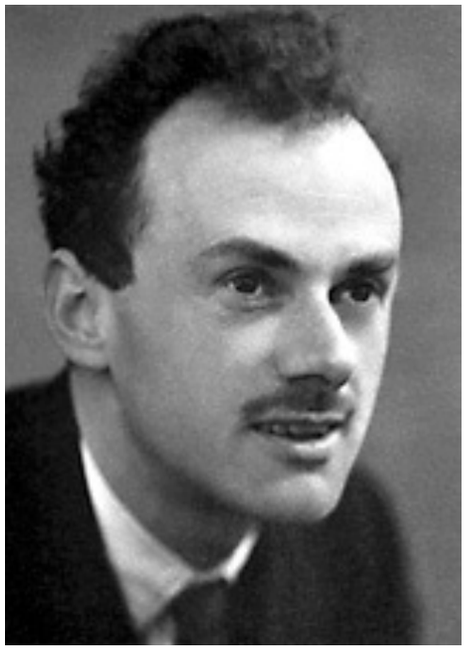
Too Beautiful to Ignore

In the honor of Pierre Fayet

Pierre Ramond
University of Florida



Dirac's

1939 James Scott Prize Lecture on

the relation between

Mathematics and Physics

Experiment and Observation

Mathematical Reasoning

Newton: Simplicity

Einstein: Mathematical Beauty

where simplicity and beauty clash ...

Opt for Beauty!

some concepts are too beautiful to ignore:

Supersymmetry 1970-1976

1939: Wigner finds two weird massless "Infinite Spin" representations with different helicity strings

$$\cdots, -\frac{5}{2}, -\frac{3}{2}, -\frac{1}{2}, +\frac{1}{2}, +\frac{3}{2}, +\frac{5}{2}, \cdots$$

?

$$\cdots, -2, -1, 0, +1, +2, \cdots$$

Supersymmetry
born on both sides of the iron curtain in 1970

from S-Matrix to Superstrings

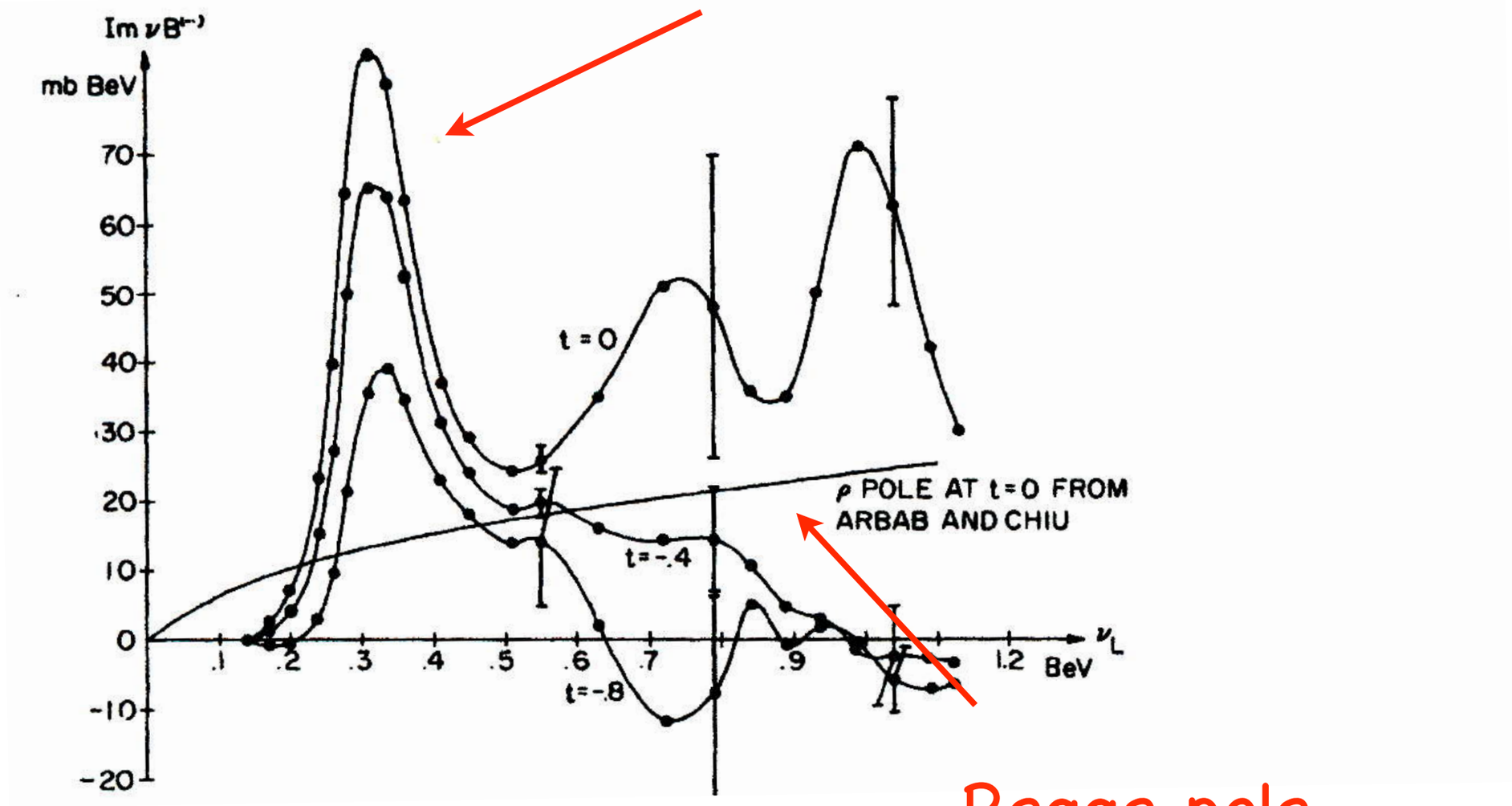
PREDICTION OF REGGE PARAMETERS OF ρ POLES FROM LOW-ENERGY πN DATA*

R. Dolen, D. Horn,† and C. Schmid
California Institute of Technology, Pasadena, California
(Received 23 June 1967)

Using finite-energy sum rules we predict important features of the Regge structure of ρ poles from low-energy πN data. The combined effect of N^* resonances in generating (via the sum rules) properties of the exchanged ρ poles is discussed, thus starting a new type of bootstrap calculation.

π - N scattering

resonances

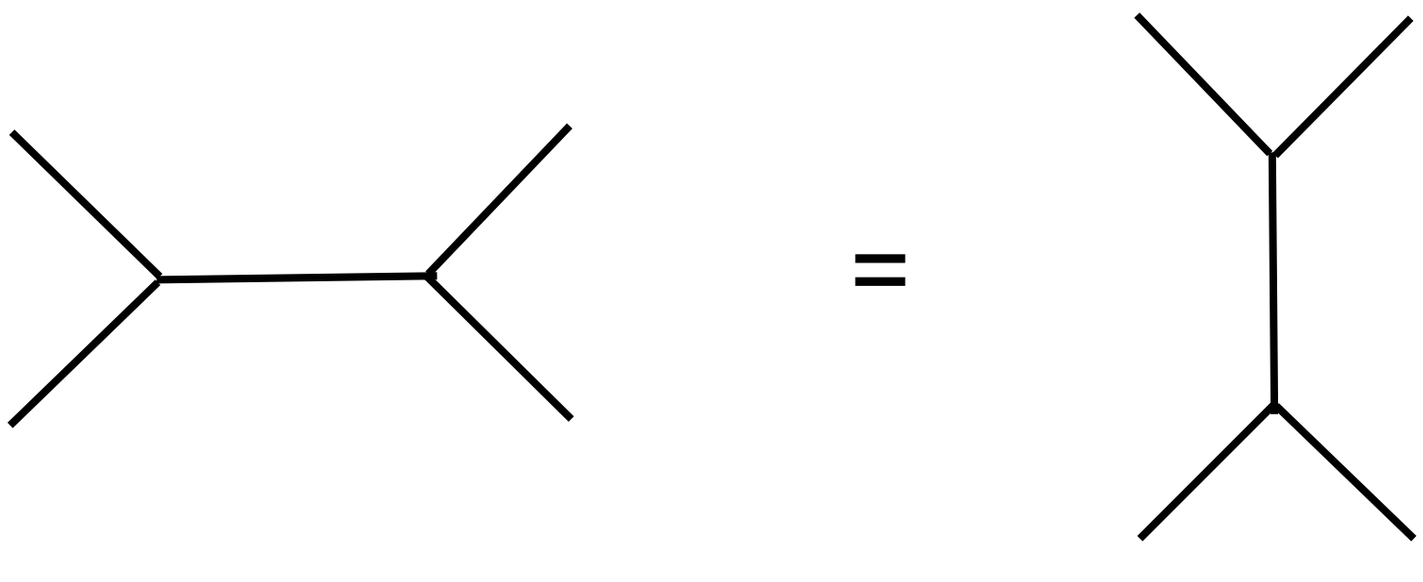


Regge pole

boson-fermion!

Veneziano Model

(bosons only)



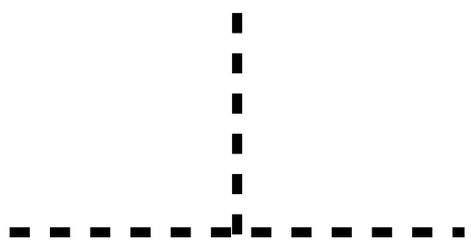
extract vertex & propagator
from amplitudes

String Model

$$\frac{1}{L_0 + m^2}$$

$$L_0 = p^2 + \text{oscillators} = P \cdot P$$

$$P_\mu = p_\mu + (\text{oscillators})_\mu$$



$$e^{ik\cdot Q}$$

$$P_\mu = \dot{Q}_\mu$$

PHYSICAL REVIEW D VOLUME 3, NUMBER 10 15 MAY 1971

Dual Theory for Free Fermions

P. RAMOND
National Accelerator Laboratory, Batavia, Illinois 60150
(Received 4 January 1971)

A wave equation for free fermions is proposed based on the structure of the dual theory for bosons. Its formal properties preserve the role played by the Virasoro algebra. Additional Ward-like identities, compatible with the equation, are shown to exist. Its solutions lie on linear trajectories. In particular, the parent is shown to be doubly degenerate, but these solutions lie on different sheets of the cut j plane.

Dirac equation $\gamma_\mu p^\mu + m = 0$

$$P_\mu = p_\mu + (\text{oscillators})_\mu$$

Generalized Dirac equation

$$\Gamma_\mu P_\mu + m = 0$$

$$\{\Gamma_\mu, \Gamma_\nu\} = \eta_{\mu\nu}$$

$$\gamma_\mu \quad \rightarrow \quad \Gamma_\mu = \gamma_\mu + \gamma_5 (\text{oscillators})_\mu$$

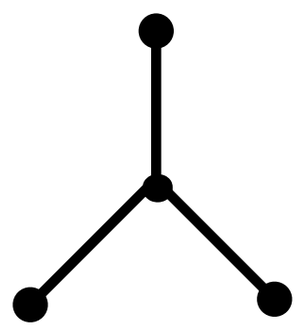
"The α's are new dynamical variables which it is necessary to introduce in order to satisfy the conditions of the problem. They may be regarded as describing some internal motion of the electron. .... We shall call them the spin variables." (Dirac)

Dirac structure requires

anticommuting oscillators with vector indices

learned much later that in D=10 space-time dimensions,
the little group vector and spinor
have the same dimension

Mercedes-Benz Dynkin diagram!



new kind of symmetry

(square root of the Virasoro algebra)

$$\{ F_n , F_m \} = 2L_{n+m} \qquad\qquad [L_n , F_m] = (2m-n)F_{m+n}$$

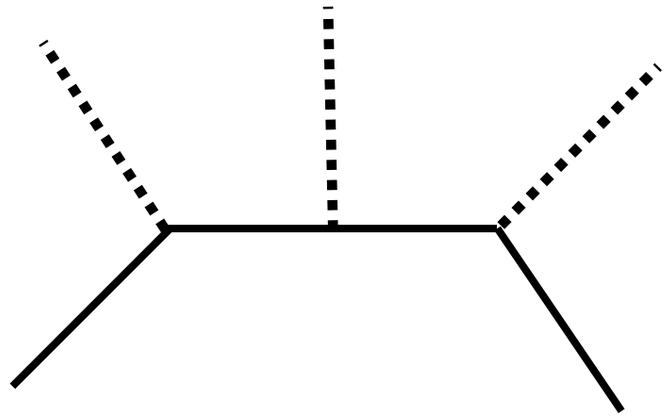
$$[L_n , L_m] = (m-n)L_{m+n}$$

L_n generate the (2-d conformal) Virasoro algebra

F_n generate 2-d superconformal algebra

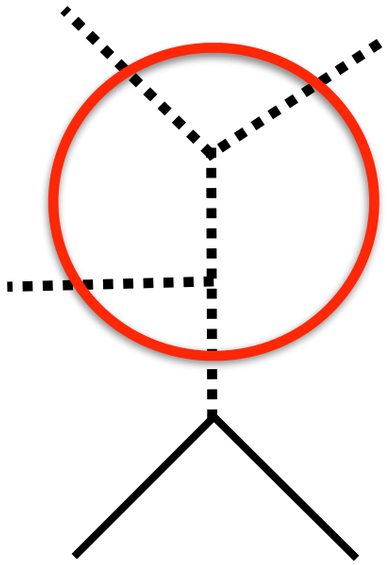
2-d supersymmetry

Superstring amplitudes



=

Dual Pion Model



fermion ⟷ boson

8.A.1

Nuclear Physics B31 (1971) 86-112. North-Holland Publishing Company

FACTORIZABLE DUAL MODEL OF PIONS*

A. NEVEU** and J. H. SCHWARZ
Joseph Henry Laboratories, Princeton University,
Princeton, New Jersey 08540

Received 25 March 1971

TACHYON-FREE DUAL MODEL WITH A POSITIVE-INTERCEPT TRAJECTORY*

A. NEVEU ** and J. H. SCHWARZ
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540, *USA*

Received 15 February 1971

A dual-reasonance model with two kinds of trajectories split by one-half unit is constructed. The lowest mass state on the leading trajectory has spin one, although the G-parity assignments are unsuitable for an identification with π's and ρ's.

7.A.1
8.A.1

Nuclear Physics B34 (1971) 632-639. North-Holland Publishing Company

FIELD THEORY INTERPRETATION OF SUPERGAUGES IN DUAL MODELS

J. -L. GERVAIS
Laboratoire de Physique Théorique et Hautes Energies, Orsay, France *

and

B. SAKITA **
Institut des Hautes Etudes Scientifiques, 91-Bures-sur-Yvette, France
and
Laboratoire de Physique Théorique et Hautes Energies, Orsay, France

Received 13 August 1971

Dual Pion Model

fermion and boson:

same theory

different boundary conditions

long soviet winters,

long soviet summers,



also lead to

supersymmetry

Berezin & Kac, 1970

Mat. Sbornik
Tom 82 (124) (1970), No. 3

Math. USSR Sbornik
Vol. 11 (1970), No. 3

LIE GROUPS WITH COMMUTING AND ANTICOMMUTING PARAMETERS

F. A. BEREZIN AND G. I. KAC

UDC 519.46

Abstract. In this paper we study analogs of Lie algebras and formal Lie groups. These analogs of groups differ from usual Lie groups, roughly speaking, in that they admit anticommuting canonical parameters. The analogs of Lie algebras differ from usual Lie algebras by properties of the commutator. In the definition of these objects an essential role is played by the gradient. In case it is trivial they become Lie groups and algebras in the usual sense. To these generalized objects we carry over classical theorems on the connection berween Lie groups and algebras and the basic representation theory.

Gol'fand & Likhtman, 1971

EXTENSION OF THE ALGEBRA OF POINCARE GROUP GENERATORS AND VIOLATION OF P INVARIANCE

Yu.A. Gol'fand and E.P. Likhtman
Physics Institute, USSR Academy of Sciences
Submitted 10 March 1971
ZhETF Pis. Red. 13, No. 8, 452 - 455 (20 April 1971)

The extension of the algebra $\mathcal{P}$ is carried out in the following manner: we add to the generators P_μ and $M_{\mu\nu}$ the bispinor generators W_α and $\bar{W}_\beta$, which we shall call the generators of spinor translations.

$$[M_{\mu\nu}, M_{\sigma\lambda}]_- = i(\delta_{\mu\sigma}M_{\nu\lambda} + \delta_{\nu\lambda}M_{\mu\sigma} - \delta_{\mu\lambda}M_{\nu\sigma} - \delta_{\nu\sigma}M_{\mu\lambda}); \quad [P_\mu, P_\nu]_- = 0;$$

$$[M_{\mu\nu}, P_\lambda]_- = i(\delta_{\mu\lambda}P_\nu - \delta_{\nu\lambda}P_\mu); \quad [M_{\mu\nu}, W]_- = \frac{i}{4}[\gamma_\mu, \gamma_\nu]_- W; \quad \bar{W} = W^+\gamma_0.$$

$$[W_\pm, \bar{W}]_+ = \gamma_\mu P_\mu; \quad [W, W]_+ = 0; \quad [P_\mu, W]_- = 0,$$

extension of space-time symmetry

posit super-invariant interaction between

Wess-Zumino and gauge multiplets

$$L(x) = (\partial_\alpha \phi^* - i g A_\alpha \phi^*)(\partial_\alpha \phi + i g A_\alpha \phi) - m^2 \phi^* \phi + (\partial_\alpha \omega^* - i g A_\alpha \omega^*)$$

$$\times (\partial_\alpha \omega + i g A_\alpha \omega) - m^2 \omega^* \omega + \frac{i}{2} \psi_1 \gamma_\alpha \overleftrightarrow{\partial}_\alpha \psi_1 - m \bar{\psi}_1 \psi_1 - g \psi_1 \gamma_\alpha \psi_1 A_\alpha$$

$$+ \frac{i}{2} \bar{\psi}_2 \gamma_\alpha \overleftrightarrow{\partial}_\alpha \psi_2 - \mu \bar{\psi}_2 \psi_2 - \frac{1}{2} (\partial_\beta A_\alpha)^2 + \frac{\mu^2}{2} A_\alpha A_\alpha + \frac{1}{2} (\partial_\alpha X)^2 - \frac{\mu^2}{2} X^2$$

$$+ g\mu (\phi^* \phi - \omega \omega^*) X - \frac{g^2}{2} (\phi^* \phi - \omega^* \omega)^2 + \sqrt{2} g (\bar{\phi}_1 \bar{s} \psi_2 \phi + \bar{\psi}_2 \overset{+}{s} \psi_1 \phi^*)$$

$$- \sqrt{2} g (\psi_1^c \bar{s} \psi_2 \omega^* + \bar{\psi}_2 \bar{s} \psi_1^c \omega) . \quad \text{(not quite correct)}$$

nobody notices

Volkov & Akulov, 1972

POSSIBLE UNIVERSAL NEUTRINO INTERACTION

D.V. Volkov and V.P. Akulov
Physico-technical Institute, Ukrainian Academy of Sciences
Submitted 13 October 1972
ZhETF Pis. Red. 16, No. 11, 621 - 624 (5 December 1972)

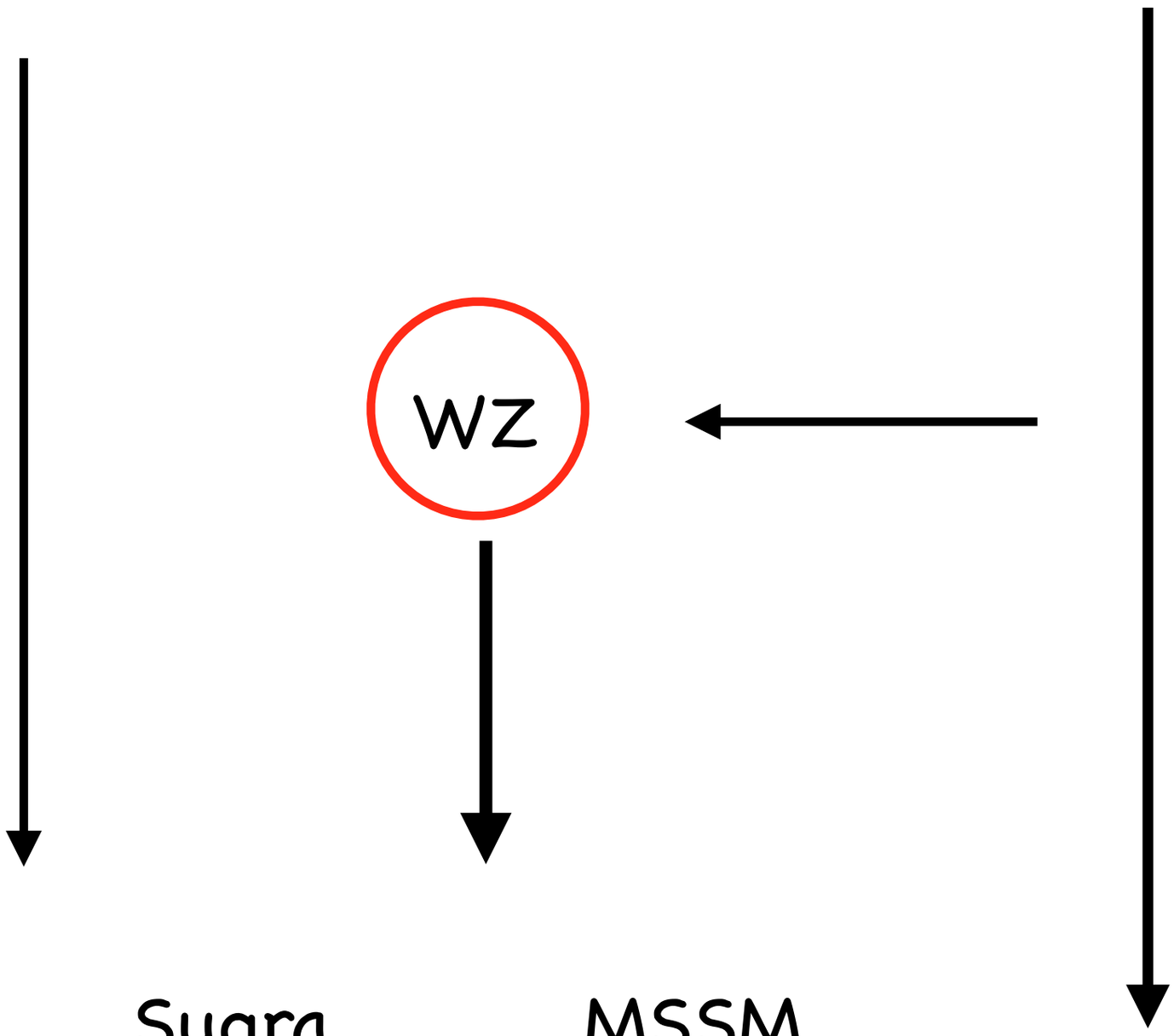
neutrino as a Nambu-Goldstone particle

$$\psi \rightarrow \psi' = \psi + \zeta \qquad x_\mu \rightarrow x'_\mu - \frac{a}{2i}(\zeta^\dagger \sigma_\mu \psi - \psi^\dagger \sigma_\mu \zeta)$$

nonlinear super σ-model

" ... if we introduce gauge fields corresponding to the(se) transformations, then as a consequence of the Higgs effect, a massive gauge field with spin 3/2 arises and the Goldstone particle with spin 1/2 vanishes"

1970 Russians Superstrings



1973

1976 Sugra MSSM

Nuclear Physics B70 (1974) 39–50. North-Holland Publishing Company

Wess & Zumino, 1973

SUPERGAUGE TRANSFORMATIONS IN FOUR DIMENSIONS

J. WESS
Karlsruhe University

B. ZUMINO
CERN, Geneva

Received 5 October 1973

from the superstring side to four dimensions

free scalar and vector supermultiplets with auxiliary fields

Wess & Zumino, 1974

Volume 49B, number 1 PHYSICS LETTERS 18 March 1974

A LAGRANGIAN MODEL INVARIANT UNDER SUPERGAUGE TRANSFORMATIONS

J. WESS
Karlsruhe University, Germany

and

B. ZUMINO
CERN, Geneva, Switzerland

Received 4 January 1974

one loop structure of WZ multiplet

no quadratic divergences — Likthman, 1975

only wave function renormalization — Källen, 1949

Super Poincaré Group

$$(\lambda, \lambda+\frac{1}{2}) \quad \overset{\text{CPT}}{+} \quad (-\lambda, -\lambda-\frac{1}{2})$$

Two helicities multiplets

Wess-Zumino
Gol'fand-Likthman

SuperGauge

SuperGravity

self-conjugate multiplets (Gell-Mann 1974)

N=4 Super Yang-Mills

$$\Big(1\Big) + 4\Big(\frac{1}{2}\Big) + 6\Big(0\Big) + 4\Big(-\frac{1}{2}\Big) + \Big(-1\Big)$$

N=8 SuperGravity

$$\Big(2\Big) + 8\Big(\frac{3}{2}\Big) + 28\Big(1\Big) + 56\Big(\frac{1}{2}\Big) + 70\Big(0\Big) + 56\Big(-\frac{1}{2}\Big) + 28\Big(-1\Big) + 8\Big(-\frac{3}{2}\Big) + \Big(-2\Big)$$

Fayet 1974

Volume 51B, number 5 PHYSICS LETTERS 2 September 1974

SPONTANEOUSLY BROKEN SUPERGAUGE SYMMETRIES AND GOLDSTONE SPINORS

P FAYET and J ILIOPOULOS
Laboratoire de Physique Théorique, Ecole Normale Supérieure, Paris, France*

Received 3 July 1974

We present a model with a spontaneously broken supergauge symmetry which results in the appearance of a massless Goldstone spinor The model combines supergauge invariance with ordinary gauge invariance After the breaking the gauge boson acquires a mass as a result of the Higgs mechanism

Super Higgs mechanism

Nuclear Physics B90 (1975) 104–124
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SUPERGAUGE INVARIANT EXTENSION OF THE HIGGS MECHANISM AND A MODEL FOR THE ELECTRON AND ITS NEUTRINO

Pierre FAYET
*Laboratoire de Physique Théorique, Ecole Normale Supérieure, Paris, France**

Received 4 December 1974

R-symmetry

neutrino as Goldstone fermion

1976

Freedman, van Nieuwenhuisen & Ferrara

PHYSICAL REVIEW D VOLUME 13, NUMBER 12 15 JUNE 1976

Progress toward a theory of supergravity*

Daniel Z. Freedman and P. van Nieuwenhuizen
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11794
S. Ferrara
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France
(Received 29 March 1976)

N=1 Supergravity

graviton-gravitino interacting theory

1976

Brink, Schwarz & Scherk

interacting N=4 SuperYang-Mills

Nuclear Physics B121 (1977) 77–92
© North-Holland Publishing Company

SUPERSYMMETRIC YANG-MILLS THEORIES *

Lars BRINK ** and John H. SCHWARZ
California Institute of Technology, Pasadena, California 91125

J. SCHERK
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris, France

Received 22 December 1976

1976

Gliozzi, Olive & Scherk

Nuclear Physics B122 (1977) 253–290
© North-Holland Publishing Company

SUPERSYMMETRY, SUPERGRAVITY THEORIES AND THE DUAL SPINOR MODEL

F. GLIOZZI * and J. SCHERK
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **

D. OLIVE
CERN, Geneva
and
The Niels Bohr Institute, Copenhagen

Received 14 January 1977

it comes full circle

supersymmetric string in ten dimensions

1976

Gildener & Weinberg

PHYSICAL REVIEW D VOLUME 13, NUMBER 12 15 JUNE 1976

Symmetry breaking and scalar bosons*

Eldad Gildener and Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 January 1976)

One possibility is that the super-strong symmetry breakdown leaves both a chiral symmetry and a supersymmetry[11] unbroken, so that there is a multiplet including massless scalars and fermions. Unfortunately, the subsequent ordinary breakdown which gives masses to the intermediate vector bosons would then produce Goldstone fermions.

gauge hierarchy

1976

Fayet

Volume 64B, number 2 PHYSICS LETTERS 13 September 1976

SUPERSYMMETRY AND WEAK, ELECTROMAGNETIC AND STRONG INTERACTIONS

P. FAYET

*Laboratoire de Physique Théorique de l'Ecole Normale Supérieure *, Paris, France*

Received 9 July 1976

Birth of the Supersymmetric Standard Model

two scalar superfields

leptons & quarks in WZ multiplets

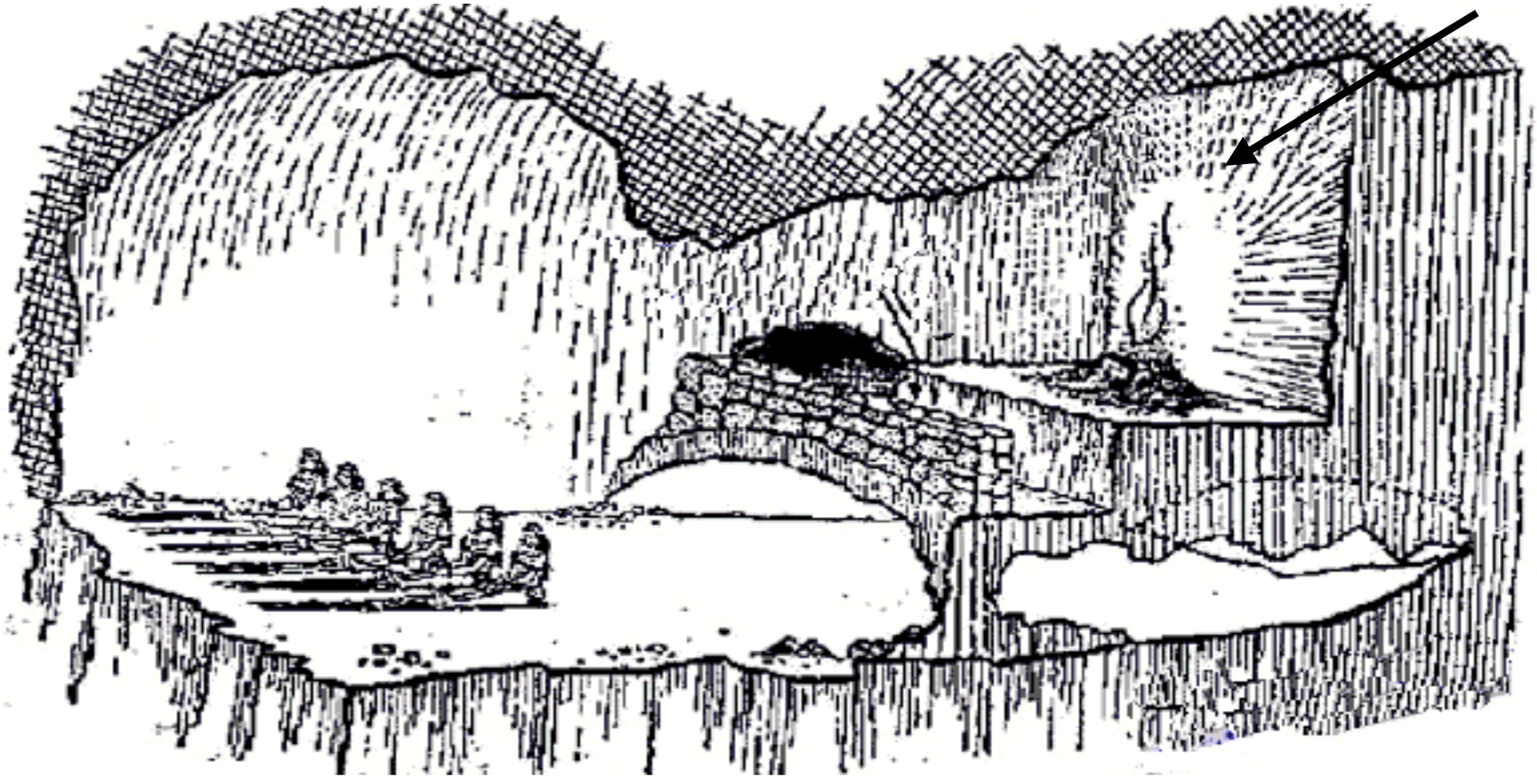
continuous R-symmetry

Superstrings still in flight



Plato's Cave

Coset Physics



Supersymmetry

too beautiful to ignore

Pierre Fayet did not!

1931

Blanche Calloway



"It Looks like Susie"

It looks like Susie

It must be Susie

I'm sure it's Susie

But I don't know

Could be Virginia

With her eyes of Blue

Could be Mary

Sweet MaryLou

But it looks like Susy

She talks like Susy

She walks like Susy

. . . . .