The Birth of Supersymmetry

(1970-1976)

Pierre Ramond

University of Florida

still alive

Supersymmetry

born on both sides

of the iron curtain

in the west

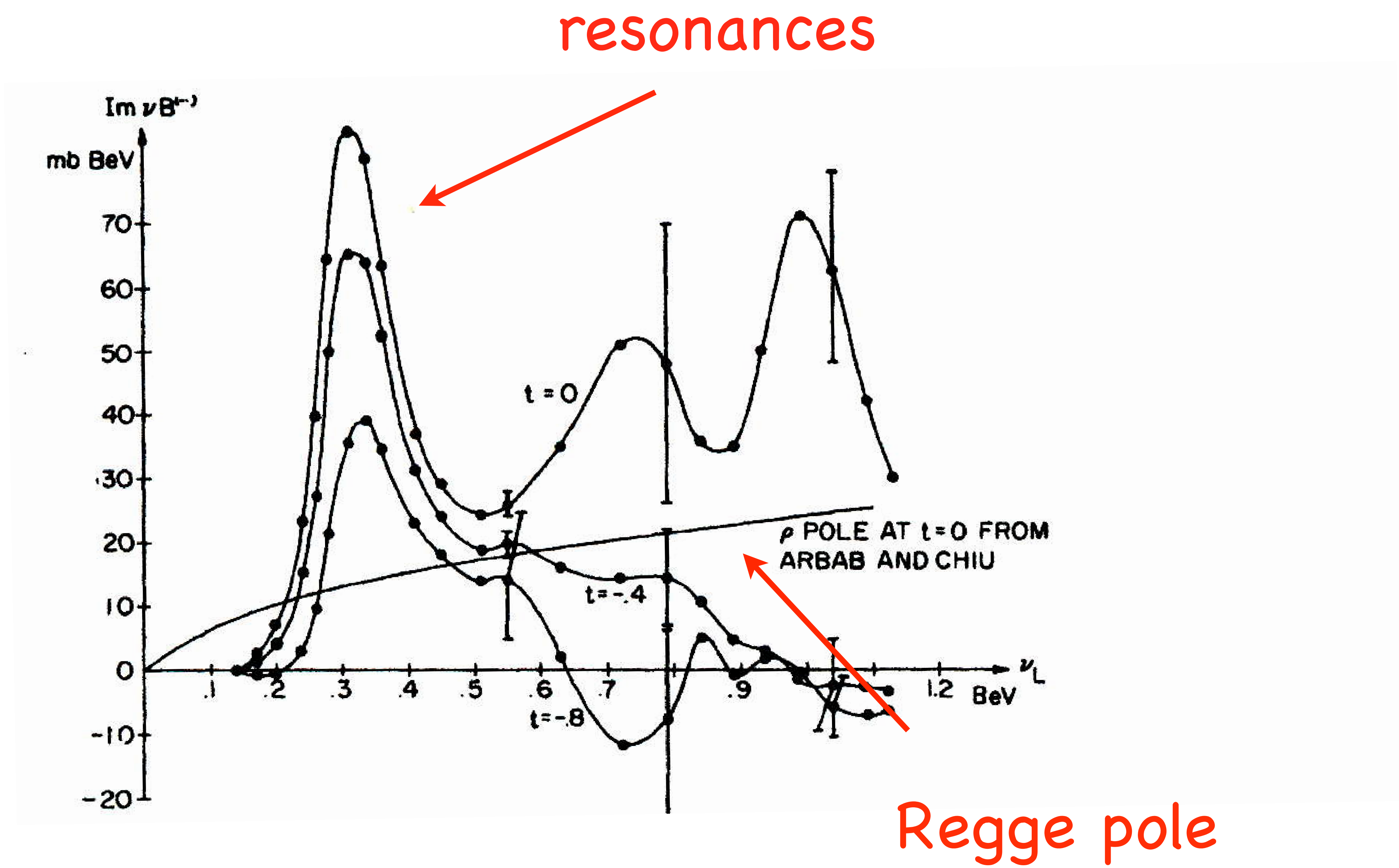
S-Matrix to Superstrings

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

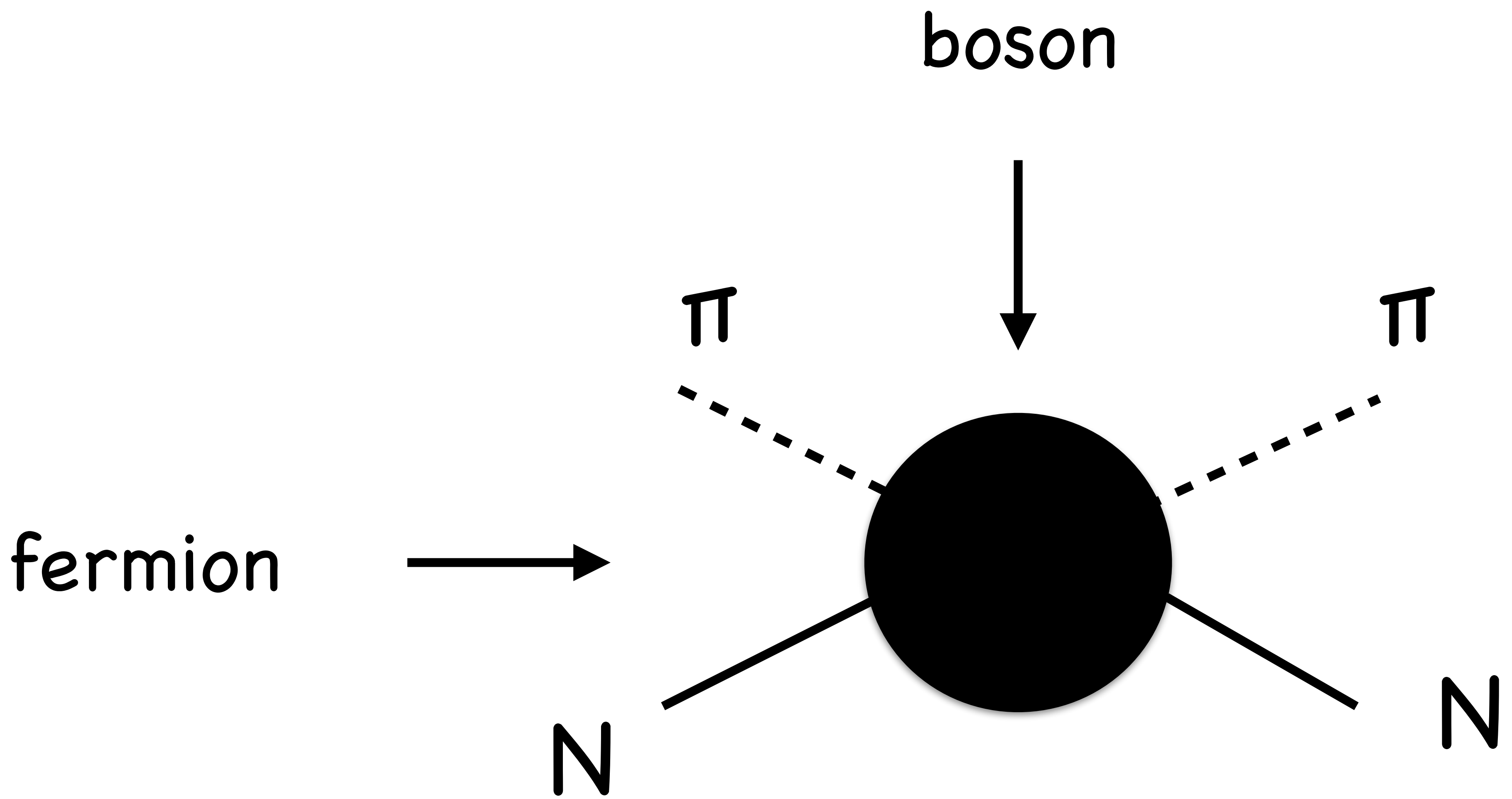
R. Dolen, D. Horn,† and C. Schmid
California Institute of Technology, Pasadena, California
(Received 23 June 1967)

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



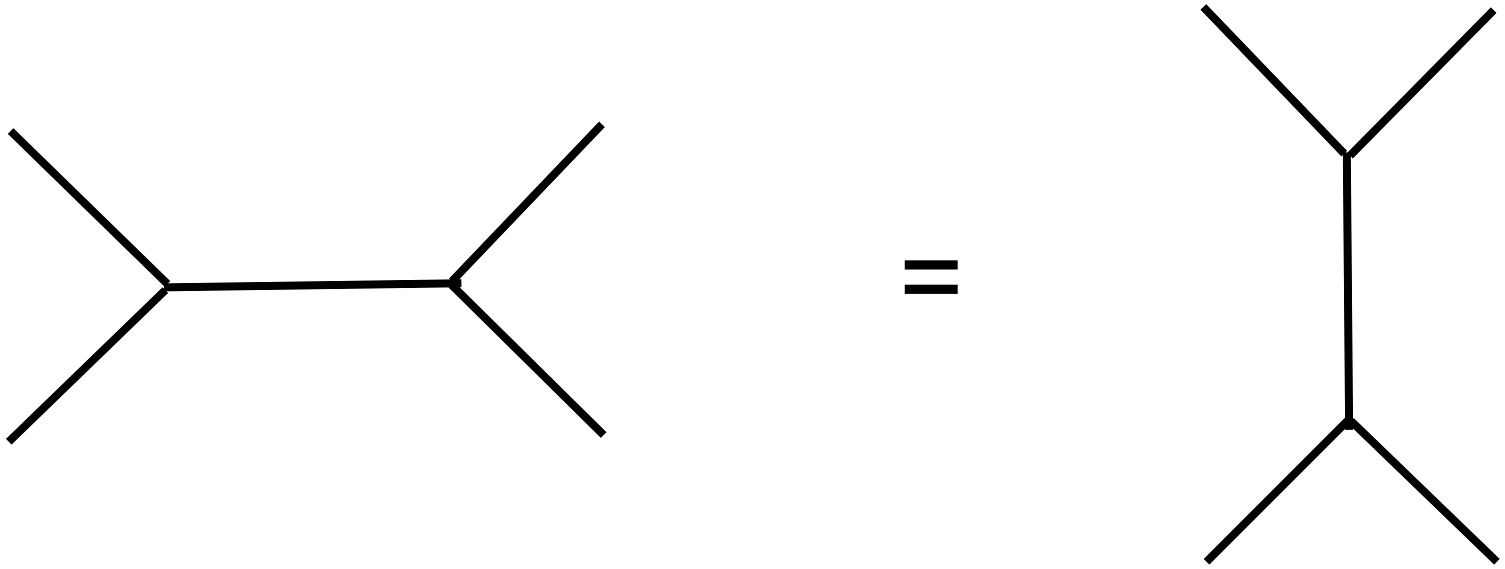
π – N scattering



fermion ⟷ boson

Veneziano Model

(bosons only)



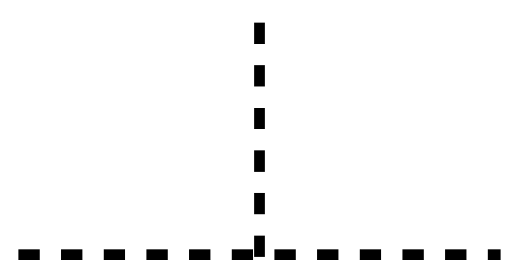
extract vertex & propagator
from amplitudes

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)

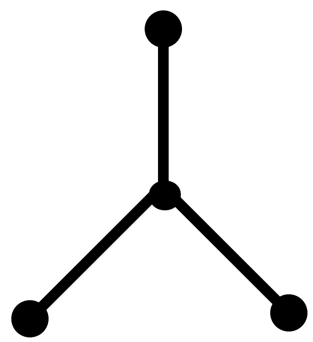
Dirac structure requires

anticommuting oscillators with vector indices!!!!

Spin-Statistics?

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

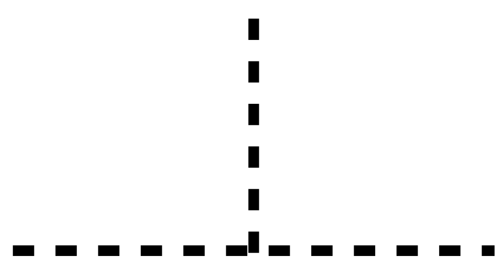
Superstring

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

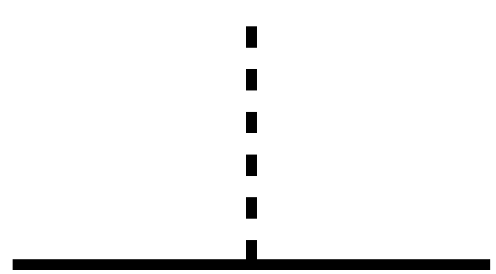
$$L_0 = p^2 + \text{oscillators} = P \cdot P$$

$$\frac{1}{F_0 + m}$$

$$F_0 = \Gamma \cdot P + m = \gamma \cdot p + \text{oscillators}$$



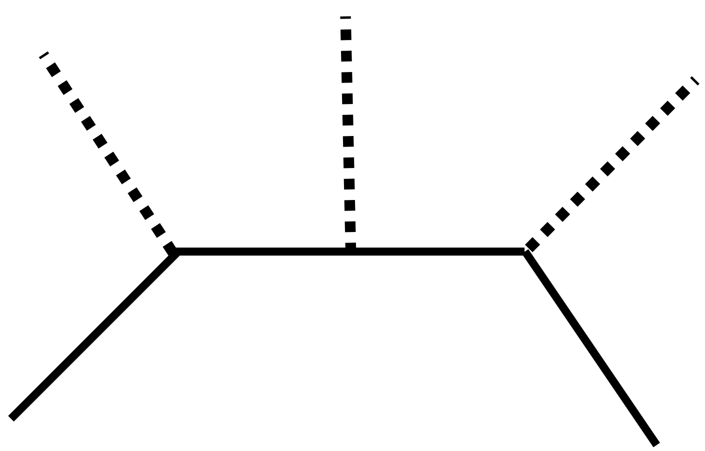
$$e^{ik \cdot Q}$$



$$\Gamma_5 e^{ik \cdot Q}$$

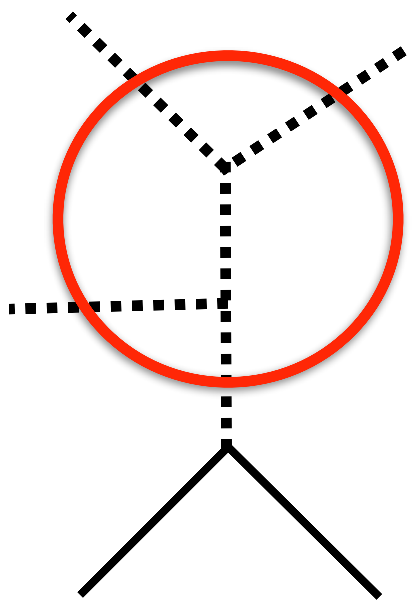
(Neveu & Schwarz)

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 sectors:

supergauges

different boundary condition

long russian winters,

long soviet summers,

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 between 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.

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

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

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

extension of space-time symmetries!

write invariant interaction between

(Wess-Zumino) and gauge supermultiplets

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

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

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

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

$$- \sqrt{2}g(\bar{\psi}_1^c \bar{s}\psi_2\omega^* + \bar{\psi}_2 \bar{s}\psi_1^c\omega) .$$

(not totally correct)

Volkov & Akulov, 1972

POSSIBLE UNIVERSAL NEUTRINO INTERACTION

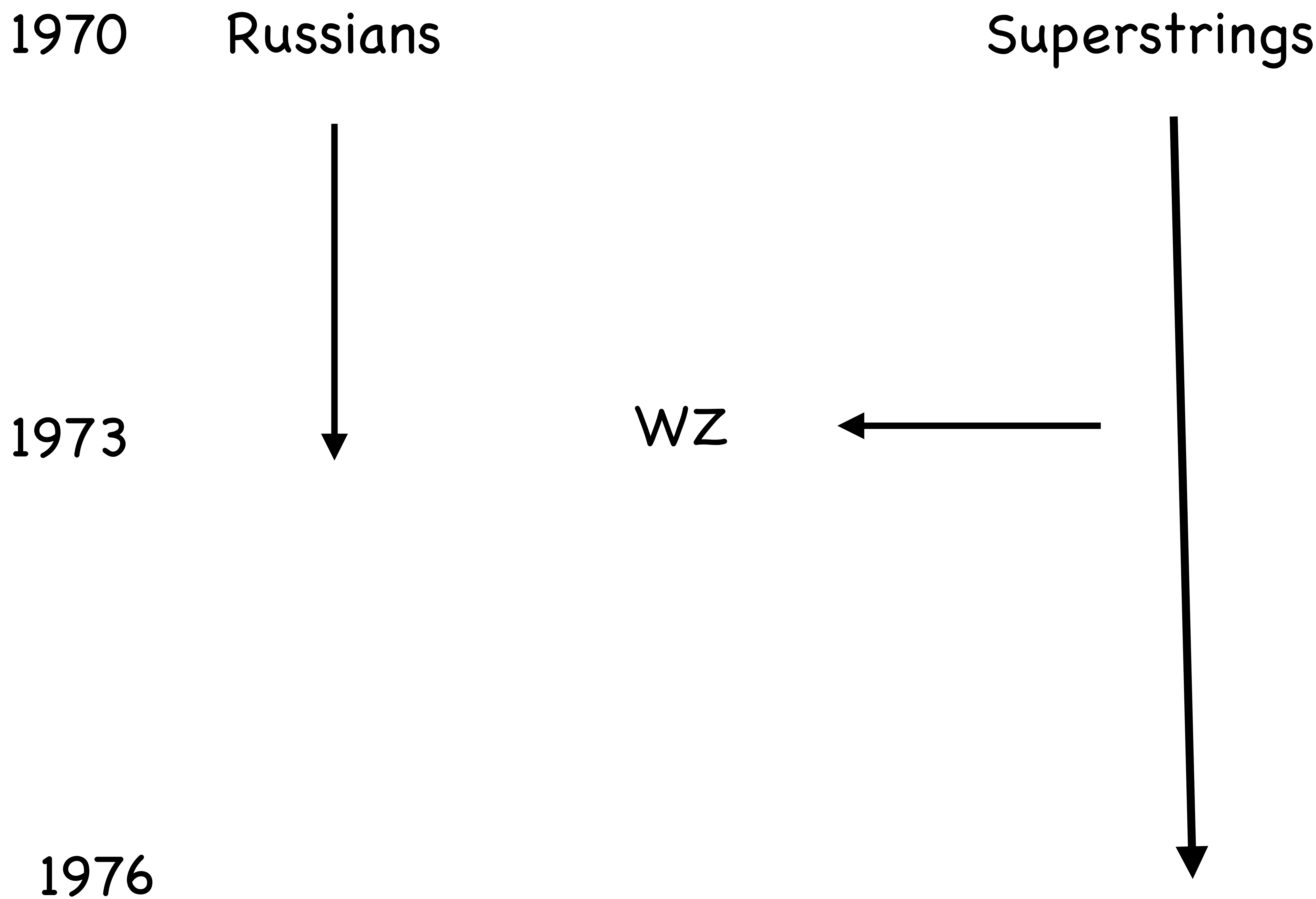
D.V. Volkov and V.P. Akulov
Physico-technical Institute, Ukrainian Academy of Sciences
Submitted 13 October 1972
ZhETF Pis. Red. 16, No. 11, 621 - 624 (5 December 1972)

neutrino as a Nambu-Goldstone particle

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

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
WZ
1976

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

SUPERGAUGE TRANSFORMATIONS IN FOUR DIMENSIONS

J. WESS
Karlsruhe University

B. ZUMINO
CERN, Geneva

Received 5 October 1973

from the superstring side to four dimensions

scalar and vector supermultiplets with auxiliary fields

no interactions

Volume 49B, number 1 PHYSICS LETTERS 18 March 1974

Wess & Zumino, 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

Fields and the Super Poincaré Group

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

CPT

Wess-Zumino multiplet
(Gol'fand&Likthman)

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

SuperGauge multiplet

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

SuperGravity multiplet

$$\Big(2\Big) + \Big(\frac{3}{2}\Big) + \Big(-\frac{3}{2}\Big) + \Big(-2\Big)$$

Gell-Mann 1974

self-conjugate multiplets

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

Nuclear Physics B90 (1975) 104–124

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

SuSy Higgs mechanism

R-symmetry

neutrino as Goldstone fermion!

1976

Ferrara, Freedman & van Nieuwenhuisen

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 and gravitino

Super Einstein tour de force!

1976

Brink, Schwarz & Scherk

N=4 SuperYang-Mills

Nuclear Physics B121 (1977) 77–92

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

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 all comes together
superstring states are space-time supersymmetric
(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 superstrong 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 paper

1976

Fayet

Volume 64B, number 2 PHYSICS LETTERS 13 September 1976

SUPERSYMMETRY AND WEAK, ELECTROMAGNETIC AND STRONG INTERACTIONS

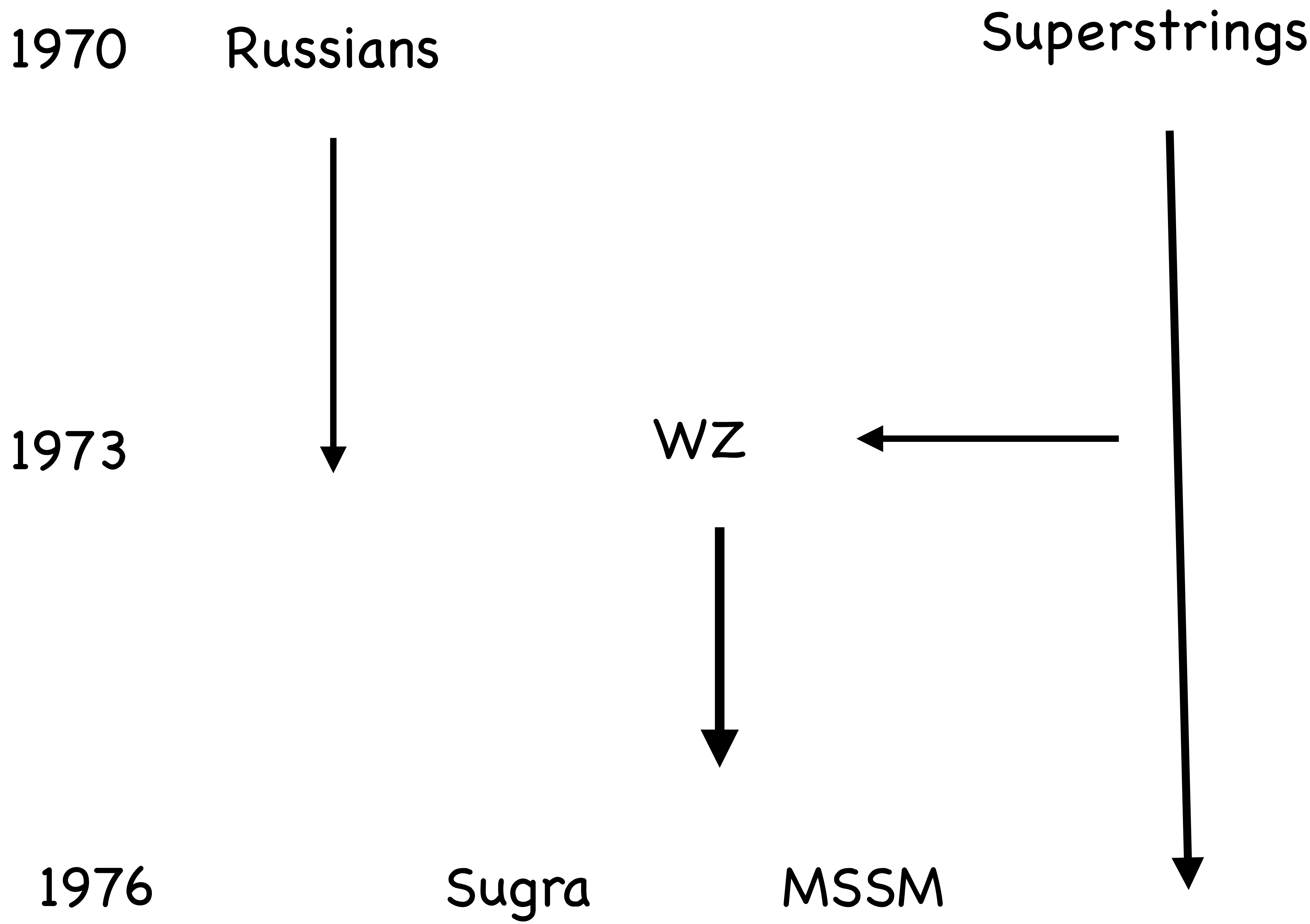
P. FAYET

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

Received 9 July 1976

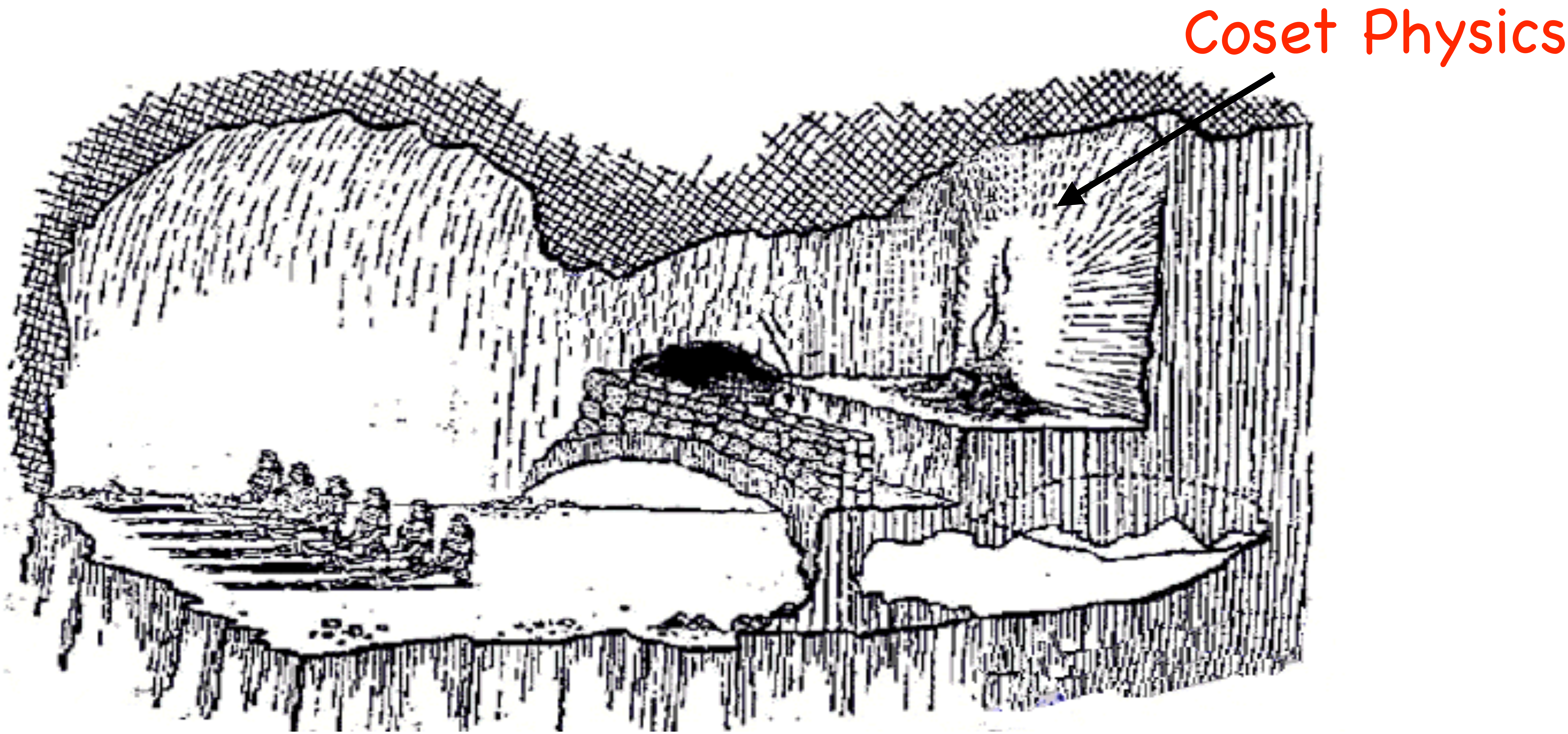
Birth of the Supersymmetric Standard Model

- require two scalar superfields
- leptons & quarks in WZ multiplets
- continuous R-symmetry


1970
Russians
Superstrings
1973
WZ
1976
Sugra
MSSM

Superstrings still in flight

Plato's Cave



paraphrasing Dirac

Supersymmetry is

too beautiful to ignore

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

. . . . .

early hint: Wigner, 1939

Representations of the Poincaré Group

massless particle representations with fixed helicity λ

$\vec{p}$	momentum	energy $E = cp$
λ	helicity	$0, \pm\frac{1}{2}, \pm 1, \pm\frac{3}{2}, \pm 2, \pm\frac{5}{2}, \cdots$

the familiar particles

Wigner: massless "Infinite Spin" representations

with different helicity strings

$\vec{p}$ momentum energy $E = cp$

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

?

λ helicity string $\cdots, -2, -1, 0, +1, +2, \cdots$

not found in Nature