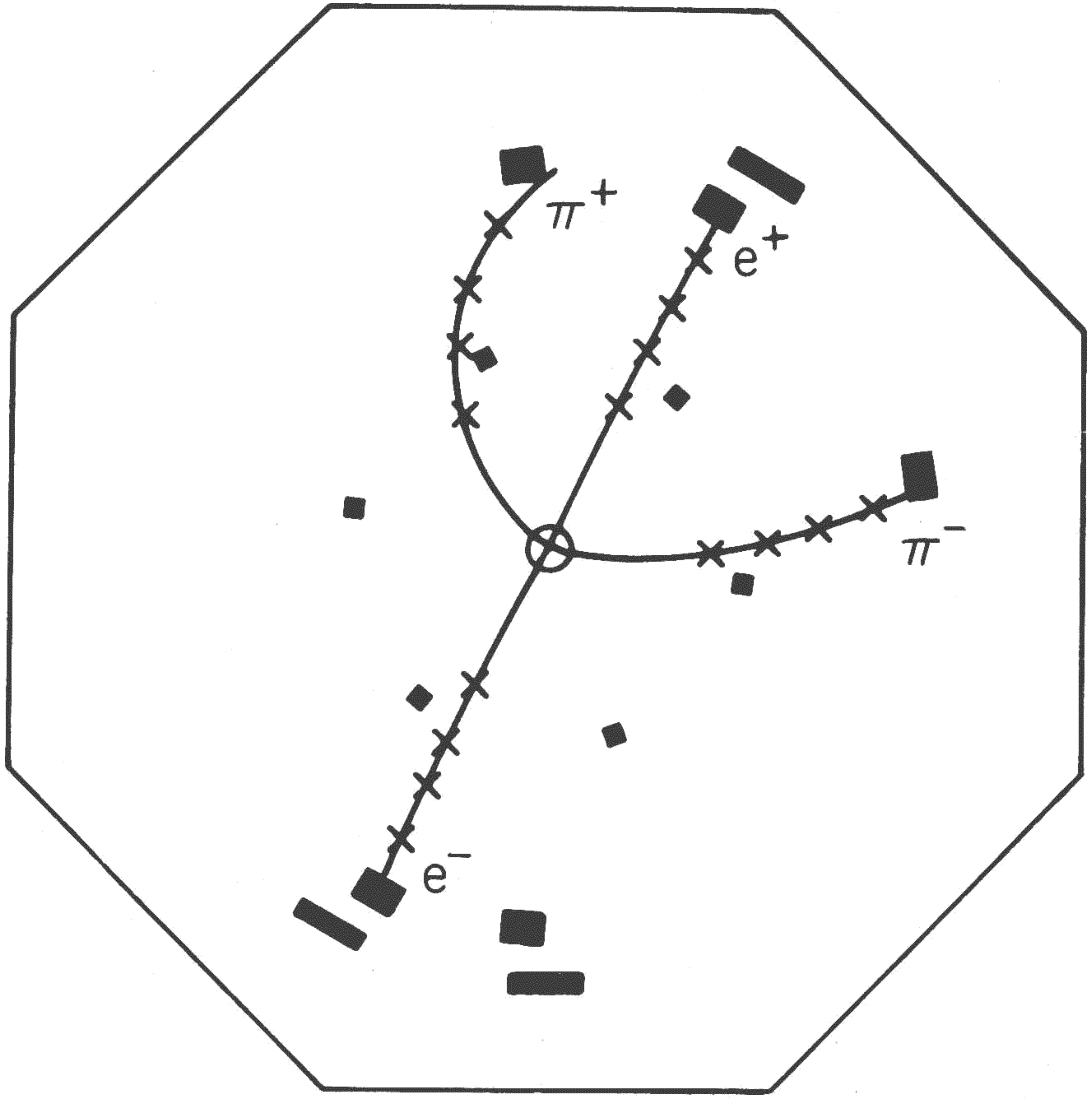
MIB Predicts one at 1.897!

MCC HAS COMPUTER TROUBLES SO NO FILL. TRY A SCAN STARTING AT 1.890.

04:30 DAMN - LINAC BACK UP. Dump & Refil.

Alan Litke's first shift!

$e^+e^- \to \psi' \to \pi^+\pi^- J/\psi$



New and Surprising Type Of Atomic Particle Found

By WALTER SULLIVAN

Experiments conducted independently on the East and West Coasts have disclosed a new type of atomic particle.

Its properties are so unexpected that there are differing views as to how it might fit into current theories on the elementary nature of matter.

The experiments were done at the Stanford Linear Accelerator in Palo Alto, Calif., by a team under Dr. Burton Richter and at the Brookhaven National Laboratory in Upton, L.I., by a group under Dr. Samuel C. C. Ting of the Massachusetts Institute of Technology.

In a statement yesterday, the two men said:

"The suddenness of the discovery coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kinds of structure.

"The theorists are working frantically to fit it into the framework of our present knowledge of the elementary particle. We experimenters hope to keep them busy for some time to come."

Some scientists believe that the new particle will prove to be the long-sought manifestation of the so-called weak force—one of the four basic forces in nature. The others are gravity, electromagnetism and the strong force that binds together the atomic nucleus.

It is also suspected that the particle may be related to a recently developed theory equating two of those forces — electromagnetism and the weak force— as manifestations of the same phenomenon. However, the properties of the newly discovered particle are not those predicted for either

Continued on Page 29, Column 1

The New York Times
Published: November 17, 1974

PRL, Jan 6, 1975

Is Bound Charm Found?*

A. De Rújula
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

S. L. Glashow†
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 27 November 1974)

We argue that the newly discovered narrow resonance at 3.1 GeV is a $^3S_1$ bound state of charmed quarks and we show the consistency of this interpretation with known meson systematics. The crucial test of this notion is the existence of charmed hadrons near 2 GeV.

Remarks on the New Resonances at 3.1 and 3.7 GeV*

C. G. Callan, R. L. Kingsley, S. B. Treiman, F. Wilczek, and A. Zee†
Jadwin Physical Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 9 December 1974)

This is a collection of comments which may be useful in the search for an understanding of the recently discovered narrow resonances at 3.1 and 3.7 GeV.

Possible Explanation of the New Resonance in e^+e^- Annihilation*

S. Borchardt, V. S. Mathur, and S. Okubo
University of Rochester, Rochester, New York 14623
(Received 18 November 1974)

We propose that the recently discovered resonance in e^+e^- annihilation is a member of the $15 \oplus 1$ dimensional representation of the SU(4) group. This hypothesis is consistent with the various experimental features reported for the resonance. In addition, we make a prediction for the masses of the charmed vector mesons belonging to the same representation.

Model with Three Charmed Quarks*

R. Michael Barnett
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 25 November 1974)

The spectroscopy and weak couplings of a quark model with three charmed quarks are discussed in the context of recent results from Brookhaven National Laboratory, Stanford Linear Accelerator Center, and Fermi National Accelerator Laboratory.

J. L. Rosner, "The Arrival of Charm"

Are the New Particles Baryon-Antibaryon Nuclei?

Alfred S. Goldhaber
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794*

and

Maurice Goldhaber
Physics Department, Brookhaven National Laboratory,† Upton, New York 11973
(Received 25 November 1974)

Baryon-antibaryon bound states and resonances could account for the new particles, as well as narrow states near nucleon-antinucleon threshold, which were reported earlier.

Note added.—The public announcement by the Stanford Linear Accelerator group of a second very sharp resonance at 3.7 GeV lends additional support to this interpretation, and diminishes the appeal of any alternative interpretation that does not provide a natural setting for more than one such particle.

Intermediate Boson in the Fermion-Current Model of Neutral Currents*

J. J. Sakurai
Department of Physics, University of California, Los Angeles, California 90024
(Received 25 November 1974)

The intermediate-boson version of the earlier proposed fermion-current model of neutral currents is discussed. In particular I speculate on the possibility that the recently discovered 3.105-GeV particle may be identified with the intermediate boson of the fermion-current model.

Interpretation of a Narrow Resonance in e^+e^- Annihilation*

Julian Schwinger
University of California at Los Angeles, Los Angeles, California 90024
(Received 25 November 1974)

A previously published unified theory of electromagnetic and weak interactions proposed a mixing between two types of unit-spin mesons, one of which would have precisely the characteristics of the newly discovered neutral resonance at 3.1 GeV. With this interpretation, a substantial fraction of the small hadronic decay rate can be accounted for. It is also remarked that other long-lived particles should exist in order to complete the analogy with ρ^0, ω, and φ.

Possible Interactions of the *J* Particle*

H. T. Nieh
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794

and

Tai Tsun Wu
Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts 02138

and

Chen Ning Yang
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794
(Received 25 November 1974)

We discuss some possible interaction schemes for the newly discovered particle *J* and their experimental implications, as well as the possible existence of two J^0's like the K_S-K_L case. Of particular interest is the case where the *J* particle has strong interactions with the hadrons. In this case *J* can be produced by associated production in hadron-hadron collisions and also singly in relative abundance in *ep* and μp collisions.

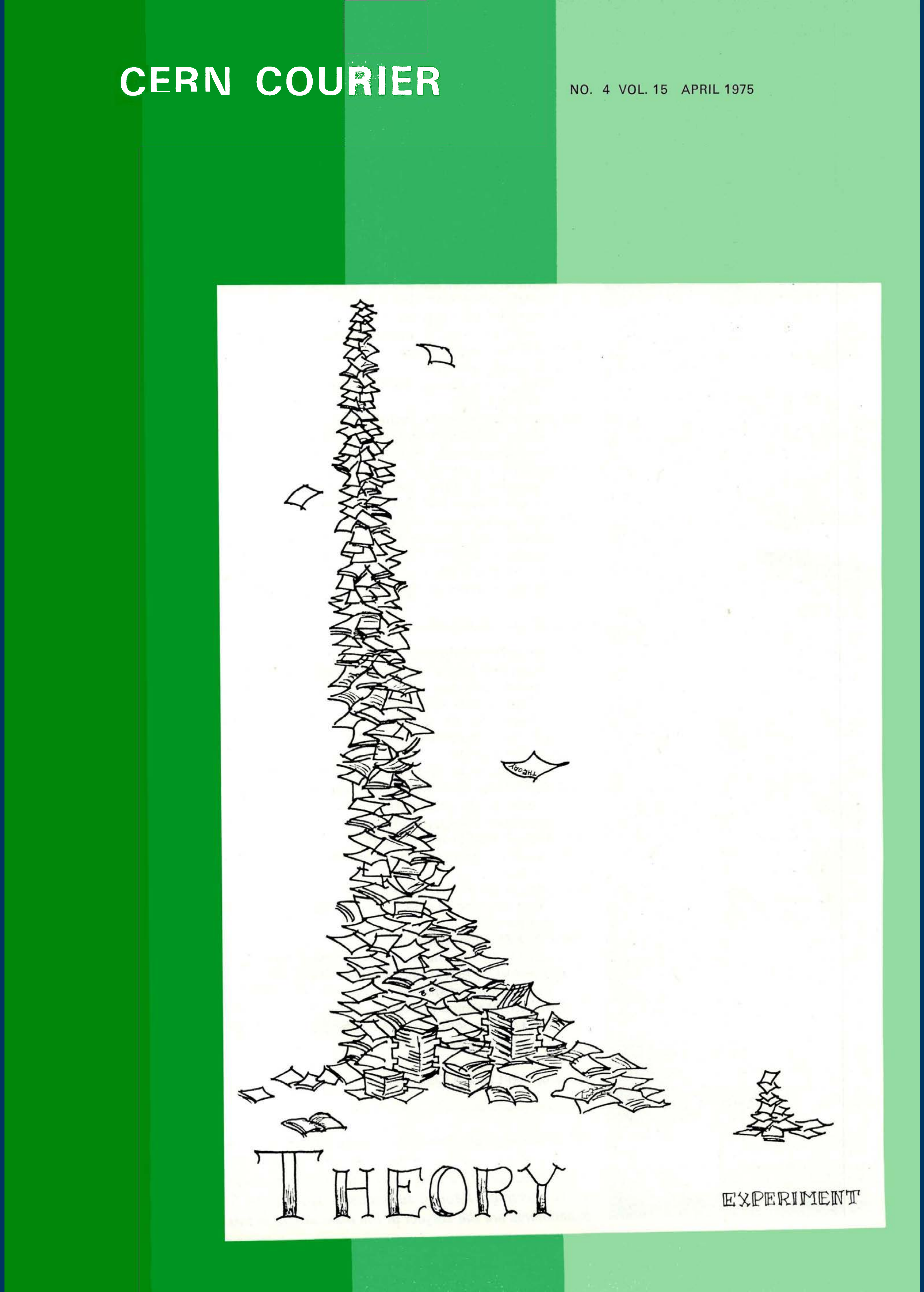
Is the 3104 MeV Vector Meson the φ_c or the W_0?

G. Altarelli, N. Cabibbo and R. Petronzio
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

L. Maiani
Laboratori di Fisica, Istituto Superiore di Sanità - Roma
Istituto Nazionale di Fisica Nucleare - Sezione Sanità di Roma

G. Parisi
Istituto Nazionale di Fisica Nucleare - Laboratorio di Frascati

We are grateful to the members of the experimental and machine groups of the Frascati National Laboratories for many exciting discussions. We are also grateful to the Administration of the Telephone Service in Italy and abroad for efficiently conveying the many exciting rumours about Brookhaven and SPEAR results.



J. D. Jackson drawing

The discovery of charmonium
catalyzed a phase transition
in our understanding
of the natural world.

Questions for the National Accelerator Laboratory "200-BeV Machine" (January 1968)

Which, if any, of the particles that have so far been discovered, is, in fact, elementary, and is there any validity in the concept of "elementary" particles?

What new particles can be made at energies that have not yet been reached? Is there some set of building blocks that is still more fundamental than the neutron and the proton?

Is there a law that correctly predicts the existence and nature of all the particles, and if so, what is that law?

Will the characteristics of some of the very short-lived particles appear to be different when they are produced at such higher velocities that they no longer spend their entire lives within the strong influence of the particle from which they are produced?

Do new symmetries appear or old ones disappear for high momentum-transfer events?

What is the connection, if any, of electromagnetism and strong interactions?

Do the laws of electromagnetic radiation, which are now known to hold over an enormous range of lengths and frequencies, continue to hold in the wavelength domain characteristic of the subnuclear particles?

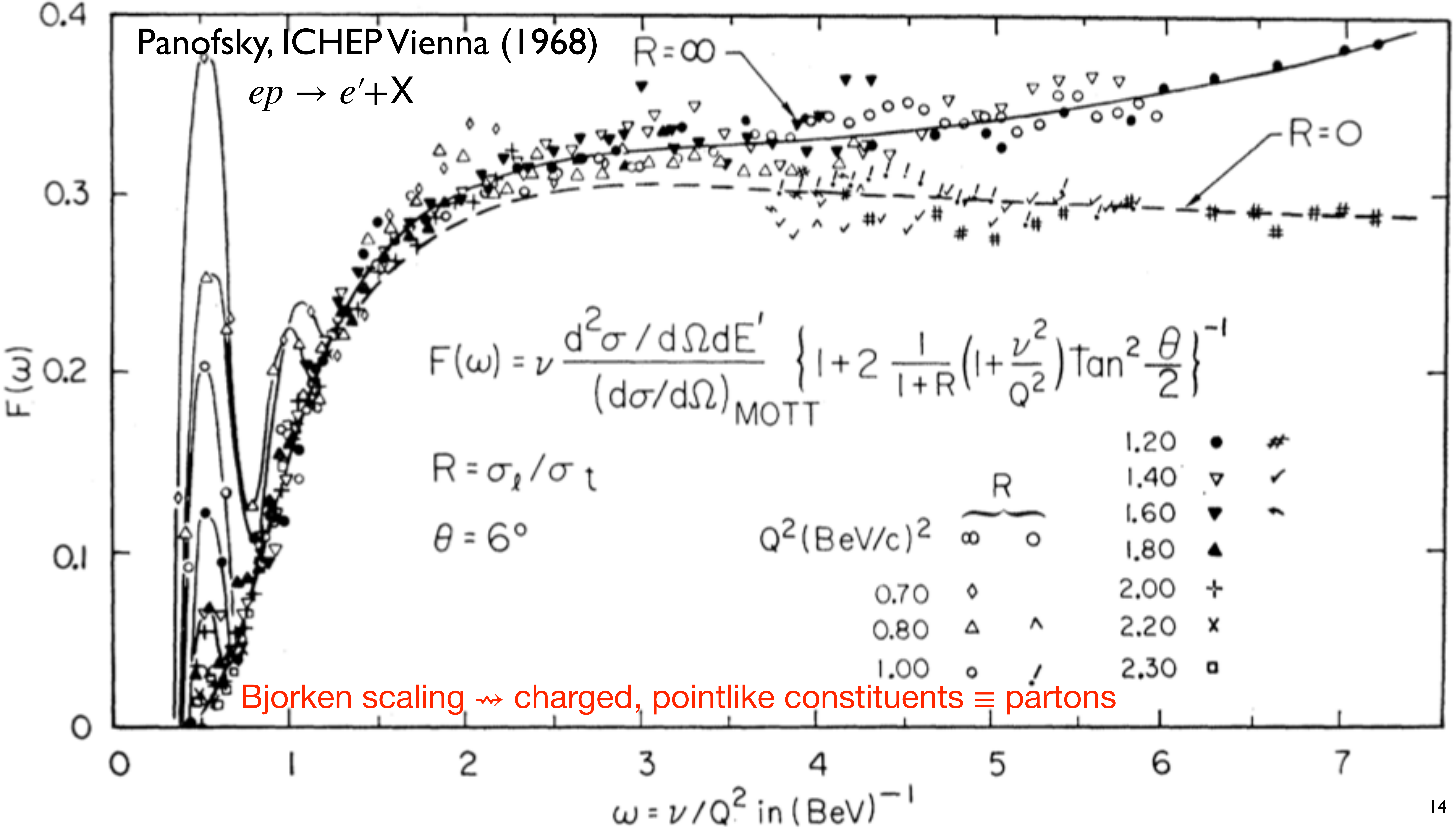
What is the connection between the weak interaction that is associated with the massless neutrino and the strong one that acts between neutron and proton?

Is there some new particle underlying the action of the "weak" forces, just as, in the case of the nuclear force, there are mesons, and, in the case of the electromagnetic force, there are photons? If there is not, why not?

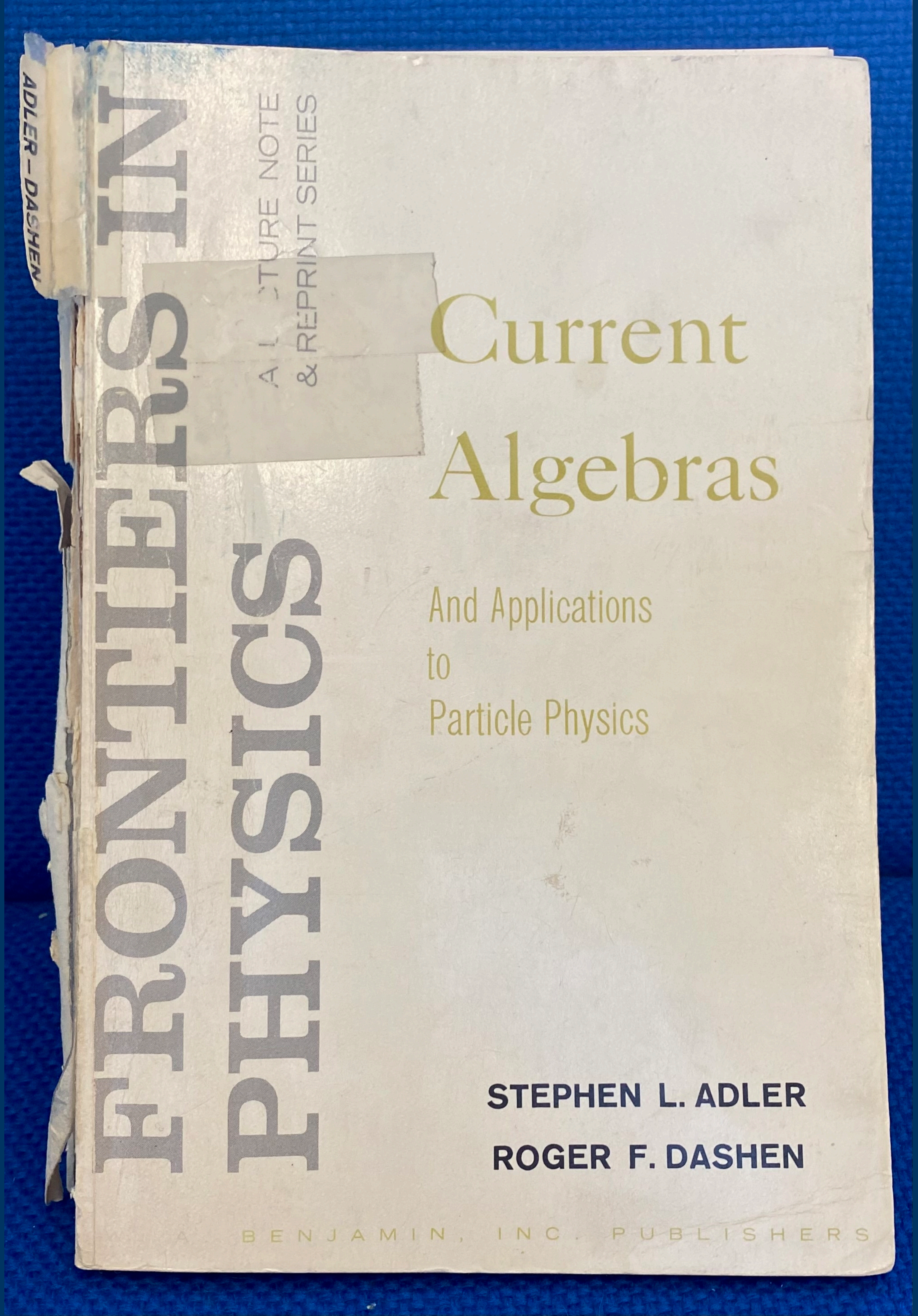
In more technical terms: Is local field theory valid? A failure in locality may imply a failure in our concept of space. What are the fields relevant to a correct local field theory? What are the form factors of the particles? What exactly is the explanation of the electromagnetic mass difference? Do "weak" interactions become strong at sufficiently small distances? Is the Pomeranchuk theorem true? Do the total cross sections become constant at high energy? Will new symmetries appear, or old ones disappear, at higher energy?

Panofsky, ICHEP Vienna (1968)

$ep \to e' + X$



Bjorken scaling ⇝ charged, pointlike constituents ≡ partons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"Bootstrap": A Scientific Idea?

The place of the bootstrap idea in science is analyzed, from the broad and limited points of view.

Geoffrey F. Chew

Although the term *bootstrap* has different significance for different scientists, in a uniformly accepted implication self-consistency is accorded a central role. In the broadest sense, bootstrap philosophy asserts that "nature is as it is because this is the only possible nature consistent with itself." In such vague terms the bootstrap idea is much older than particle physics, but within the last decade substantial numbers of physicists have begun serious study of bootstrap notions. Most have been driven to this extremity by an avalanche of unexpected experimental data on strongly interacting nuclear particles (*1*), the hadrons—data which have resisted physics' traditional description of natural phenomena through equations of motion for fundamental degrees of freedom. Some physicists additionally have been motivated by esthetics, finding all proposed alternatives to the bootstrap idea ugly.

In the first part of this article I point out that, in the broad sense, the bootstrap idea, although fascinating and useful, is unscientific. In the remainder of the article I describe a limited bootstrap hypothesis that concerns hadrons only.

We shall find that the scientific status of this partial bootstrap hypothesis is strangely resistant to clarification.

The Complete Bootstrap Hypothesis

Conventional science requires the a priori acceptance of certain concepts, so that "questions" can be formulated and experiments performed to give answers. The role of theory is to provide a set of rules for predicting the results of experiment, but rules necessarily are formulated in a language of commonly accepted ideas. Examples of currently unquestioned prerequisites for science are the following.

1) For macroscopic phenomena, a three-dimensional space and a time that moves in only one direction.

2) The arrangement of macroscopic matter into blobs of reasonably well defined shape and permanency, so that the "isolated system" or "object" concept can be used.

3) The existence of "gentle forces," like electromagnetism, that allow one macroscopic "object" to survive a "measurement" made upon it by another.

4) The existence of objects whose complexity is so great that "consciousness" of measurement becomes meaningful.

The author is a professor in the physics department of the University of California, Berkeley, and a member of the staff of the University's Lawrence Radiation Laboratory.

(Another sensation of ICHEP 1968)

IL NUOVO CIMENTO Vol. LVII A, N. 1 1° Settembre 1968

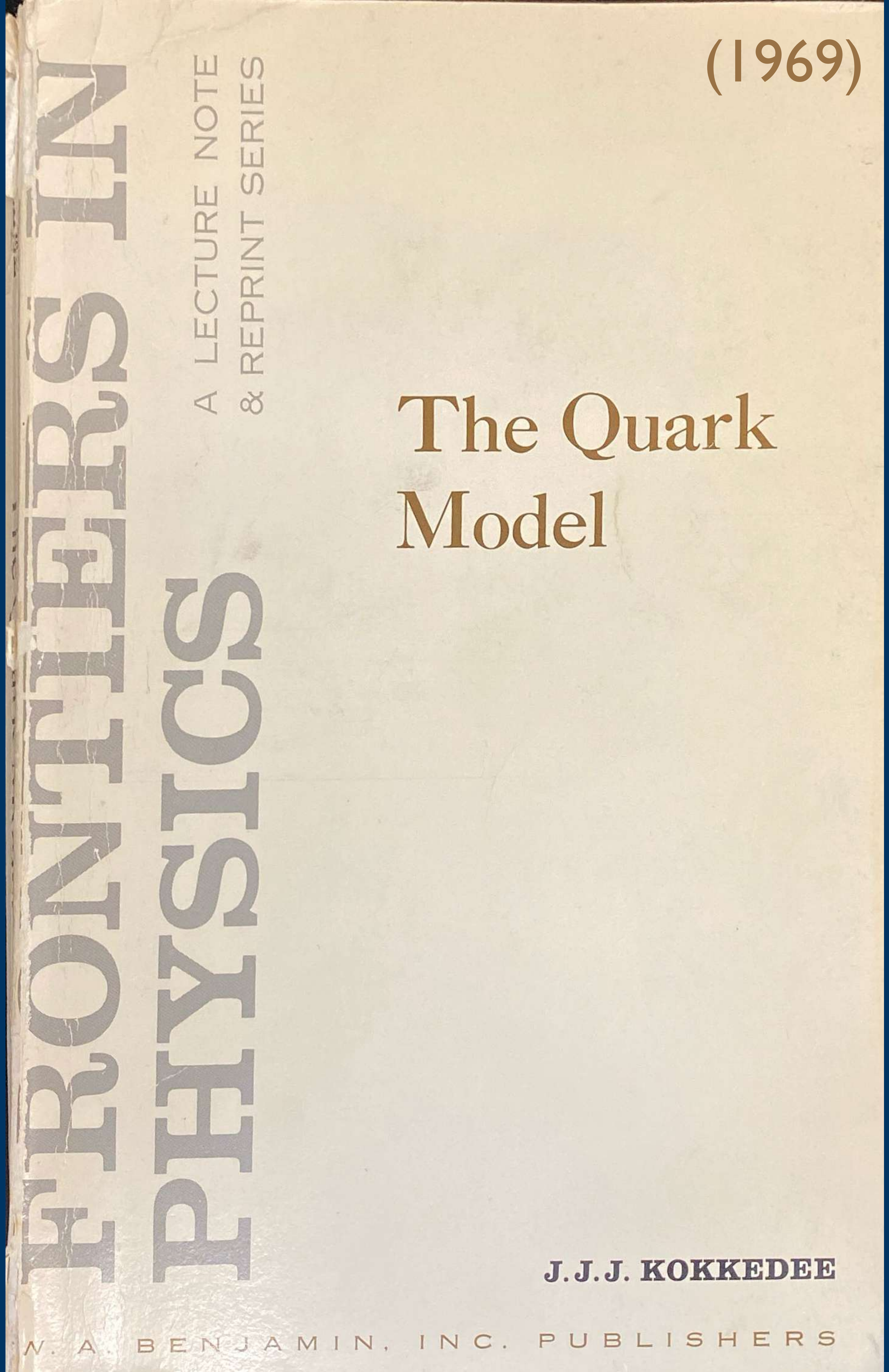
Construction of a Crossing-Simmetric, Regge-Behaved Amplitude for Linearly Rising Trajectories.

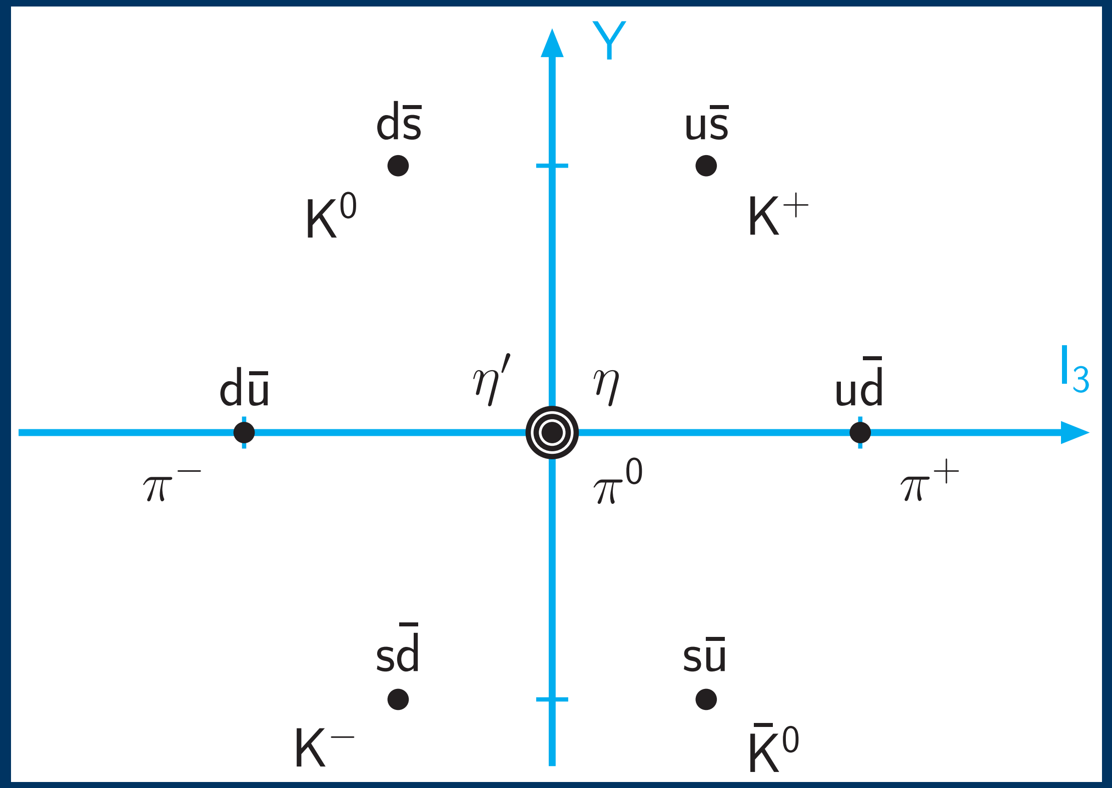
G. Veneziano (*)

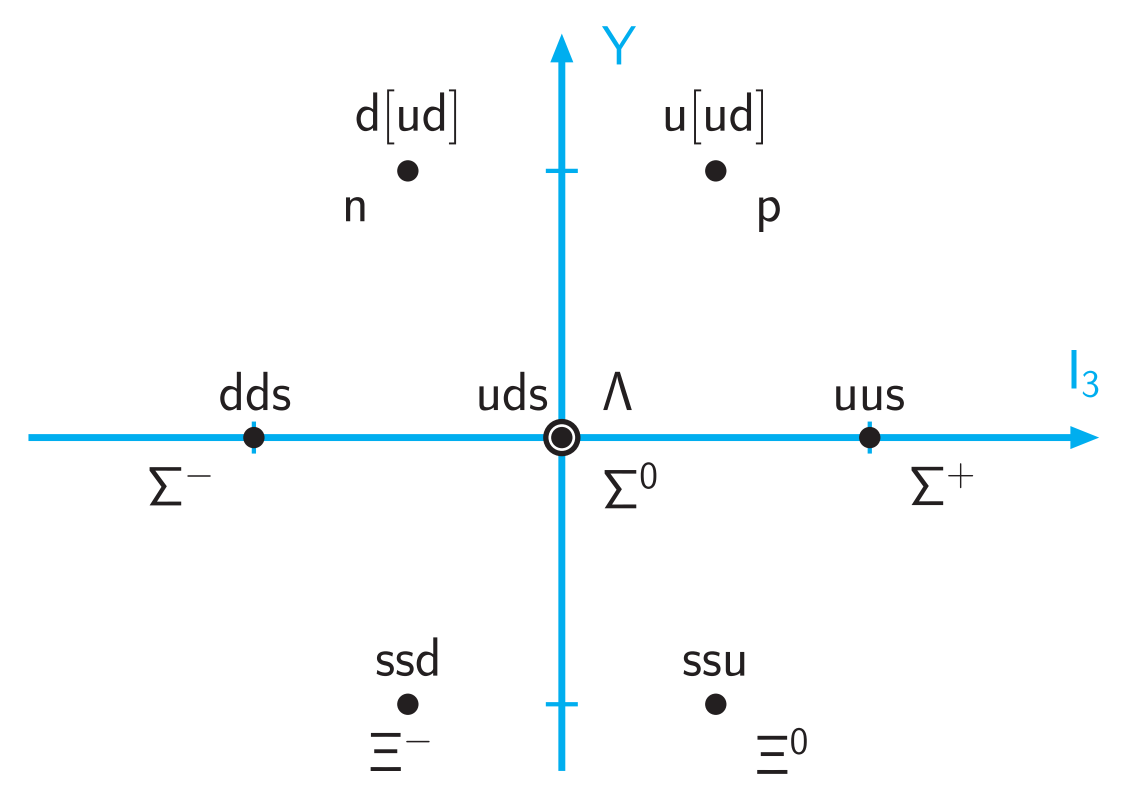
CERN - Geneva

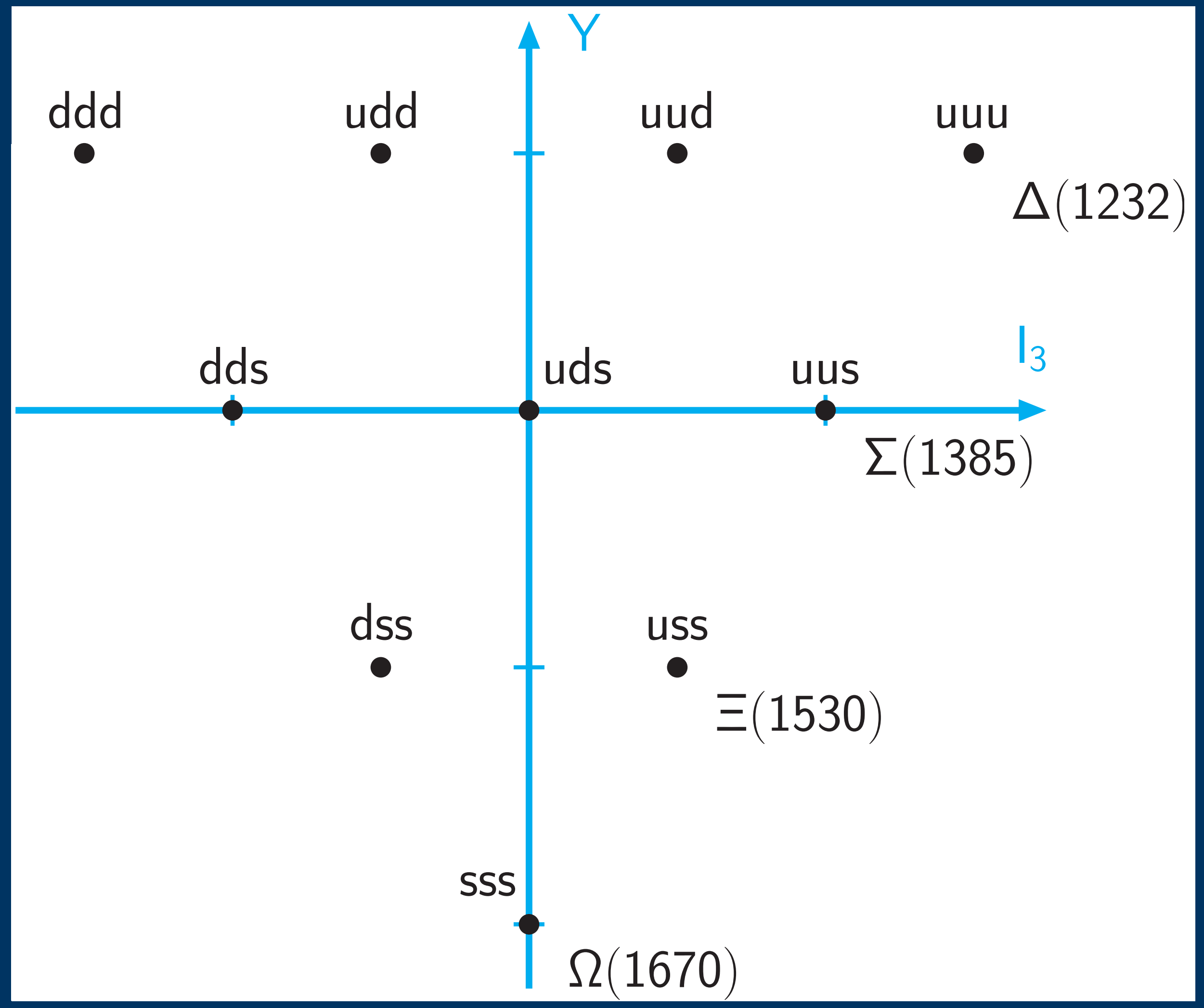
(ricevuto il 29 Luglio 1968)

The seed of string theories





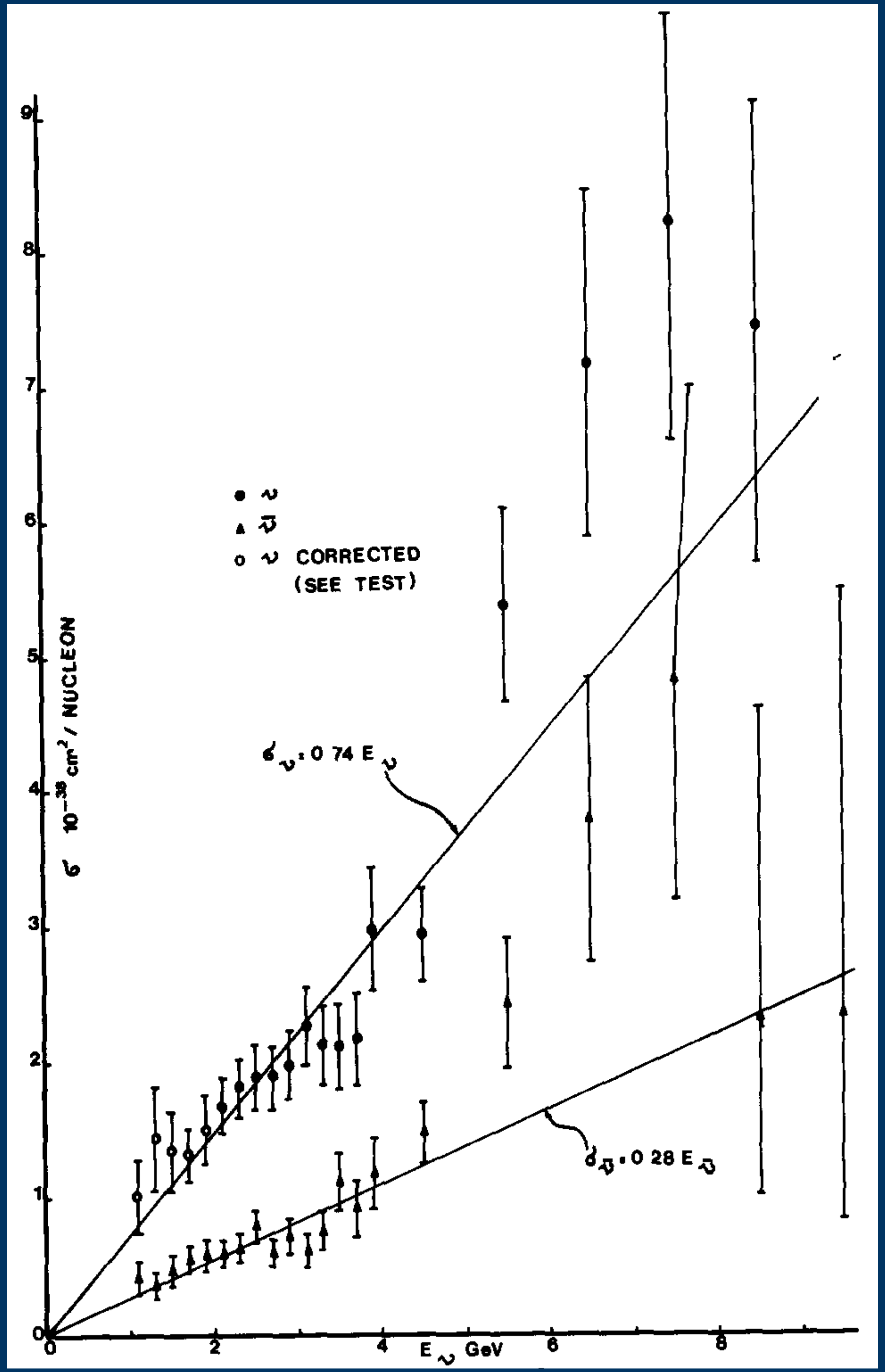




Parastatistics?

Bjorken & Paschos (1969)
quark-parton model
$qqq + q\bar{q}$ sea

Gargamelle cross sections, momentum fraction (1973)

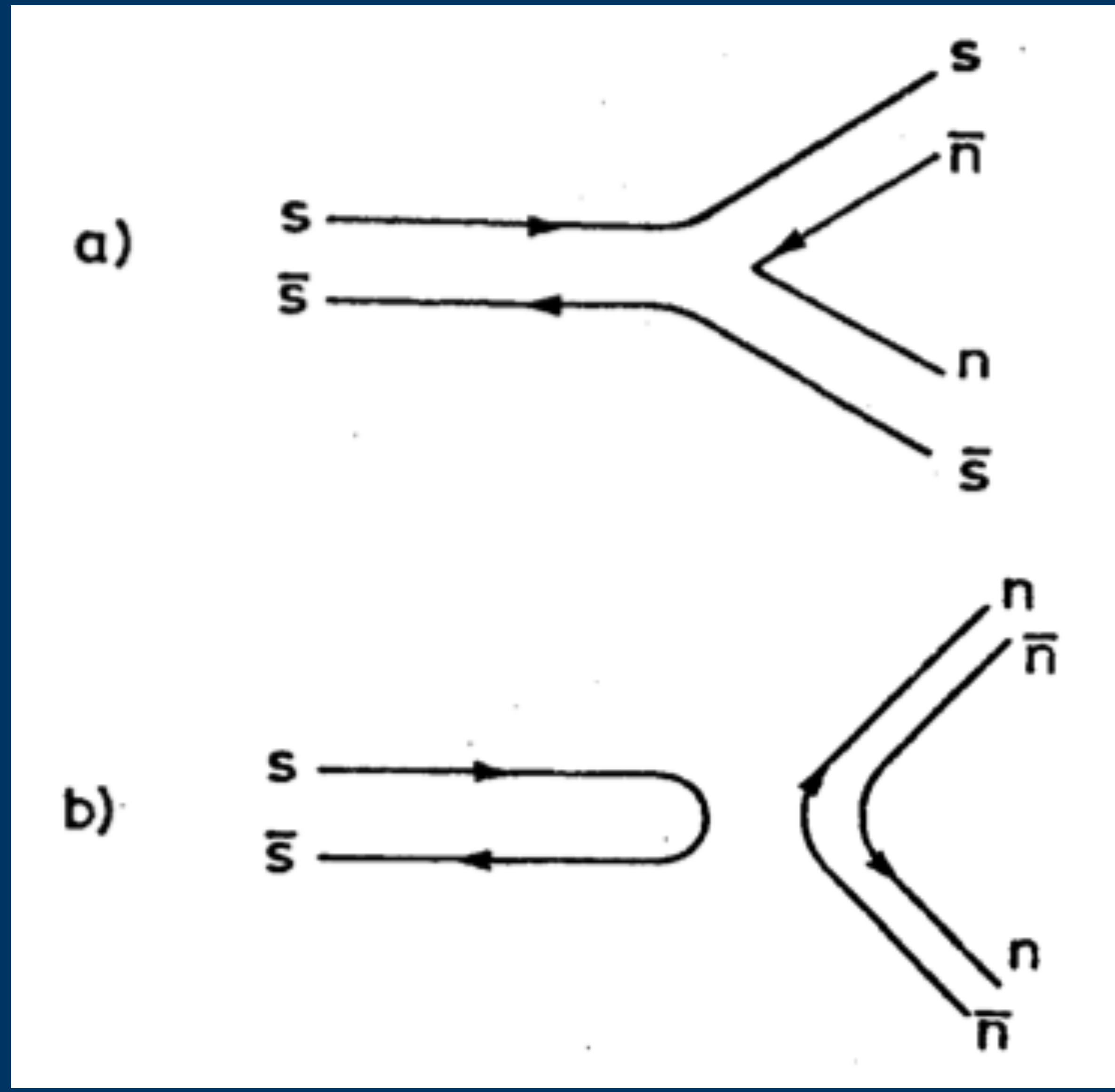


Accumulated insights from (light-)hadron spectroscopy

SU(3) flavor symmetry, SU(6) flavor-spin symmetry

mass formulas (later, QCD-informed)

"OZI rule": dissociation + dressing allowed, annihilation suppressed – $\phi(1020)$



Issues in the air approaching ν'72

Remarkable success of V–A effective theory ("four-fermion")

Status and origin of $\Delta I = \frac{1}{2}$ rule

Existence of Intermediate Vector Bosons, $W^{\pm}$

Testing lepton universality:

$\sigma(\nu_e e) \leq 40\sigma_{V-A}$; $\sigma(\bar{\nu}_e e) \leq 4\sigma_{V-A}$

Existence, properties of Neutral Currents

$K_L \rightarrow \mu^+\mu^-$ puzzle

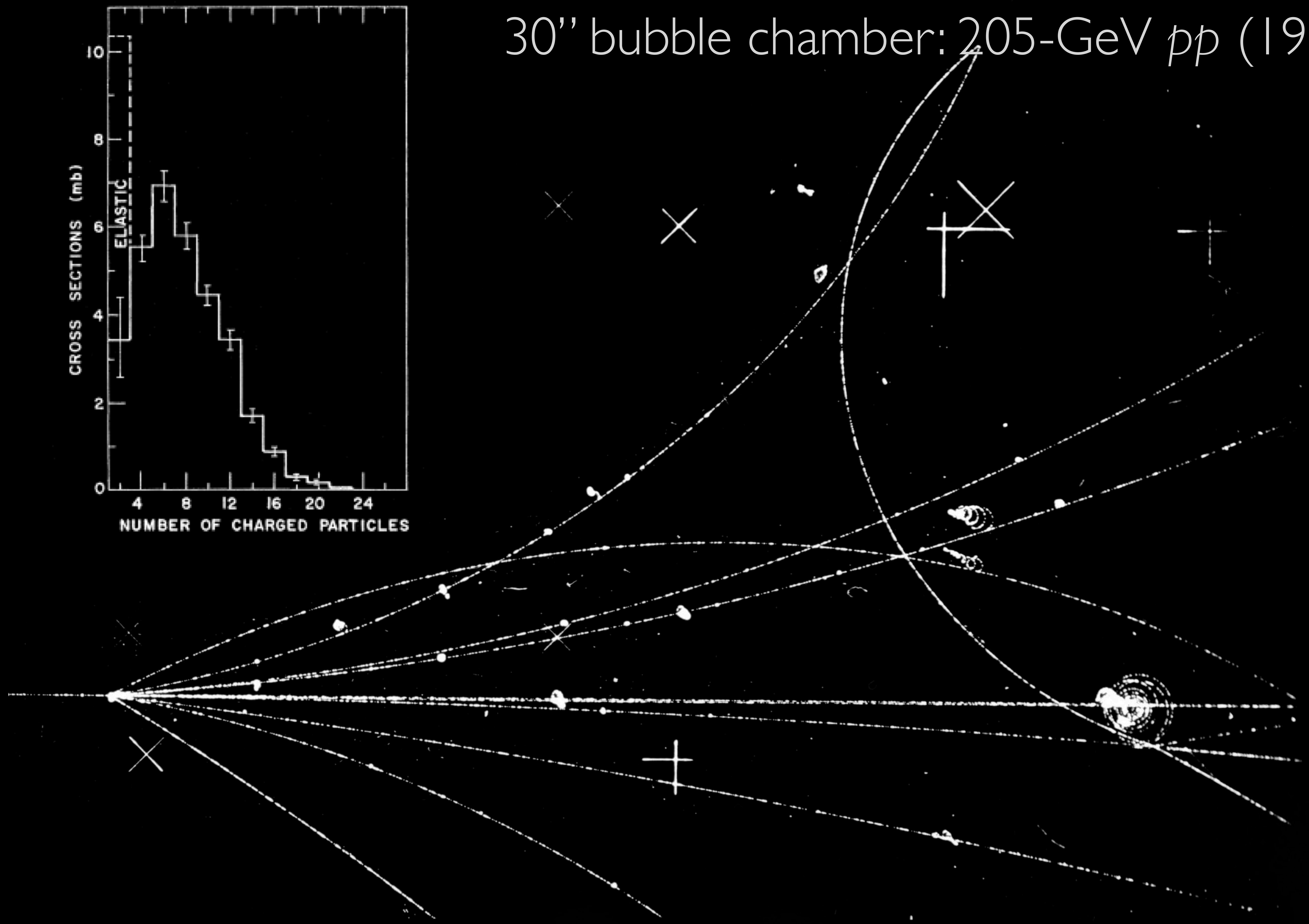
Mystery of CP Violation

Search for second-class currents

Implications of Bjorken scaling, partons

$SU(2)_L \otimes U(1)_Y$ Electroweak Theory

30” bubble chamber: 205-GeV *pp* (1972) + ISR



Slow to penetrate the common consciousness

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

Non-Abelian gauge theory ⇝ Asymptotic Freedom

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

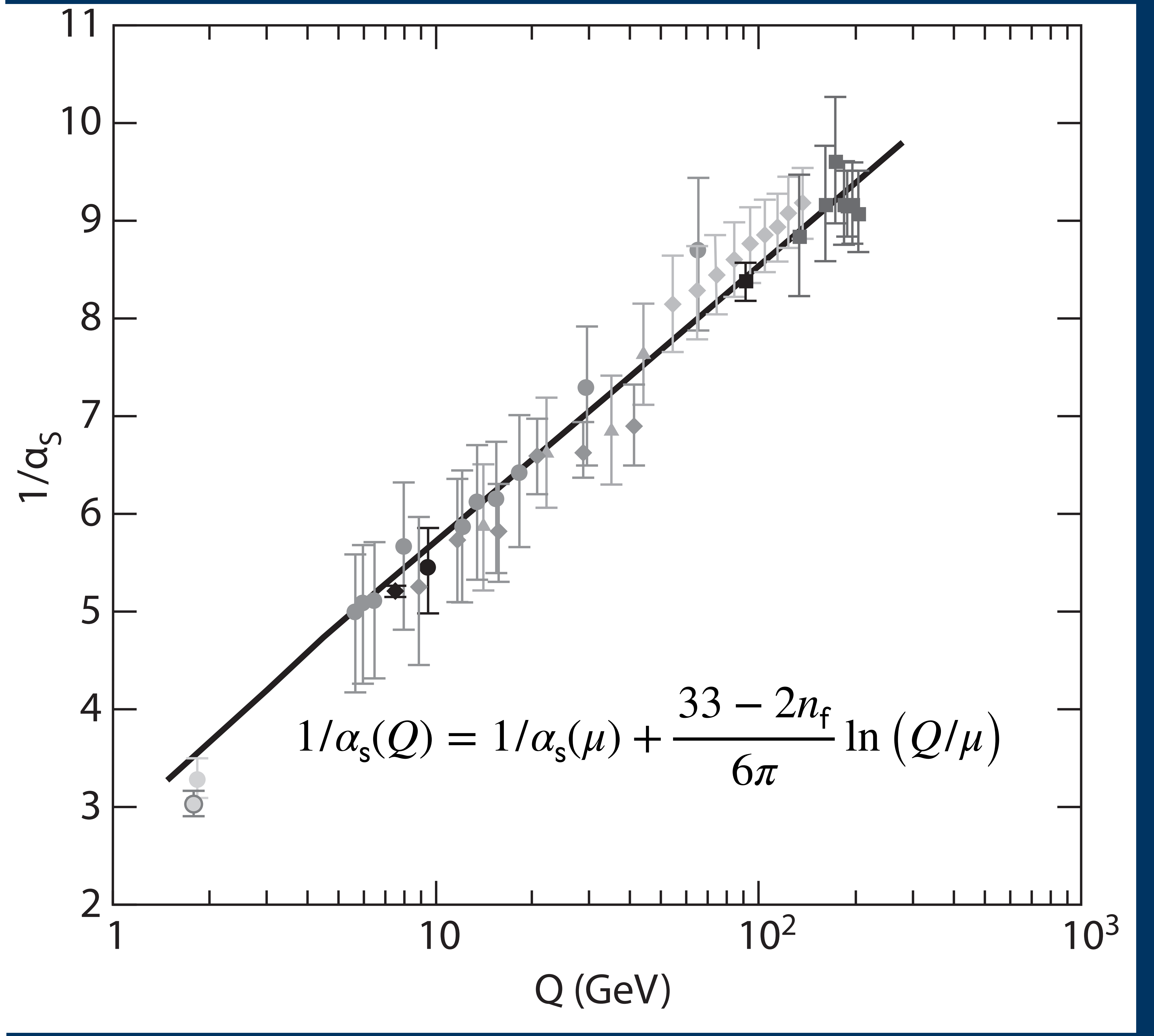
David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.



Gargamelle (CERN, 1973)

P. Galison, *How Experiments End* and "How the First Neutral Current Experiments Ended"

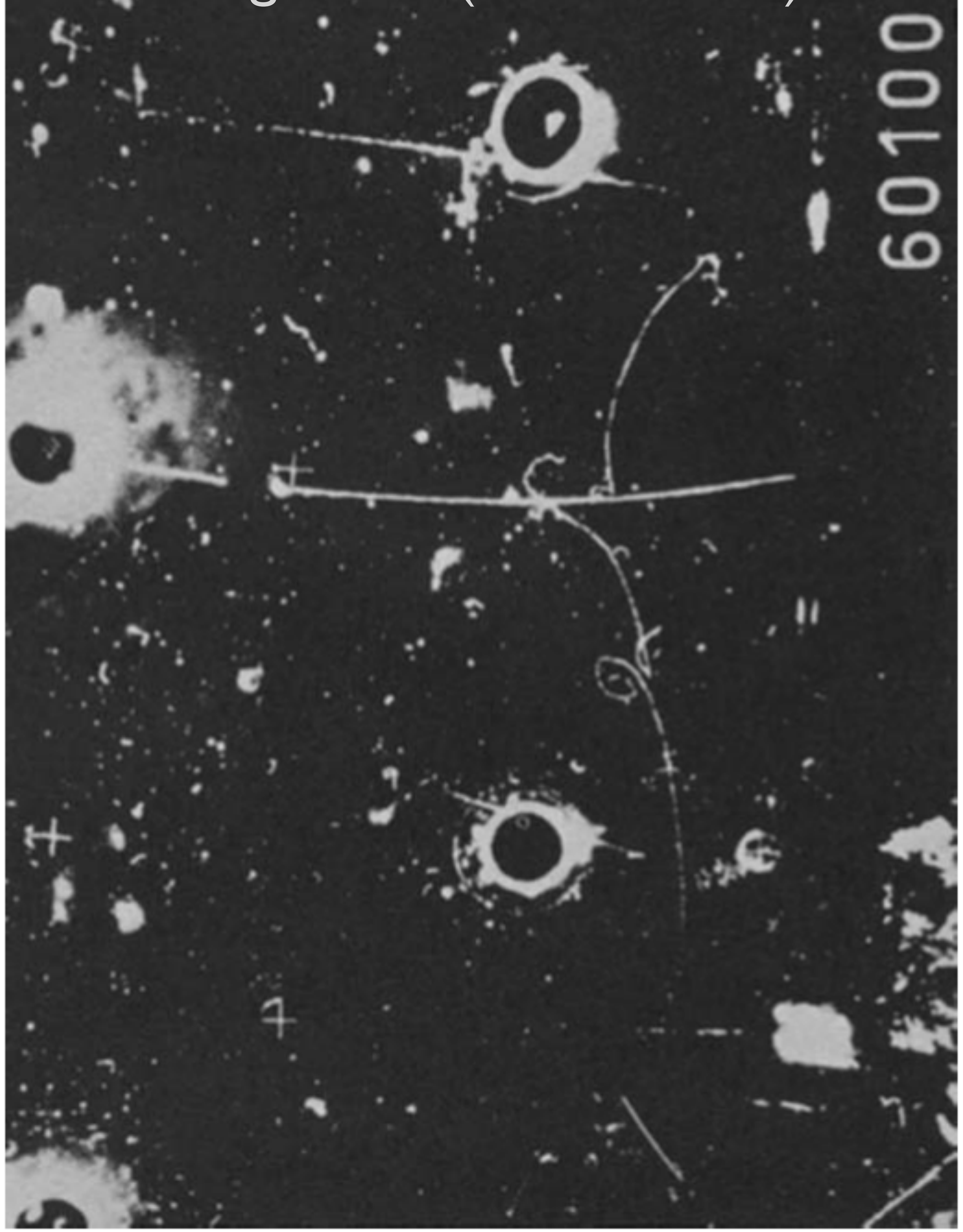
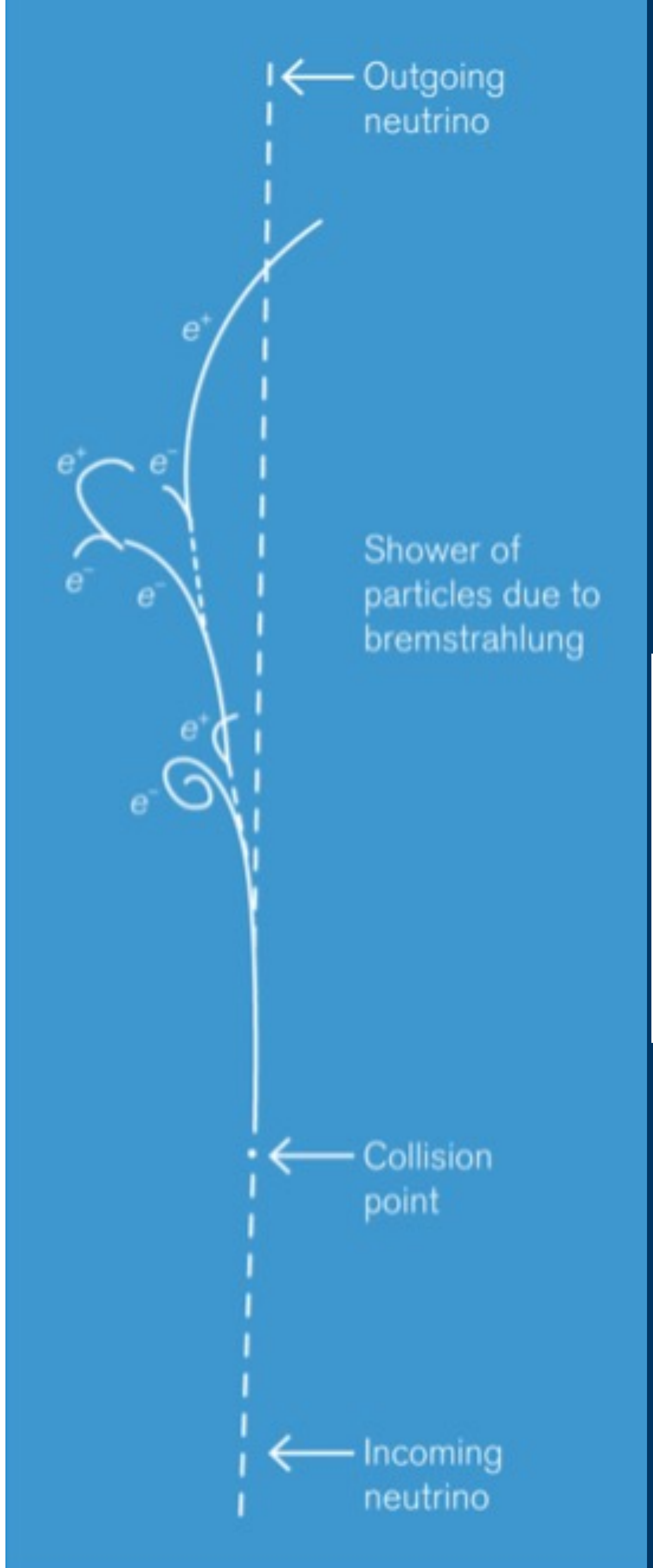
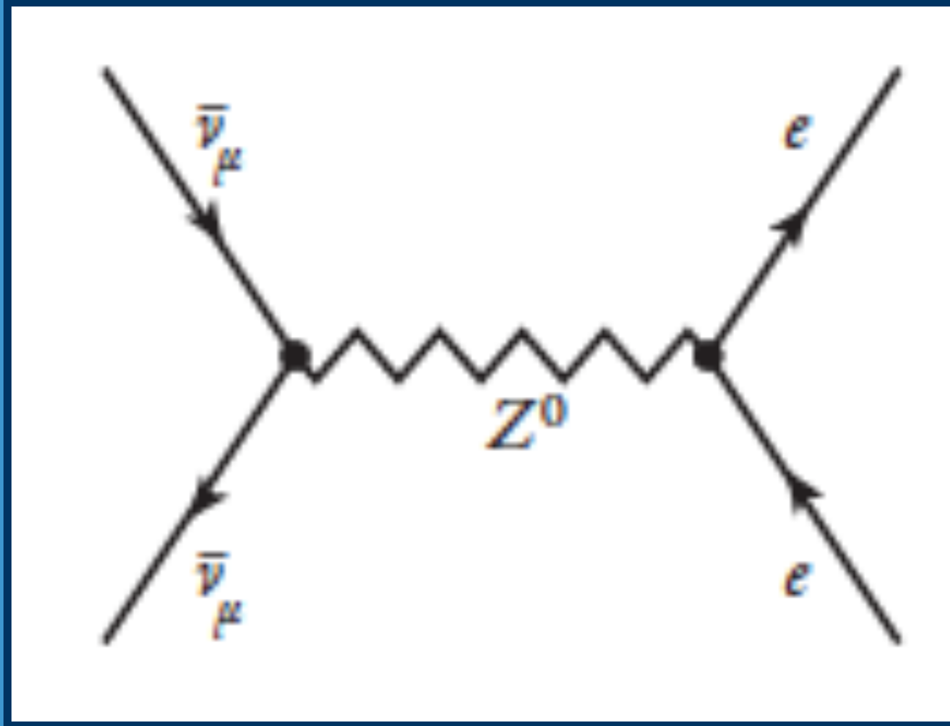


Fig. 1. Possible event of the type $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.





Fact and fancy in neutrino physics*

A. De. Rújula, Howard Georgi†, S. L. Glashow, and Helen R. Quinn

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

This paper reviews the success of the quark model in describing deep-inelastic lepton scattering. The neutral current predictions of a variety of unified gauge models are given and it is shown how experiment may distinguish among them. All the models involve new hadronic quantum numbers (charm or fancy). Their effects at high energy are explored.

CONTENTS

These are the proceedings of an imagined round-table discussion of fact and fiction in neutrino physics, performed at Harvard on December 3, 1973. The participants are *Moderator*—an experimentalist; *Speaker*—a conservative theorist; *Model Builder*—a not-so-conservative theorist; and *Computer*—a talking computer. The reader is warned that all the participants are partisans of quarks and gauge theories, and that their discussion is not a critical review of the status of weak-interaction theory or experiment. We have divided the discussion into six sections and an appendix:

I. SPEAKER PRESENTS THE NAIVE QUARK MODEL PREDICTIONS FOR NEUTRINO EXPERIMENTS

Moderator: In recent months, we have seen rapid developments in both weak-interaction theory and experiment. We now have renormalizable theories of weak interactions (Weinberg, 1967, 1973; Salam, 1968) which make striking new experimental predictions. Neutrino experiments which can test these theories have been done and are now in progress (Musset, 1973). Our round-table discussion is concerned with these developments, with what has already been learned, and with what can be learned in the near future.

Speaker will begin the discussion with a brief talk about deep-inelastic lepton scattering in the context of the naive quark model.

Speaker: Imagine the triumphs of the naive quark model! How else can we see why hadron states occur just in those *SU*(3) multiplets built from three quarks or a quark–antiquark pair? What simpler explanation of the observed 3/2 ratio for baryon–baryon/meson–baryon total cross sections? These are but two examples of how well the naive quark model describes strong-interaction phenomena.

This remarkable success extends to predictions for deep-inelastic lepton scattering. The model accurately predicts all inclusive charged-current neutrino and antineutrino data in terms of electroproduction information. Many of these predictions are already well known (Bjorken and Paschos, 1969, 1970).[1]

By the naive quark model, I mean the assertion that the nucleon—probed by weak or electromagnetic interactions in the deep-inelastic region—behaves as if it were composed exclusively of free pointlike *p*-type and *n*-type quarks (but no antiquarks), with a possible neutral background unseen by the probe. Deep-inelastic lepton scattering is described in terms of the quark distributions $p(x)$ and $n(x)$. They are the probability densities to find a given type of quark carrying a fraction x of the proton's longitudinal momentum, in the infinite momentum frame.[2] With this hypothesis, I can express the cross sections in terms of the distributions and the weak and electromagnetic properties of free quarks.

I assume, as do their inventors, that the quarks have fractional electric charges. Whether there is just one pair of quarks or a pair of color triplets will not matter. For muonic weak cross sections

$$\nu(\bar{\nu}) + N \rightarrow \mu(\bar{\mu}) + \cdots, \qquad (1)$$

I use the conventional model of weak interaction. I interpret the recently reported muonless cross sections (Hasert *et al.*, 1973b; Benvenuti *et al.*, 1974a) as neutral-current effects

$$\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + \cdots, \qquad (2)$$

and I use Weinberg-Salam (Weinberg, 1967; Salam, 1968) model to describe them. The electromagnetic coupling and the relevant effective charged and neutral weak couplings are:

$$\mathfrak{L}(\text{electromag.}) = (e^2/q^2)(\bar{e}\gamma^\alpha e)(\tfrac{2}{3}\bar{p}\gamma_\alpha p - \tfrac{1}{3}\bar{n}\gamma_\alpha n), \qquad (3a)$$

$$\mathfrak{L}(\text{charged}) = (G/\sqrt{2})[\bar{\mu}\gamma^\alpha(1+\gamma_5)\nu][\bar{p}\gamma_\alpha(1+\gamma_5)n] + \text{h.c.}, \qquad (3b)$$

$$\mathfrak{L}(\text{neutral}) = (G/\sqrt{2})[\bar{\nu}\gamma^\alpha(1+\gamma_5)\nu] \times \{\bar{p}\gamma_\alpha[a(1+\gamma_5)+c(1-\gamma_5)]p + \bar{n}\gamma_\alpha[b(1+\gamma_5)+d(1-\gamma_5)]n\}. \qquad (3c)$$

In the Weinberg model the quantities a, b, c, d are of order 1,

* Work supported in part by the Air Force Office of Scientific Research under contract F44620-70-C-0030 and in part by the National Science Foundation under grant GP40397X.

† Junior Fellow, Society of Fellows, Harvard University.

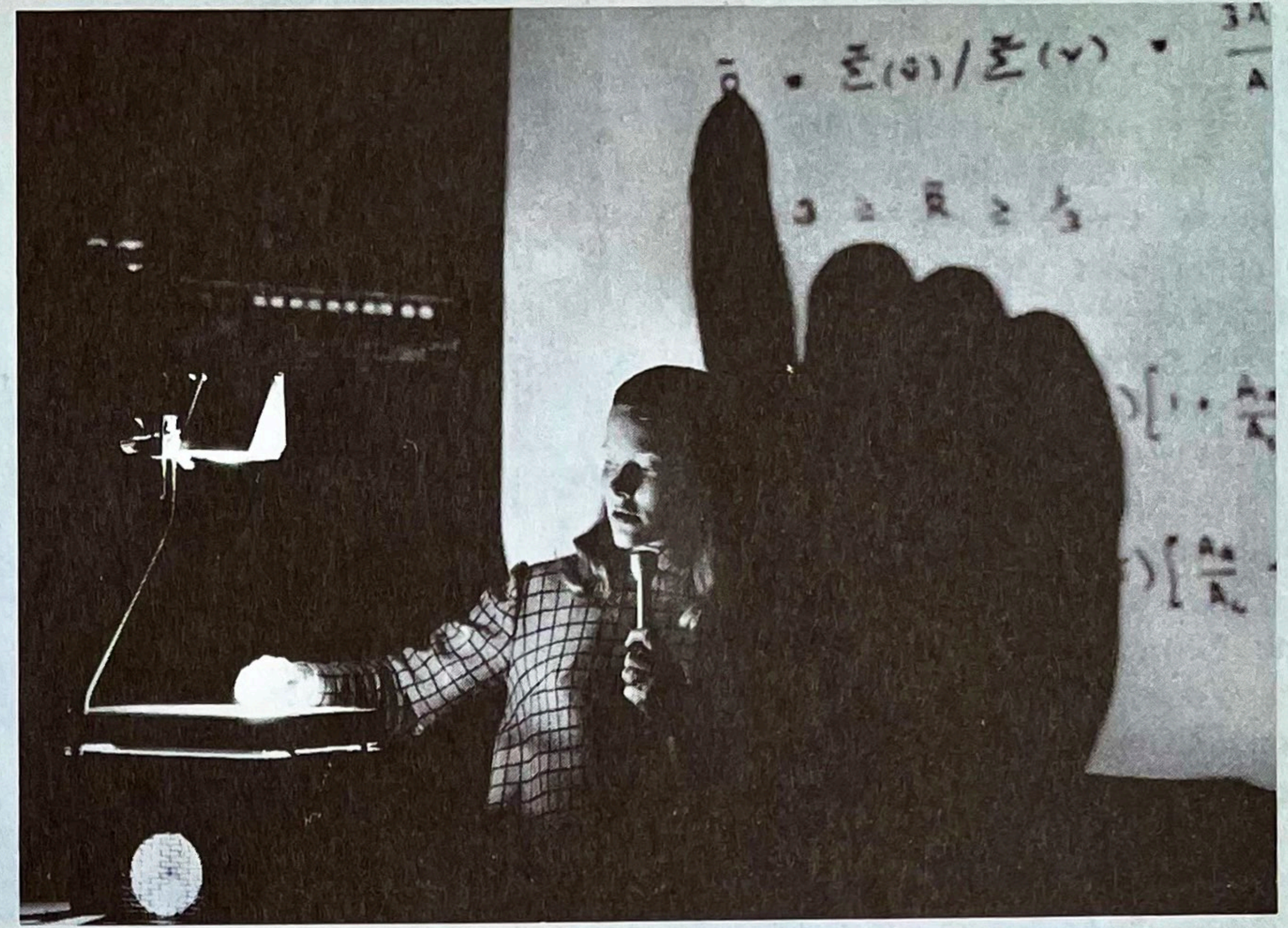
[1] For a review see Llewellyn-Smith, 1972.

[2] See, for example, Feynman, 1972.

QUARK, n. Physics. Any of three hypothetical subatomic particles . . . proposed as the fundamental units of matter. [From a line in Joyce's *Finnegan's Wake*, "three quarks for Mr. Marks."]

Harvard Magazine, January 1974

The hunting of the quark



Aided by a projection device, Assistant Professor Helen Quinn ends the neutrino show with a telegram consisting entirely of equations.

We were loitering in the halls of Jefferson physics lab one afternoon, trying not to look lost, when a knot of graduate students swept by. "Come on," they said as one, "you'll be late for the neutrino show." So, like Alice hurrying after the White Rabbit, we came.

After many turns and windings through Jefferson's cuniculous corridors, we arrived at lecture room 250, where a sizable audience had already gathered. Most had the air of knowing what was going on. "What's going on?" we whispered to our neighbor.

"You mean you've never been to a physics colloquium before?" His tone hovered between mild disapproval and pity. "Are you a physicist, then?"

"No," we admitted, "we are a drama critic."

"Well you may be in luck," he replied. "This colloquium is going to be a play. It's about neutrino scattering. Glashow is reexamining the naive quark model in light of . . ." Before we could inquire as to the meaning of neutrino scattering, Glashow, or naive quarks, four sober-looking physicists filed out and faced us across the lab table. There was no curtain, nor were there any costumes or props. "Minimal theater," we opined knowledgeably.

Despite its avant-garde set, the play opened in a traditional, one might almost say melodramatic, mode. Alvaro de Rujula, research fellow in physics, playing a research fellow in physics, presented an impassioned defense of an entity known as the "naive quark." As we conceived the naive quark to be a sort of subatomic ingenue whose reputation was being besmirched by physicists of sinister designs, our sympathy was easily enlisted.

Rujula was about to join forces with a benevolent computer (played with commendable metallic monotony by junior fellow Howard Georgi) when a new figure leapt into the spotlight. "Stop! Abort your calculations," cried the interloper (Professor Sheldon Glashow). We perceived at once that Glashow was a villain of the modern-ambiguous-breakdown-of-traditional-morality school, whose genial smile and lucid manner concealed the most horrid designs upon the virtue of the naive quark. Our worst fears were realized when Glashow threatened the defenseless quark with a bombardment of muons, hadrons, and heavy leptons, surely a more fiendish brand of villainy than the traditional railroad-track gambit.

Periodic choric interpolations by Helen Quinn, assistant professor of physics, a skeptical experimentalist doubtless representing the voice of reason, served merely to heighten suspense without resolving the fate of the imperiled quark.

Suddenly a *deus ex machina* intervened, in the form of a messenger who clattered allegorically down the aisle two steps at a time, brandishing a telegram. ("Is it from Sweden?" muttered Rujulo *sotto voce.*) The telegram consisted entirely of equations. It was greeted by a round of applause. "Brilliant," said our neighbor, getting up to leave. "That resolves everything." —KIM FADIMAN

Experimental Meson Spectroscopy (April 1974)

CHARM: AN INVENTION AWAITS DISCOVERY*

Sheldon Lee Glashow
Harvard University, Cambridge, Massachusetts 02138

A most important question in experimental meson spectroscopy is to determine what are the hadronic quantum numbers. Charm, a conjectured strong interaction quantum number for which the theoretical raison d'etre is is all but compelling, has not yet been found in the laboratory. I would bet on charm's existence and discovery, but I am not so sure it will be the hadron spectroscopist who first finds it. Not unless he puts aside for a time his fascination with such bumps, resonances, and Deck-effects as have been discussed at length at this meeting. Charm will not come so easily as strangeness, yet no concerted, deliberate search has been launched.

WHAT TO EXPECT AT EMS-76

There are just three possibilities:

1. Charm is not found, and I eat my hat.
2. Charm is found by hadron spectroscopers, and we celebrate.
3. Charm is found by outlanders, and you eat your hats.

Neutral currents (not flavor-changing) need GIM mechanism (1970)

Search for charm

Mary K. Gaillard* and Benjamin W. Lee

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Jonathan L. Rosner

University of Minnesota, Minneapolis, Minnesota 55455

A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the $SU(4)$ spectroscopy of the lowest lying baryon and meson states, their masses, decay modes, lifetimes, and various production mechanisms. We also present a brief discussion of searches for short-lived tracks. Our discussion is largely based on intuition gained from the familiar —but not necessarily understood— phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

Preprint, August 1974:

$$\phi_c(c\bar{c}) : \quad M(\phi_c) \approx 3 \text{ GeV} \quad \Gamma(\phi_c) \approx 2 \text{ MeV}$$

$$BR(\phi_c \to e^+e^-) \approx 1\%$$

Paired quark/lepton doublets cancel anomalies (1972)

Bouchiat, Iliopoulos, Meyer | Gross & Jackiw

Unified Theories of Strong, Weak, and Electromagnetic Interactions

PHYSICAL REVIEW D VOLUME 10, NUMBER 1 1 JULY 1974

Lepton number as the fourth "color"

Jogesh C. Pati*
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy
and Imperial College, London, England
(Received 25 February 1974)

Universal strong, weak, and electromagnetic interactions of leptons and hadrons are generated by gauging a non-Abelian renormalizable anomaly-free subgroup of the fundamental symmetry structure $SU(4)_L \times SU(4)_R \times SU(4')$, which unites three quartets of "colored" baryonic quarks and the quartet of known leptons into 16-folds of chiral fermionic multiplets, with lepton number treated as the fourth "color" quantum number. Experimental consequences of this scheme are discussed. These include (1) the emergence and effects of exotic gauge mesons carrying both baryonic as well as leptonic quantum numbers, particularly in semileptonic processes, (2) the manifestation of anomalous strong interactions among leptonic and semileptonic processes at high energies, (3) the independent possibility of baryon-lepton number violation in quark and proton decays, and (4) the occurrence of $(V+A)$ weak-current effects.

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

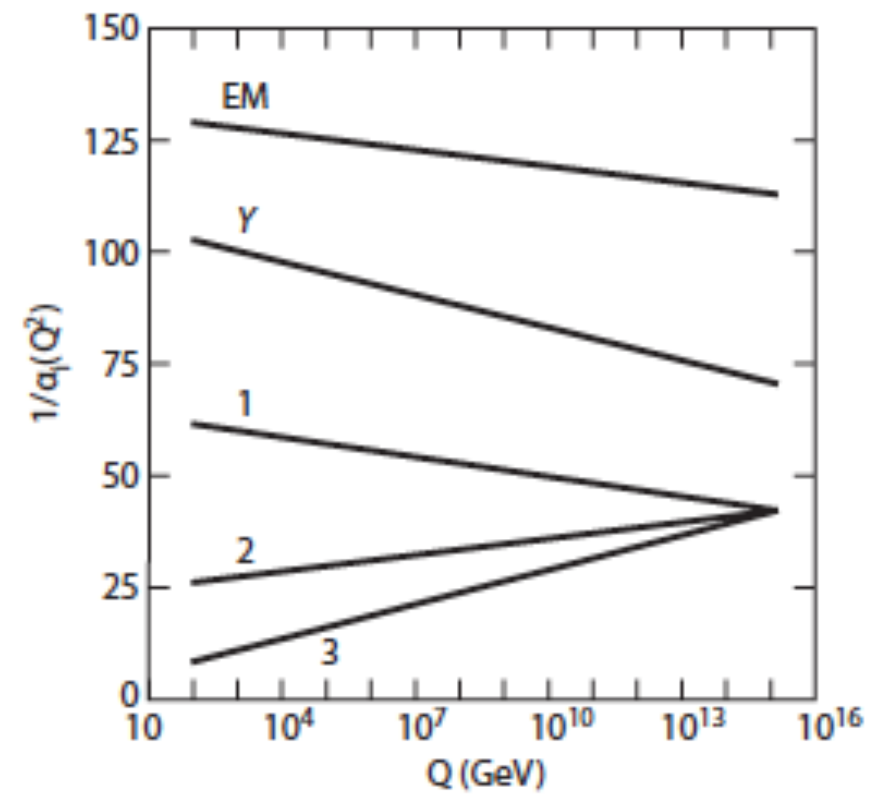
Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

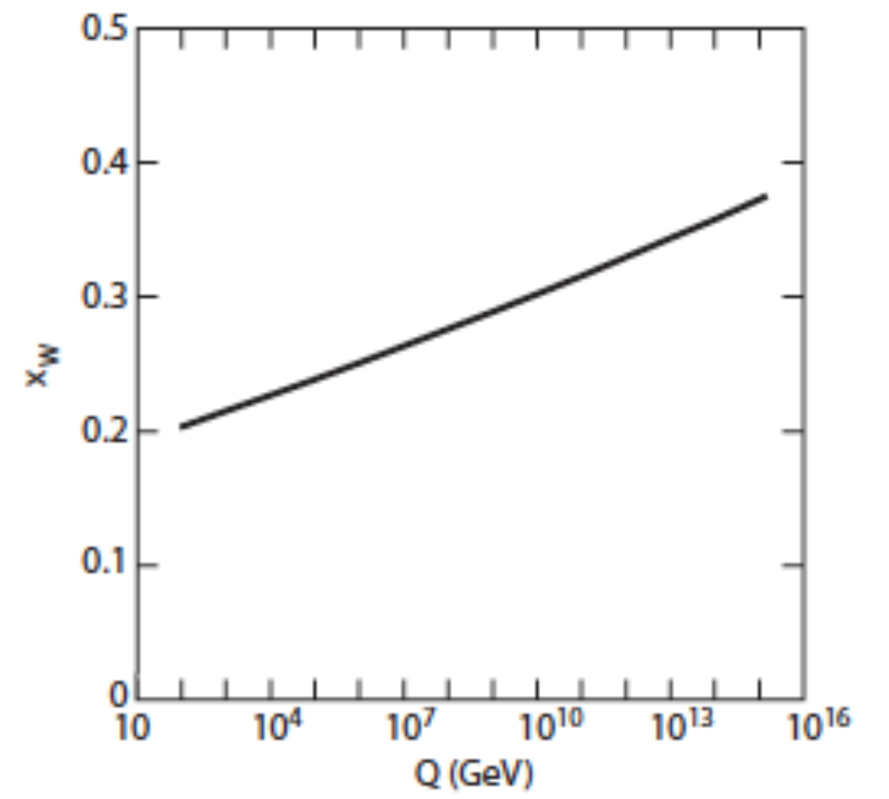
VOLUME 33, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1974

Hierarchy of Interactions in Unified Gauge Theories*

H. Georgi,† H. R. Quinn, and S. Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 15 May 1974)

We present a general formalism for calculating the renormalization effects which make strong interactions strong in simple gauge theories of strong, electromagnetic, and weak interactions. In an SU(5) model the superheavy gauge bosons arising in the spontaneous breakdown to observed interactions have mass perhaps as large as 10^{17} GeV, almost the Planck mass. Mixing-angle predictions are substantially modified.



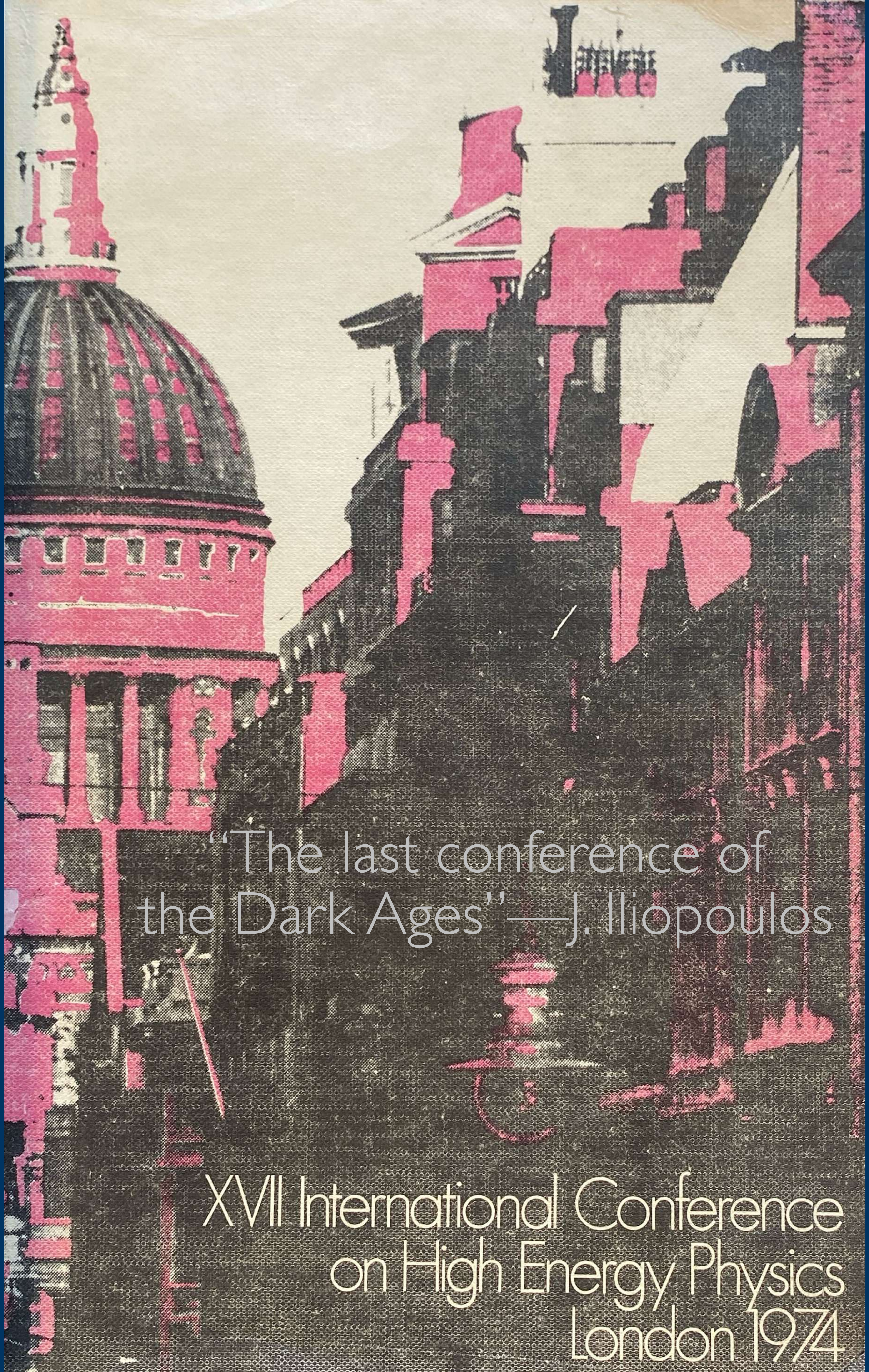


PHYSICAL REVIEW D VOLUME 10, NUMBER 8 15 OCTOBER 1974

Confinement of quarks*

Kenneth G. Wilson
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
(Received 12 June 1974)

A mechanism for total confinement of quarks, similar to that of Schwinger, is defined which requires the existence of Abelian or non-Abelian gauge fields. It is shown how to quantize a gauge field theory on a discrete lattice in Euclidean space-time, preserving exact gauge invariance and treating the gauge fields as angular variables (which makes a gauge-fixing term unnecessary). The lattice gauge theory has a computable strong-coupling limit; in this limit the binding mechanism applies and there are no free quarks. There is unfortunately no Lorentz (or Euclidean) invariance in the strong-coupling limit. The strong-coupling expansion involves sums over all quark paths and sums over all surfaces (on the lattice) joining quark paths. This structure is reminiscent of relativistic string models of hadrons.



"The last conference of the Dark Ages"—J. Iliopoulos

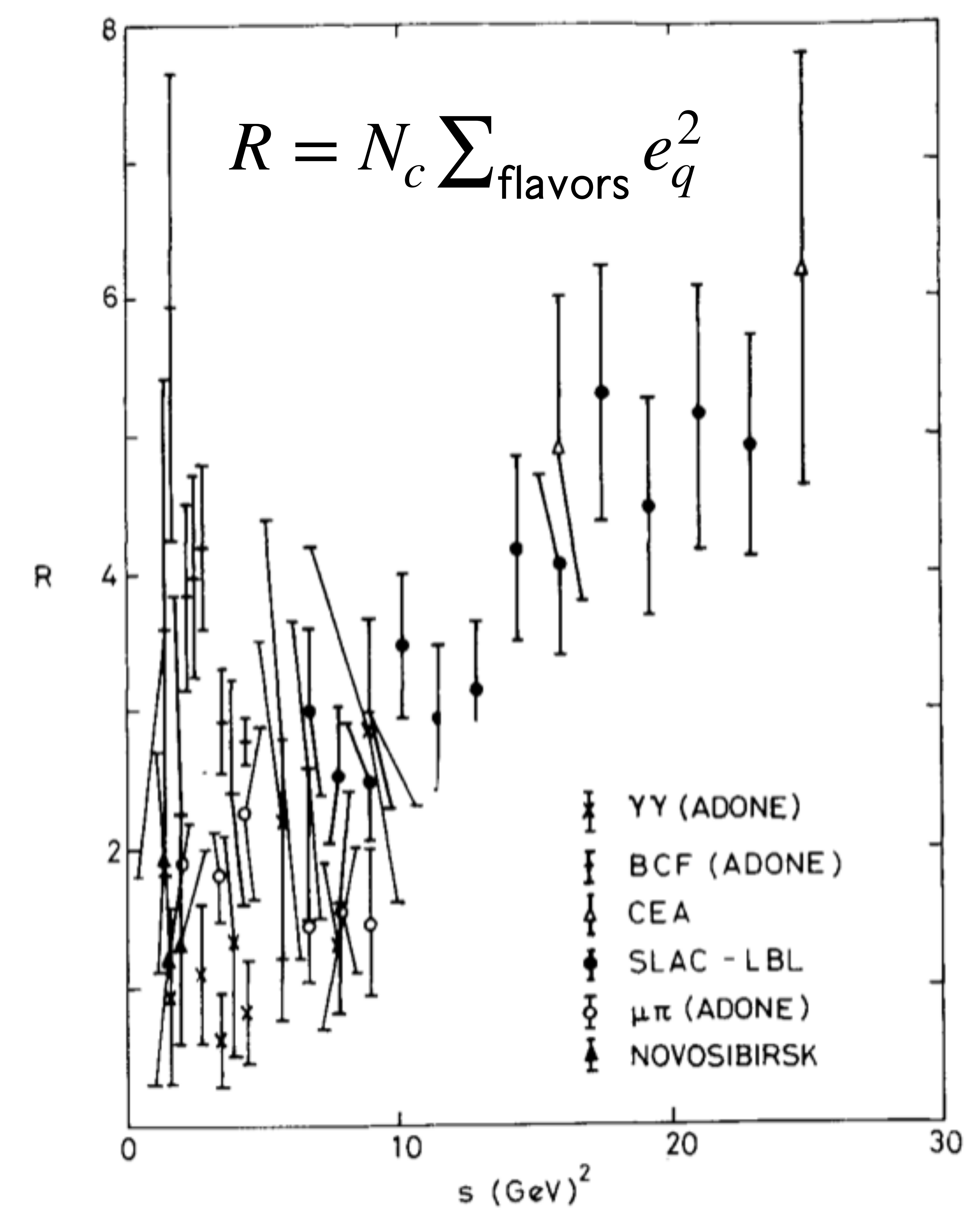
ICHEP, London: Summer 1974

IV-50 B Richter

X THEORY

The e^+e^- annihilation data contradict both the simple quark-parton model and the Bjorken scaling hypothesis. This has come as a shock for they were both doing so well - giving an understanding of multiplet structure, cross section relationships, decay branching ratios, deep inelastic electron, neutrino, and muon scattering, etc. Indeed, scaling was tested and found to work to 10% to 20 % over three orders of magnitude in the structure functions and for values of momentum transfer ranging up to 60 to 70 $(GeV/c)^2$ and values of inelasticity out to 100 GeV. Most of the 61 theoretical contributions to this session of the conference, which range from the bizarre to the ordinary, attempt to resolve the contradiction between the success of simple models in the space-like momentum transfer region and their failure in the time-like momentum transfer region.

$$R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$$



Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

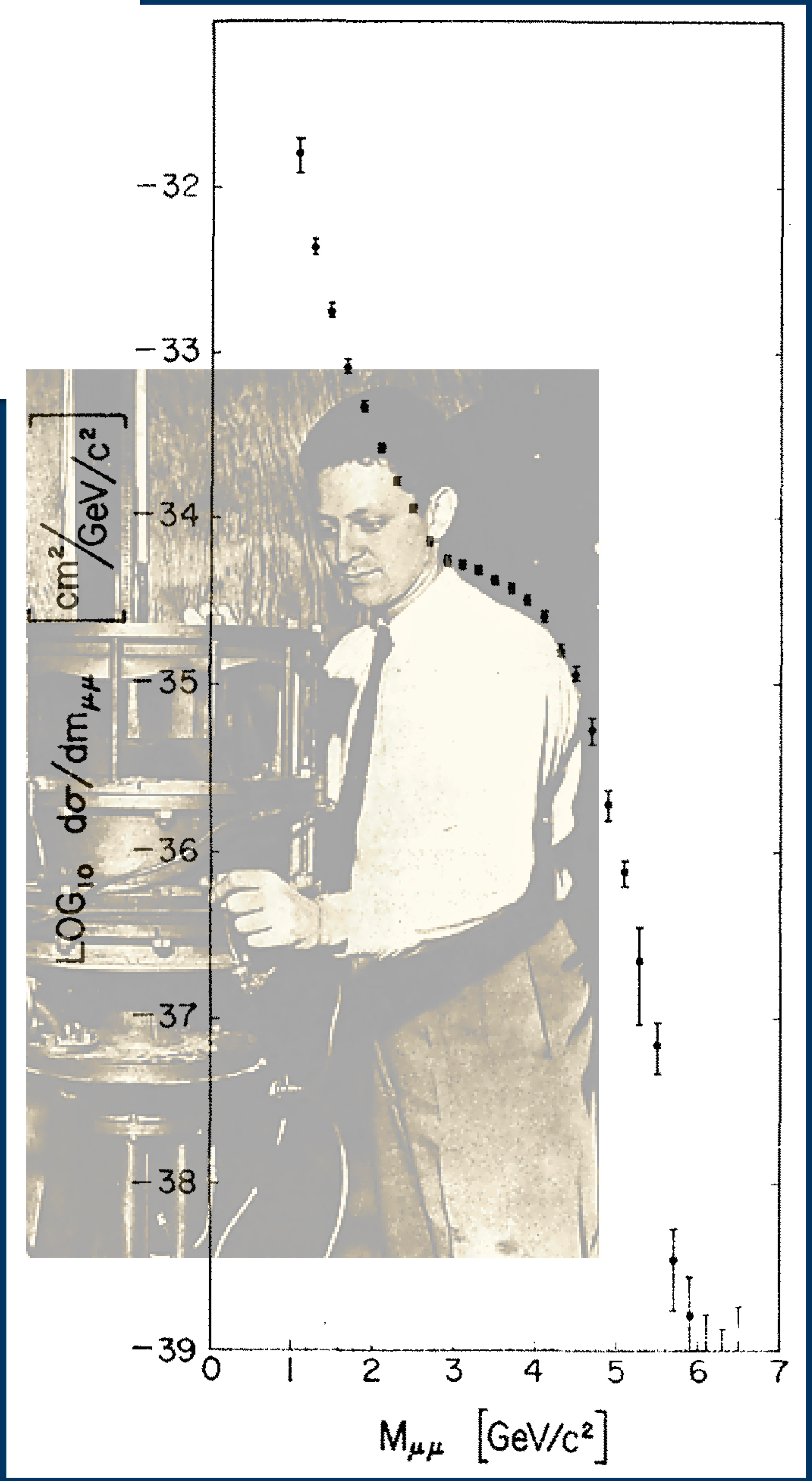
E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}{}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

Muons penetrated 10 feet of steel

"[I]n the mass region near 3.5 GeV,
the observed spectrum may be
reproduced by a composite
of a resonance and a steeper continuum."

History: J. Rak & M. Tannenbaum,
High-p_T Physics in the Heavy-Ion Era, c. 7 & 8



ICHEP 1974

CHAIRMAN'S SUMMARY

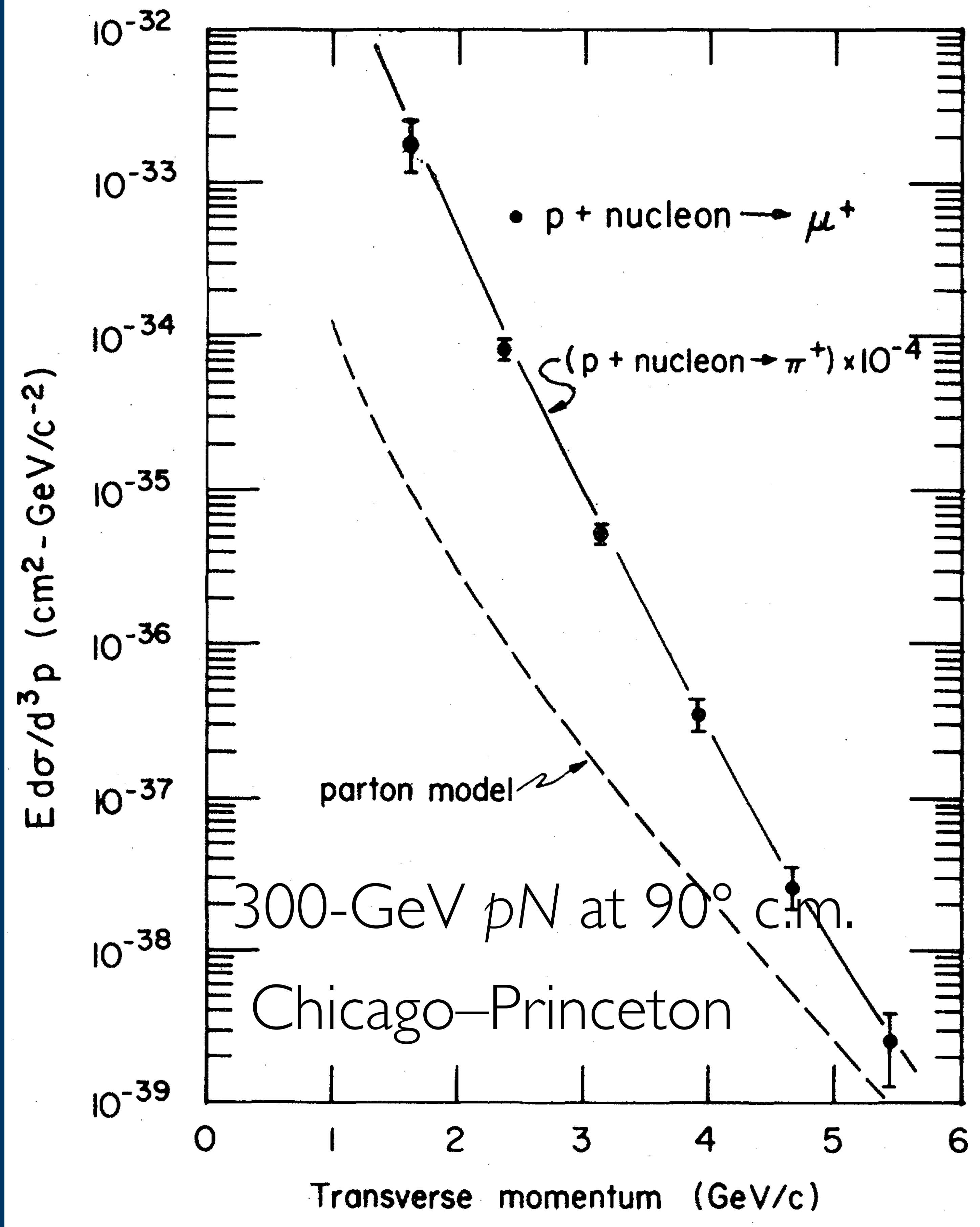
L M Lederman

Columbia University

1. $\left(\frac{e}{\pi}\right)^+ \cong \left(\frac{e}{\pi}\right)^- \cong \left(\frac{\mu}{\pi}\right)^+ \cong \left(\frac{\mu}{\pi}\right)^- \cong 10^{-4}$
2. This is independent of P_T from 1.5 to 5 GeV/c.
3. This is independent of nucleon target size.
4. This is independent of CM viewing angle.
5. This is independent of s from $\sqrt{s}$ = 7 to $\sqrt{s}$ = 53

convert these limits to mass limits because the necessary models are currently discredited.

The lack of $P_\perp$ "bumps" means there are no significant heavy objects (M from 3 → 10 GeV) decaying into <u>two leptons</u>.



ICHEP London (1974)

PLENARY REPORT

ON

PROGRESS IN GAUGE THEORIES

J Iliopoulos

Laboratoire de Physique Théorique, Ecole Normale Supérieure, Paris*

> I have won already several bottles of wine by betting for the neutral currents and I am ready to bet now a whole case that if the weak interaction sessions of this Conference were dominated by the discovery of the neutral currents, the entire next Conference will be dominated by the discovery of the charmed particles.

+ Iliopoulos DIS 2024

"All the News That's Fit to Print"

The New York Times

LATE CITY EDITION

Weather: Partly cloudy today; cool tonight. Fair, pleasant tomorrow. Temp. range: today 65-78; Thursday 64-85. Highest Temp.-Hum. Index yesterday: 75. Details on Page 66.

VOL. CXXIII . . No. 42,566 | NEW YORK, FRIDAY, AUGUST 9, 1974 | 15 CENTS

NIXON RESIGNS

HE URGES A TIME OF 'HEALING'; FORD WILL TAKE OFFICE TODAY

'Sacrifice' Is Praised; Kissinger to Remain

By ANTHONY RIPLEY
Special to The New York Times

WASHINGTON, Aug. 8—Vice President Ford praised President Nixon tonight for "one of the greatest personal sacrifices for the country and one of the finest personal decisions on behalf of all of us as Americans."

Mr. Ford, who will take office as the 38th President at noon tomorrow, vowed to continue Mr. Nixon's foreign policy and announced that Secretary of State Kissinger had agreed to stay on in the new Administration.

"I pledge to you tonight, as I will pledge to you tomorrow and in the future, my best efforts in cooperation, leadership and dedication to what's good for America and good for the world," he said.

The Vice President, who never sought the nation's highest office and disclaimed any intention of seeking it after Mr. Nixon's term, will take the oath of office in a private ceremony at the White House.

Thus will he become the first man to serve as President without being chosen by the American people in an election. Tomorrow night he will address the nation on radio and television. It is expected that he will speak at 6 P.M.

All day today the signs of the historic change were in the air, sensed by the crowds that gathered along Pennsylvania

Text of Mr. Ford's remarks appears on Page 2.

Avenue near the White House. Applause rang out from the crowds when Mr. Ford appeared briefly.

After watching Mr. Nixon on television tonight with his family, the Vice President stepped outside into a slight drizzle at his suburban split-level home in nearby Alexandria, Va., to face television cameras and photographers assembled in the street and about 100 cheering neighbors.

Speaks Outside Home

Speaking without notes or a prepared text, Mr. Ford pledged to continue the Nixon foreign policy and called the Secretary of State "a very great man" whom he has known for many

SPECULATION RIFE ON VICE PRESIDENT

Some Ford Associates Say Selecting a Successor Could Take Weeks

By CHRISTOPHER LYDON
Special to The New York Times

WASHINGTON, Aug. 8 — Potentially the most revealing and most important decision of Gerald R. Ford's Presidential debut — his choice of a successor in the Vice Presidency — was a much-discussed mystery here today.

Close friends of Mr. Ford continued to feed speculation about more than a dozen possible candidates. But none of the friends claimed to have discussed the Vice-Presidential question with Mr. Ford or to be speaking for him on it. A number of Ford associates

Vice President Ford meeting with newsmen last night

The New York Times/William E. Sauro

President Nixon on TV as he announced his resignation

United Press International

POLITICAL SCENE SHARPLY ALTERED

G.O.P. Prospects Improved, Ford in Good Spot for '76 and Watergate Fades

By R. W. APPLE Jr.
Special to The New York Times

WASHINGTON, Aug. 8—President Nixon's resignation drastically altered the American political landscape.

It improved Republican prospects for the Congressional elections in November, thrust Vice President Ford into the favorite's role for the 1976 Presidential election, ended the

Rise and Fall
Appraisal of Nixon Career

By ROBERT B. SEMPLE Jr.

The central question is how a man who won so much could have lost so much. How could a public figure who so well perceived the instincts of the majority of his countrymen have misused the powers and duties those same countrymen so eagerly ceded him?

The historians will be kept busy on these questions, but for those who spent their time observing Mr. Nixon for the last six years the answer may well be found in a phrase he often applied to himself. "At bottom," he used to say, "I

and who, on reaching his destination, was not always certain what to do when he got there—except, perhaps, to keep going.

That image has only been reinforced and deepened by the transcripts of three conversations with H. R. Haldeman on June 23, 1972, six days after the Watergate break-in, which were released on Aug. 5, and the edited transcripts of White House conversations published April 30. Whatever history's judgment of those tapes, this much was clear: Faced with mounting evi-

JAWORSKI ASSERTS NO DEAL WAS MADE

Says Nixon Did Not Ask for and Was Not Given a Way to Avoid Prosecution

By RICHARD D. LYONS
Special to The New York Times

WASHINGTON, Aug. 8—Leon Jaworski, the special Watergate prosecutor, said tonight after President Nixon's resignation speech that no deals had been either made or offered that would have given Mr. Nixon immunity from prosecution on any charges that might stem from the Watergate scan-

The 37th President Is First to Quit Post

By JOHN HERBERS
Special to The New York Times

WASHINGTON, Aug. 8—Richard Milhous Nixon, the 37th President of the United States, announced tonight that he had given up his long and arduous fight to remain in office and would resign, effective at noon tomorrow.

At that hour, Gerald Rudolph Ford, whom Mr. Nixon nominated for Vice President last Oct. 12, will be sworn in as the 38th President, to serve out the 895 days remaining in Mr. Nixon's second term.

Less that two years after his landslide re-election victory, Mr. Nixon, in a conciliatory address on national

Text of the address will be found on Page 2.

television, said that he was leaving not with a sense of bitterness but with a hope that his departure would start a "process of healing that is so desperately needed in America."

He spoke of regret for any "injuries" done "in the course of the events that led to this decision." He acknowledged that some of his judgments had been wrong.

The 61-year-old Mr. Nixon, appearing calm and resigned to his fate as a victim of the Watergate scandal, became the first President in the history of the Republic to resign from office. Only 10 months earlier Spiro Agnew resigned the Vice-Presidency.

Speaks of Pain at Yielding Post

Mr. Nixon, speaking from the Oval Office, where his successor will be sworn in tomorrow, may well have delivered his most effective speech since the Watergate scandals began to swamp his Administration in early 1973.

In tone and content, the 15-minute address was in sharp contrast to his frequently combative language of the past, especially his first "farewell" appearance—that of 1962, when he announced he was retiring from politics after losing the California governorship race and declared that the news media would not have "Nixon to kick around" anymore.

Yet he spoke tonight of how painful it was for him to give up the office.

"I would have preferred to carry through to the finish whatever the personal agony it would have involved, and my family unanimously urged me to do so," he said.

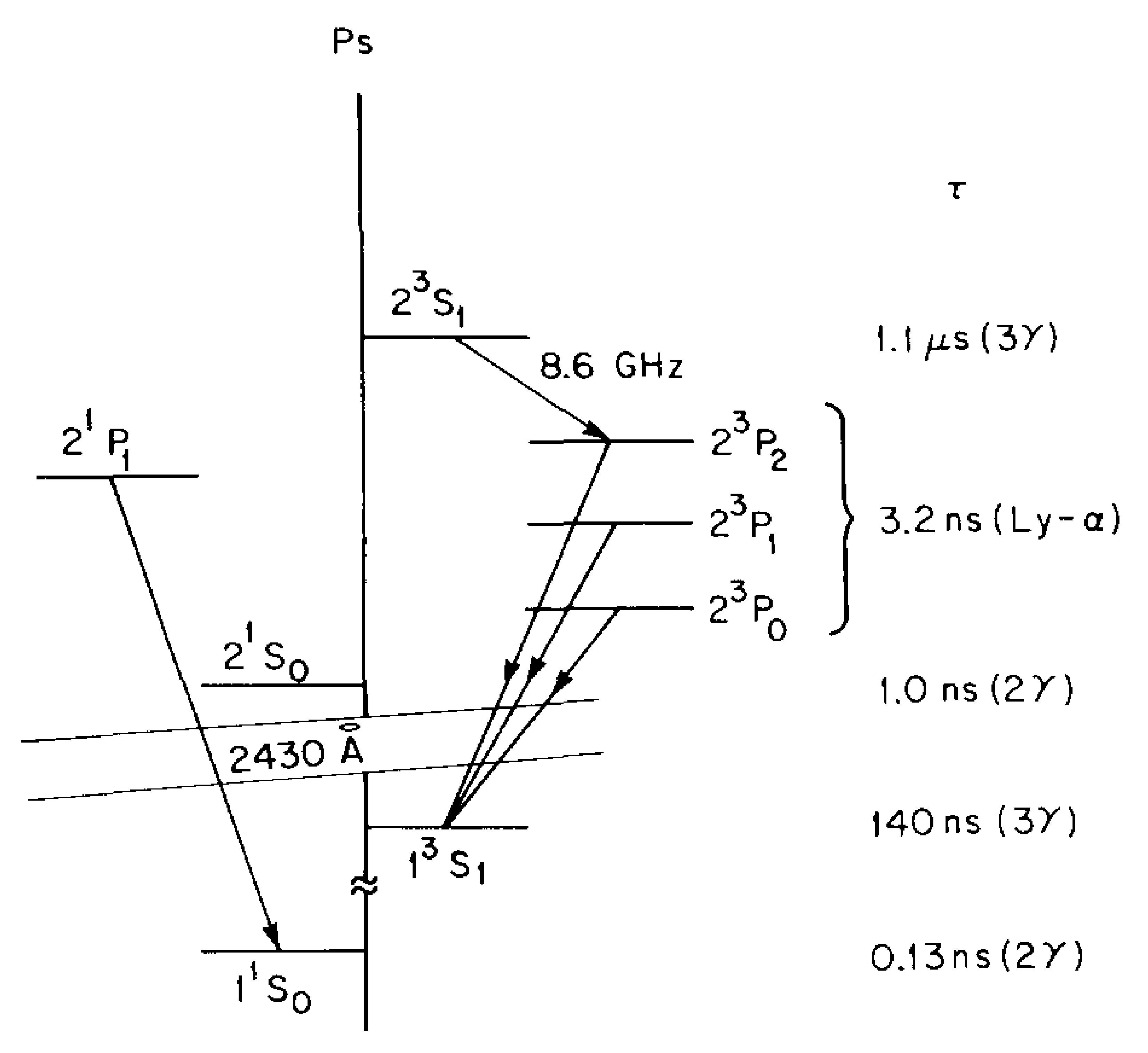
Puts 'Interests of America First'

Orthocharmonium

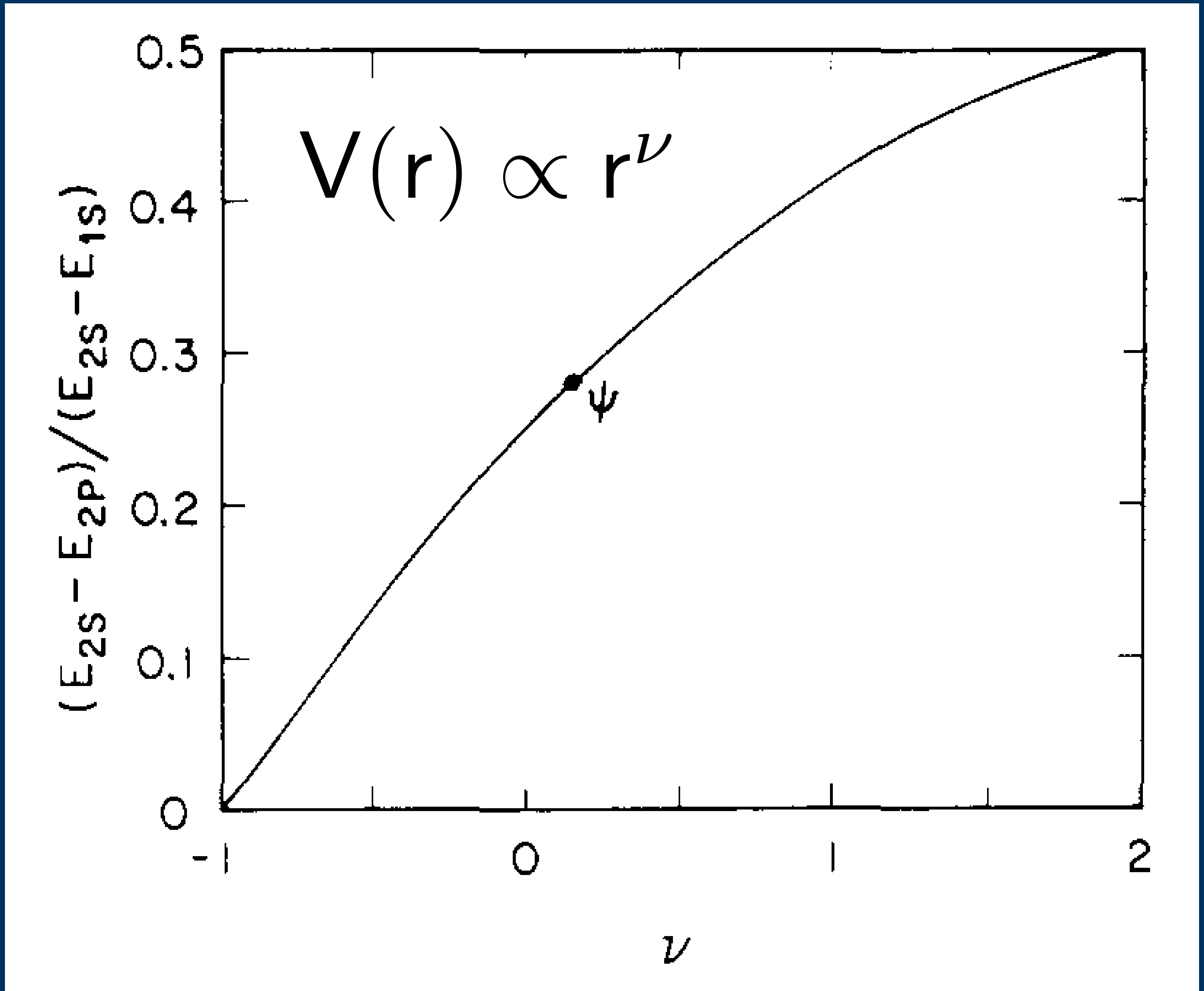
Heavy Quarks and e^+e^- Annihilation*

Thomas Appelquist† and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 November 1974)

The effects of new, heavy quarks are examined in a colored quark-gluon model. The e^+e^- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two-heavy-quark threshold, despite $\sigma_{e^+e^-}$ being a weak-coupling problem above 2 GeV. We expect spikes at the low end of this domain and a broad enhancement at the upper end.



Potential less singular than 1/r $\Longrightarrow$ 2P below 2S $\Longrightarrow$ E1 transitions



Charmonium Spectroscopy

Spectroscopy of the New Mesons*

Thomas Appelquist,† A. De Rújula, and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

S. L. Glashow§
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 11 December 1974)

The interpretation of the narrow boson resonances at 3.1 and 3.7 GeV as charmed quark-antiquark bound states implies the existence of other states. Some of these should be copiously produced in the radiative decays of the 3.7-GeV resonance. We estimate the masses and decay rates of these states and emphasize the importance of γ-ray spectroscopy.

The Spectrum of Charmonium

Spectrum of Charmed Quark-Antiquark Bound States*

E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 17 December 1974)

The discovery of narrow resonances at 3.1 and 3.7 GeV and their interpretation as charmed quark-antiquark bound states suggest additional narrow states between 3.0 and 4.3 GeV. A model which incorporates quark confinement is used to determine the quantum numbers and estimate masses and decay widths of these states. Their existence should be revealed by γ-ray transitions among them.

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

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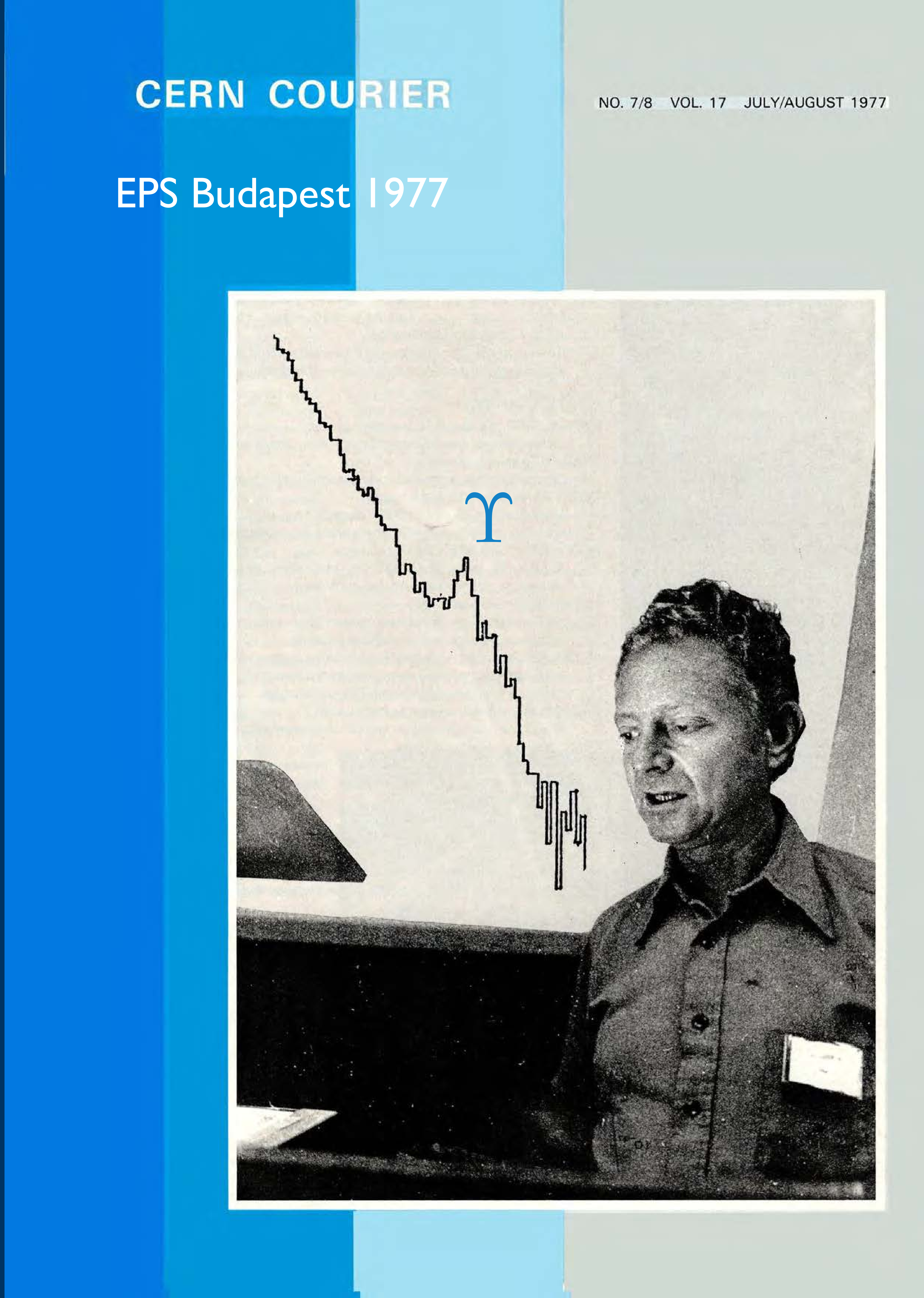
(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.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NO. 7/8 VOL. 17 JULY/AUGUST 1977
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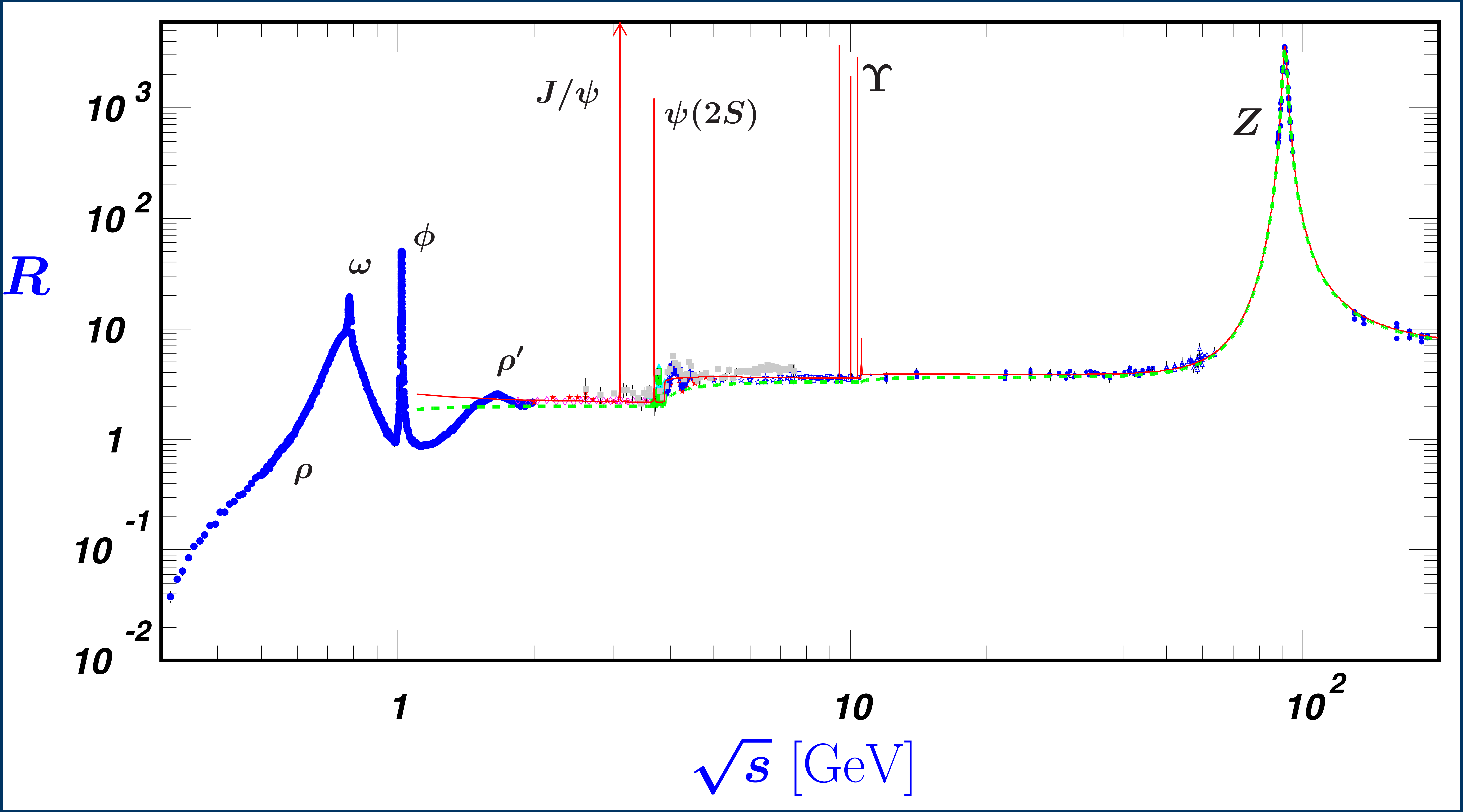
R
10^{3}
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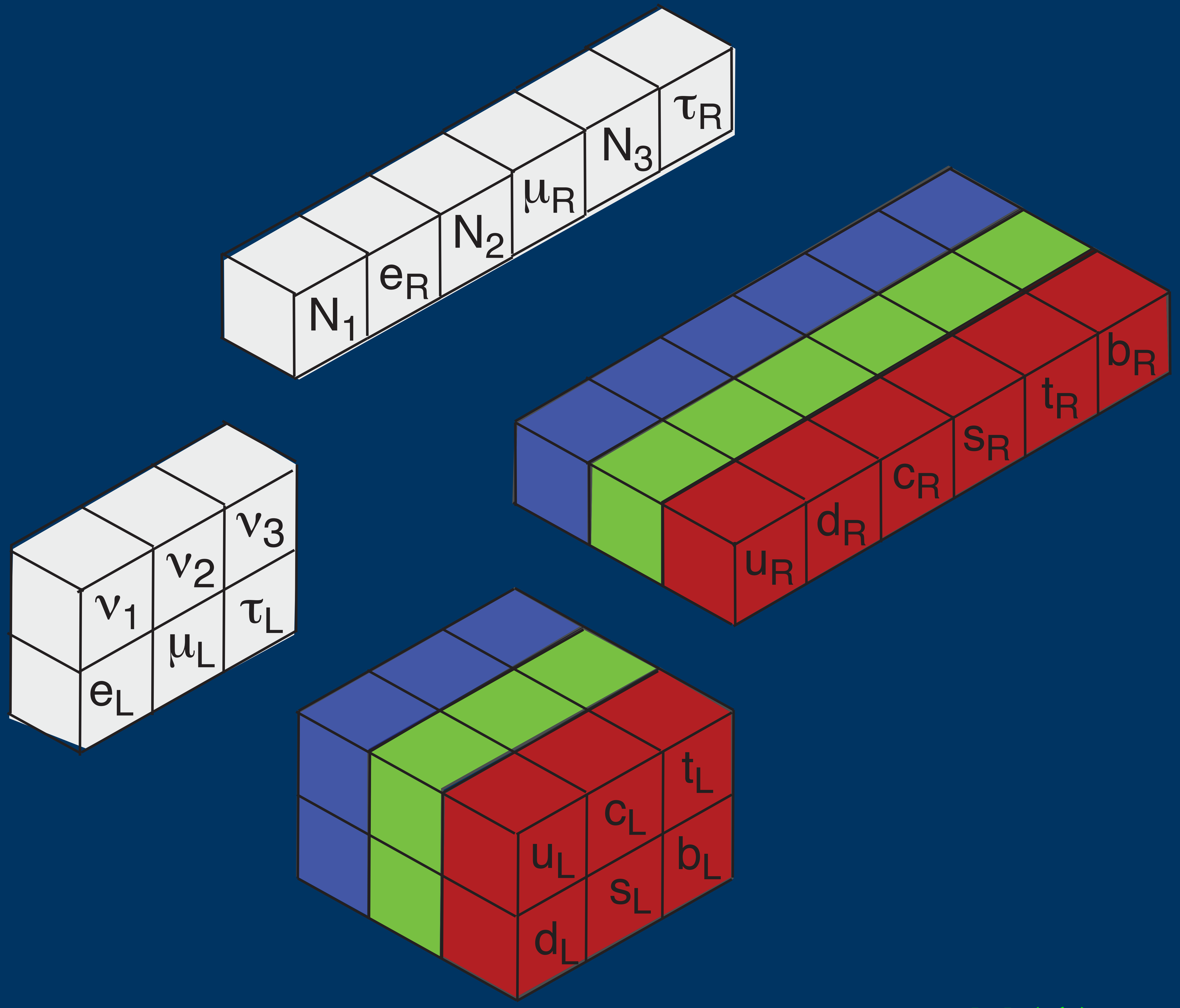
10
1
10^{-1}
10^{-2}
J/ψ
$\psi(2S)$
Υ
Z
ω
ϕ
ρ'
ρ
1
10
10^{2}
$\sqrt{s}$ [GeV]

Finding that Nature takes our ideas more seriously than we do.

There is a huge apparent distance between the equations that theorists play with at their desks, and the practical reality of atomic spectra and collision processes. It takes a certain cour age to bridge this gap, and to realize that the products of thought and mathemat ics may actually have something to do with the real world. Of course, when a branch of science is well under way, there is continual give and take between theory and experiment, and one gets used to the idea that the theory is about something real. Without the pressure of experimental data, the realization comes harder. The great thing accomplished by the discovery of the Lamb shift was not so much that it forced us to change our physical theories, as that it forced us to take them seriously. — S. Weinberg (via J. Iliopoulos)



$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$

The discovery of J/ψ launched a revolution.

The revolution is not yet ended.

bj (1934–2024)

Professor James Bjorken is one of the most broadly influential theoretical physicists of our time. His originality, backed by prodigious analytical skills, has provided ideas and frameworks that are nothing less than "enabling technologies" for many areas in nuclear and particle physics. Experimental investigations are richer and more incisive by far as a result of the directions Bjorken has set. He is a gifted teacher, not only for the legendary Bjorken & Drell volumes on quantum mechanics and quantum field theory, but also for his many inspiring lectures. He was a mentor and role model for theorists of my generation, encouraging an engagement with the raw facts of experiments as well as lofty principles, and demonstrating an intellectual courage and integrity of the highest order. His gift for stripping a problem to its essentials, capturing those in accessible physical pictures, and then creating a mathematical framework that reveals all the consequences is unmatched. His collection of conference summaries, *In Conclusion: A Collection of Summary Talks in High Energy Physics,* shows his uncanny perception and impressive range.

Bjorken's most celebrated contribution is his insight into what might be learned from highly inelastic lepton–nucleon collisions: the notion of "Bjorken scaling" that is one of the wellsprings of the parton model that set the stage for Quantum Chromodynamics, the modern theory of the strong interactions. With due acknowledgement to the gifts of Jerome Friedman, Henry Kendall, Richard Taylor, and their colleagues, it is plain that the lessons of their landmark experiments would have been drawn much more slowly had Bjorken not set the expectations and suggested insightful ways to look at the data. Once the outline of the discovery was clear, the Feynman–Bjorken dialogue showed the way to the insight that the proton is composed of small parts that behave as independent, even while they cannot be isolated from the proton. The work of Bjorken & Paschos showed how to test the conjecture that the electrically charged parts are quarks.

As theorists groped toward a field theory of the strong interactions, Bjorken was among the first to recognize that the behavior observed in deep-inelastic lepton-nucleon scattering strongly suggested copious production of pions (and other particles) at large transverse momentum in hadron-hadron collisions and in electron-positron annihilations. At the same time, he was a leader in the new study of inclusive reactions, providing many novel ideas for experimental analysis. When the states we now know as charmonium were discovered in 1974, Bjorken—a co-inventor, with Glashow, of the charmed quark—worked against a rush to (positive) judgment about the charm hypothesis, insisting that every aspect of the observations be understood before charm was implicated. In the 1980s, Bjorken turned his attention to the development of a physical picture for highly relativistic nucleus–nucleus collisions. It is no overstatement to say that his work completely recast that young field.

Bjorken's lively curiosity is further exemplified by his work on intrabeam scattering—the mutual repulsion of same-sign charged particles within accelerator beams. The resulting growth in beam emittances severely limits luminosity lifetimes in hadron colliders and compromises the performance of intense electron storage rings. Building on foundational work by Anton Piwinski and others, Bjorken and Sekazi Mtingwa gave the definitive treatment of intrabeam scattering, which was crucial for the discoveries of the top quark at Fermilab, the Higgs boson at CERN, the perfect-liquid quark–gluon plasma at Brookhaven's Relativistic Heavy Ion Collider, and is empowering many transformational discoveries in multiple disciplines at advanced light sources.

In summary, James Bjorken has profoundly influenced the development of many aspects of particle and nuclear physics. Nearly everywhere he has worked, he has helped to create a new and rich area of experimental analysis, and he has left a theoretical framework that others have mined for decades. He has enriched the scientific culture of countless colleagues. He is one of the great physicists of our day …