On Supersymmetry Breaking

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Workshop on New Physics Paradigms after Higgs and gravitational wave discoveries

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New Physics Paradigms ?

- Gravitational waves expected from classical gravitation theory
  (GR, ~ 100 years, *classical physics completed*)

- Higgs boson: last missing ingredient in the Standard Model
  (SM, ~ 50 years, *quantum field theory completed*)

- Technological developments were needed . . . (a matter of scales)

A brilliant confirmation of existing, well-established paradigms.

> Supersymmetry: understand particle interactions from symmetries (internal and space-time) in the framework of particles and field theory

Recent results leave supersymmetry in a "mixed state":

- LHC finds the Higgs with expected mass and properties (both from SM and SUSY SM). But no "second supersymmetric particle" in data . . .

- In the middle of the "big scheme", SM plus GR in a quantum formulation.

New Physics Paradigms ?

Mixed state: [in exp. one would add PRELIMINARY, theorists don't]

Supersymmetry: nowhere in LHC, everywhere in the Big Scheme SM + GR

Or maybe: nowhere in experiments, everywhere in theory ...

However:

Open problems are much related to scales and/or very small scale ratios
And simply to values of parameters (not predicted in SM)

Algebra loves equality and zero
Not the right tool, a new paradigm needed ?

It clearly seems that symmetry considerations in trouble to provide answers,
even in principle.

New Physics Paradigms ?

Quantum field theory: a framework for quantum physics omitting gravitation.
"Off-shell": symmetry ⇒ dynamical equations ⇒ physical systems

Strings/superstrings: a framework for quantum physics including gravitation.
"On-shell": physical systems (from on-shell consistency)
⇒ quantum amplitudes ⇒ ??

Don't expect prediction power from frameworks, although important part of the understanding . . .

Any consideration on the role of supersymmetry is a discussion of supersymmetry breaking . . .

The absence of any positive signal from LHC asks to seriously reassess its role/breaking, with first-level branching:
- Forget it (not a subject)
- Work again and again . . .

New Physics Paradigms ?

Mixed state:

Supersymmetry: nowhere in LHC, everywhere in the Big Scheme SM + GR

- A problem of principle however: what would be hidden, invisible supersymmetry in physics ?
  Predictions, numbers are needed even if testing may require 50 (SM) or 100 (GR) years.

- For instance: supersymmetry invoked as a technical (stability under radiative corrections) solution for the hierarchy problem
  $M_W \ll M_{GUT}, M_{\mathrm{Planck}}, \ldots$
  Leads to a natural prediction of supersymmetric particles in the
  $10^2 - 10^3$ GeV region and to tests.   *Nice science indeed.*

- Remark (algebra does not say numbers): *(Super)symmetry does not say anything on the value $M_{GUT}, M_{\mathrm{Planck}}, \ldots / M_W$*

Anyway, back to supersymmetry breaking

Supersymmetry / breaking

From day one (1973-74), supersymmetry has been considered as broken or absent in Nature. Obvious: degeneracy of fermion–boson partners.

- 1: Was developed in the 70's without strong phenomenological implications or requirements (in the wake of the success of quantum field theories and the role of symmetries)

- 2: Considered a plausible proposal (MSSM) to approach the (technical) hierarchy problem and the stability/generation of the weak scale (~ 81)

- 3: Has been promoted at the turn of the 90's to an experimental challenge for the LHC. Also, a consequence of the slow decrease of $\sin^2 \theta_W$ (coupling unification with supersymmetry instead of without in the 70's).

Point 3 in apparent trouble, point 2 exhausted after ~ 35 years of increasingly sophisticated and often marginal studies.

Breaking supersymmetry

Since supersymmetry is at most broken, many options for breaking mechanism:

- Spontaneously broken global supersymmetry.
  Compatible with SM if $\mathcal{N} = 1 \rightarrow \mathcal{N} = 0$. Massless goldstino fermion

- Softly broken ("approximate symmetry") : no goldstino, UV properties preserved.
  Somewhat similar to quark masses w.r.t. chiral symmetry.

- Low-energy approximate symmetry, from spontaneously broken local symmetry, requires supergravity, no goldstino (in the massive spin 3/2 gravitino, super-higgs mechanism).
  Classical, exp. elusive. Or superstrings, even more exp. elusive.

- Dynamical, nonperturbative: mediation,   *a model please*

Breaking supersymmetry

- Dynamical, from extra dimensions/strings, flux-induced breaking (1985 !)

- *Accept susy partners very high in energy, use then effective techniques for low-energy (LHC or next generation) descriptions. Relevant then is the effective description of the Goldstino modes (of susy breaking, of the gravitino/gravitini)*

$\implies$ Last point: nonlinear realizations of supersymmetry again on the market Recently revived, many new results and works, an old idea

$\implies$ *An interesting link with partial breaking, or several-scale breaking (superstring-suggested)*

- Again: hidden, invisible supersymmetry ? Predictions, numbers are needed. Observables ?

Needed in general: control / maintain UV character of a susy theory . . .

Nonlinear realizations

- Nonlinear symmetries play a considerable role in effective lagrangian descriptions   (chiral lagrangians, G/H sigma models, ...)

- Nonlinear symmetries in conflict with quantum field theory, however. Generically lead to non-renormalizable models (physical cutoff then)

- Nonlinear supersymmetry already in 1973 ... (before linear susy)

- Spinors only, no superpartner. By construction, or by constraints

- Ambitious attemps at a nonlinear supersymmetric Standard Model in 83–84. Tremendous complexity.
  Mild to cold reception, facing the simplicity and the many new particles of the linear option (MSSM, starting 1981)

A way to eliminate the missing susy partners ... Any testable prediction remaining ?

Nonlinear susy, constrained superfields, old

Volkov and Akulov (1973) describe a massless neutrino as a Goldstino:

IS THE NEUTRINO A GOLDSTONE PARTICLE?

D.V. VOLKOV and V.P. AKULOV

Physico-Technical Institute, Academy of Sciences of the Ukrainian SSR, Kharkov 108, USSR

Using the hypotheses, that the neutrino is a goldstone particle, a phenomenological Lagrangian is constructed, which describes an interaction of the neutrino with itself and with other particles.

From nonlinear variation: $\quad \delta\lambda_\alpha = \epsilon_\alpha \qquad \delta x^\mu = \dfrac{ia}{2}(\lambda\sigma^\mu\overline{\epsilon} - \epsilon\sigma^\mu\overline{\lambda})$

introduce: $\quad \omega^\mu = dx^\mu - \dfrac{ia}{2}(\lambda\sigma^\mu\overline{\epsilon} - \epsilon\sigma^\mu\overline{\lambda})$

and invariant action: $\quad S = a^{-1}\displaystyle\int d^4\omega$

Nonlinear susy, constrained superfields, old

Then Ivanov, Kapustnikov, ...   and

Martin Roček rederives the VA action from a constrained chiral superfield Φ

Linearizing the Volkov-Akulov Model

Martin Roček
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 9 February 1978)

The nonlinear realization of supersymmetry of Volkov and Akulov is related to a constrained linear realization in two and four dimensions.

- Imposes: $\Phi^2 = 0$ $\Phi \overline{DD\Phi} = -4\Phi$
- The second condition indeed follows from the field equation of

$$\int d^2\theta d^2\overline{\theta}\, \overline{\Phi}\Phi + \int d^2\theta\, \Phi + \int d^2\overline{\theta}\, \overline{\Phi}$$

The lagrangian compatible with $\Phi^2 = 0$

Towards matter/gravity couplings with nonlinear susy

In three papers Stuart Samuel and Julius Wess work out a formulation of global and local nonlinear supersymmetry (83–84)

$$\frac{G}{H} = \frac{\text{Super Poincaré}}{\text{Poincaré}}$$

They attempt to construct realistic models, and to find out how to confront them to experiment

A SUPERFIELD FORMULATION OF THE NON-LINEAR REALIZATION OF SUPERSYMMETRY AND ITS COUPLING TO SUPERGRAVITY*

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A thorough investigation of the non-linear realization of supersymmetry is carried out both in flat space and in curved space (supergravity). A manageable superfield formulation is developed which allows one to evaluate the physical effects of the non-linear field when it is coupled to other multiplets. We present several interesting applications (mostly in the context of supergravity) useful in model building.

Towards matter/gravity couplings with nonlinear susy

REALISTIC MODEL BUILDING WITH THE AKULOV–VOLKOV SUPERFIELD AND SUPERGRAVITY*

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The flat-space limit of a supergravity theory involving the Akulov–Volkov field as well as other matter multiplets is found to be an ordinary renormalizable globally supersymmetric theory with explicit soft-breaking mass terms. This allows one to easily construct realistic models of nature which are analyzable at the tree and one-loop level. This is carried out for QED-like and Weinberg–Salam-like models.

Towards matter/gravity couplings with nonlinear susy

SECRET SUPERSYMMETRY[*]

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Received 26 July 1983

We present new non-linear realizations of the $N = 1$ supergravity algebra. They allow us to build interesting realistic models of the four forces of nature. These models are different from all previous ones in that particles do not appear in (broken) supersymmetric multiplets.

These new non-linear realizations also permit us to construct the effective low-energy lagrangian of an arbitrary supergravity theory in which supersymmetry is spontaneously broken. We are thus able to analyze what are the model-independent low-energy effects of supergravity. We find that the number of Higgs fields and the way they couple to quark and lepton matter is a feature which distinguishes supersymmetric theories from non-supersymmetric ones.

Towards matter/gravity couplings with nonlinear susy

In "Secret supersymmetry":

> "Since there are no supersymmetric particle states, are there any indications that the underlying theory came from a supersymmetric one? In simple models like QED, we find none. The situation is slightly different for the Weinberg-Salam model. There are no signs of supersymmetry except in the Higgs sector . . ."

The sign for supersymmetry is actually the need for (at least) two Higgs doublets, as in the standard MSSM case . . .

Hence, a second Higgs doublet could be either a hint of nonlinearly-realized supersymmetry, or simply a multi-Higgs ordinary Standard Model. The absence of further partner states does not remove the ambiguity. Not the most healthy situation, and maybe not a strong enough argument to justify a 88 TeV machine

A critical examination needed, in view of its complexity

Nonlinear susy

Supersymmetry is naturally nonlinear:
in representations $n_B = n_F$, and n_B, n_F may differ off- and on-shell.

- Off-shell representations ($N = 1, 2$): interactions create nonlinearities from auxiliary field equations (or nonabelian gauge invariance)

But nonlinearities can be compatible with renormalizability ("quantum susy").

Two types :

- Preserving degrees of freedom: nonlinearities from interactions, deformations . . .

- Eliminating some degrees of freedom: supersymmetric constraints, the chiral $\Phi^2 = 0$ of Roček (Φ a chiral $\mathcal{N} = 1$ superfield with $f_\Phi \neq 0$), and many others ...

- Second type commonly a limit of the first (infinite-mass limit).

- Goldstino : from a nonlinear deformation, first type: $\delta\psi_g = A\,\epsilon + \text{linear}$
  A: mass^2 constant

Nonlinear susy, goldstino

Generalize:
simple (algebra-preserving) deformation to turn a fermion into a Goldstino:

$$\mathcal{N} = 1: \qquad \delta\,\psi_m = A_m\,\epsilon + \delta_{linear}\,\psi_m \qquad\qquad A_m \text{ complex}$$

$$\mathcal{N} > 1: \qquad \delta\,\psi_m = A_{mi}\,\epsilon_i + \delta_{linear}\,\psi_m \qquad\qquad A_{mi} \text{ complex}$$

For $\mathcal{N} > 1$: multiplets are not always off-shell and there are more deformations than auxiliary fields   (some A_{mi} cannot be $\langle \text{Auxiliary} \rangle$)

Describe breaking patterns of extended supersymmetries which are not spontaneous (with meaning: from vev's of scalar fields of off-shell representations).

Or spontaneous, with meaning: fermions with goldstinos nonlinear variation from vacuum state of a supersymmetric theory.

- Partial breaking of $\mathcal{N} = 2$ Maxwell (APT model).

$\implies$ *Hardly visible, secret broken extended supersymmetry*

Two examples of secret (second) supersymmetry

Firstly: two chiral $\mathcal{N} = 1$ superfields S and Φ, an arbitrary function $W(\Phi)$, with lagrangian

$$\mathcal{L} = i \int d^2\theta d^2\overline{\theta} \left[-\frac{1}{4} \frac{(S + \overline{S})^2}{W_\Phi - \overline{W}_{\overline{\Phi}}} + W\overline{\Phi} - \overline{W}\Phi \right]$$

$$+ \int d^2\theta \left[\widetilde{m^2}\Phi + \widetilde{M}^2 W \right] + \text{h.c.}$$

$\mathcal{N} = 1$ supersymmetric ground state if $W_{\Phi\Phi} \neq 0$

- Actually a $\mathcal{N} = 2$ hypermultiplet theory with partial breaking

$$\delta^* \mathcal{K}_S = \frac{i}{\sqrt{2}}(\eta D\Phi + \overline{\eta D\Phi}) \qquad \delta^* \Phi = -\sqrt{2}i\,\overline{\eta D}\,\mathcal{K}_S$$

and in addition the deformation $\qquad \delta^*_{nl}\,\overline{D}_{\dot{\alpha}}\mathcal{K}_S = \sqrt{2}\,\widetilde{M}^2\,\overline{\eta}_{\dot{\alpha}}$

allows the $\widetilde{M}^2$ term in the superpotential, creates one goldstino.

[Antoniadis, Markou, JPD, 2017]

Two examples of secret (second) supersymmetry

Secondly: nonlinear (DBI) $\mathcal{N} = 2$ QED coupled to a charged hypermultiplet.

$$\mathcal{L} = \int d^2\theta d^2\overline{\theta} \left[\overline{Q}_1 Q_1 e^{V_2} + \overline{Q}_2 Q_2 e^{-V_2} + \xi_2 V_2 \right]$$

$$+ \int d^2\theta \left[\left(\frac{i}{\sqrt{2}} Q_1 Q_2 - \frac{1}{4}\xi_1 \right) X(WW) + m Q_1 Q_2 + \frac{i}{2\kappa} Y \right] + \text{c.c.}$$

[Ambrosetti, Antoniadis, Tziveloglou, JPD]

- Nonlinear $\mathcal{N} = 2$ QED: $X(WW)$ solving $WW - \frac{1}{2}X\overline{DDX} = \frac{1}{\kappa}X$

- κ: deformation parameter: gaugino in W is a goldstino

- Y: chiral, supersymmetrizes a four-form field

- There is a (string/brane - like) tadpole condition.

- Q_1, Q_2: charge hypermultiplet.

Two examples of secret (second) supersymmetry

- There is a phase which breaks the $U(1)$ gauge symmetry with unbroken (linear) $\mathcal{N} = 1$ susy

- The massive vector multiplet is built with W_α (which includes the goldstino of the second, nonlinear supersymmetry) and one chiral multiplet (Q_1 or Q_2) which includes the Goldstone boson for $U(1)$ breaking

- The second chiral multiplet is massless

- Hence:
  > super-Higgs mechanism without gravity

> New supersymmetry breaking patterns from nonlinear deformations, constraints, realizations, . . .
>
> Use for more realistic systems ?