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R-PARITY, THE SUPERSYMMETRIC STANDARD MODEL

AND THE PHENOMENOLOGY OF SUPERSYMMETRY

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ABSTRACT

The supersymmetry algebra (which does not even require the existence of fundamental bosons) cannot be used to relate directly known fermions and bosons. Nevertheless, and despite all appearances of the contrary, supersymmetry may still be an invariance of the world, if we make the assumption of the existence of new *superpartners* - squarks and selectrons, gluinos and photino, winos and zinos, etc. - for all particles. This led us to the Supersymmetric Standard Model, with two Higgs doublets for the electroweak breaking. R-parity, which distinguishes ordinary (R-even) particles from (R-odd) superpartners, is related to B and L conservation laws and may be viewed as a new reflexion symmetry in superspace - next to Parity and Time-reversal. We discuss the main features of the searches for the new "supersymmetric" particles, starting with the famous "missing-energy" signature, and the first searches for gluinos and photinos, smuons and selectrons, in 1978-79.

I. R-PARITY AS A NEW (GEOMETRICAL) DISCRETE SYMMETRY.

In physics one can define discrete symmetry operators associated with geometrical symmetries of spacetime. The parity and time-reversal symmetry operators, P and T , are associated with the **reflexion** symmetries of the space and time coordinates, respectively. These transformations may be, or not, invariances for the fundamental laws of physics. They are symmetries of the strong, electromagnetic and gravitational interactions, but not of the weak interactions, especially in the case of parity.

In the framework of supersymmetry spacetime may be extended to include an anticommuting spin- $\frac{1}{2}$ Grassmann coordinate, θ . R-parity, that we shall introduce and define more precisely later, may be viewed as a new, non-trivial, discrete symmetry operator associated with a reflexion of the anticommuting coordinate in superspace.

R-parity is non-trivial in the sense that it can actually bring constraints on Lagrangian densities (in contrast with the "trivial" fermionic reflexion symmetry operator $(-1)^{2S}$, always conserved in a rotation-invariant theory). It has, therefore, the potential of being violated, and will remain a useful symmetry even if it turns out to be violated by some of the interaction terms in the Lagrangian density. But viewing R-parity as a geometrical symmetry is only optional, and one is not obliged to use this language. All this, of course, is meaningful only in the framework of supersymmetric theories.

In section II of this paper we shall discuss why it is not possible to use the supersymmetry algebra to relate directly known bosons and fermions. In particular, the photon

cannot be related with one of the known neutrinos, but should be associated with a "neutrino" of a new type that I first called in 1976 "photonic neutrino", subsequently shortened into "photino". This led to the introduction of a rather large number of new particles. Even then one had to face problems, like the definition of conserved baryonic and leptonic numbers – that appear to us as carried by fermions only, not by bosons – and the fact that the exchanges of the new spin-0 particles introduced, now known as squarks and sleptons, might lead to new unwanted interactions.

Both problems were solved simultaneously, by attributing baryon and lepton numbers to bosons as well as to fermions (this now seems obvious, once the names of squarks and sleptons have been chosen, and their possible existence has been accepted as a reasonable hypothesis), and by forbidding unwanted spin-0 exchanges using either B and L conservation laws, or a R-parity symmetry, precisely related to the spin S and the B and L quantum numbers, as we shall see.

This led us, as discussed in section III, to the Supersymmetric Standard Model, in which R-parity emerged as the remnant of a *continuous* $U(1)$ R-symmetry for both the gauge interactions of quark, lepton and Higgs superfields, and the trilinear "superpotential" interactions responsible for quark and lepton masses, through their couplings to two different doublet Higgs superfields [1]. This continuous R-symmetry, that would in general force gluinos to remain massless, must in any case be broken, in the framework of local supersymmetry, by the gravitino mass term, which reduces the continuous R-invariance to a discrete symmetry, R-parity.

R-parity is then defined as +1 for all usual particles (including the still-undiscovered Higgs bosons) and -1 for their superpartners, squarks and sleptons, gluinos and winos, etc.. Since for ordinary particles $(-1)^{2S}$ coincides with $(-1)^{3B+L}$, R-parity may be reexpressed as $(-1)^{2S} (-1)^{3B+L}$, which exhibits clearly its intimate connection with baryon and lepton number conservation laws.

The main characteristic features essential in the phenomenology of supersymmetric theories follow from R-invariance, or, once it is broken by supergravity, of R-parity [1]:

- i) the new particles should be produced in pairs, as in, for example, $e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-$, or, also, $e^+e^- \rightarrow e^+ \tilde{e}^- \tilde{\gamma}$;
- ii) superpartners should decay, usually very fast, into lighter ones, for example $\tilde{l}^\pm \rightarrow l^\pm \tilde{\gamma}$, or $\tilde{q} \rightarrow q \tilde{g}$, etc.;
- iii) superpartner decays should ultimately give the "lightest supersymmetric particle", or LSP; this one, presumably a photino or more generally a "neutralino" (although other situations may be considered), would be massive and stable, in the case of a conserved discrete R-parity (otherwise the LSP could itself decay into ordinary particles, if R-parity turned out not to be conserved).

Experimental searches for "supersymmetric particles", discussed in section IV, started in 1978 for the gluinos and photino (work in collaboration with G.R. Farrar), soon followed by searches for smuons and selectrons in e^+e^- annihilations. Many of these searches rely on the "missing energy-momentum" carried away by the emitted photinos (or neutralinos); those are also natural candidates for the non-baryonic dark matter which might be present in our Universe.

II. HOW COULD NATURE BE SUPERSYMMETRIC ?

The supersymmetry algebra involves a self-conjugate (Majorana) spin- $\frac{1}{2}$ symmetry generator, Q , satisfying the following anticommutation and commutation relations:

$$\begin{cases} \{ Q_\alpha, \bar{Q}_\beta \} = -2 (\gamma_\mu)_{\alpha\beta} P^\mu \\ [Q_\alpha, P^\mu] = 0 \end{cases} \quad (1)$$

This algebra was introduced, in the years 1971-1973, by three different groups, with totally different motivations [2]. Gol'fand and Likhtman introduced it in the hope of explaining parity-violation in weak interactions (with their notations, the supersymmetry generator was chiral, giving the impression of a parity-violating algebra). Volkov and Akulov addressed the question "Is the neutrino a Goldstone particle?", while Wess and Zumino wrote the algebra by extending to four dimensions the "supergauge transformations" acting on the two-dimensional string worldsheet, showing how to construct renormalizable supersymmetric theories in four dimensions (in contrast with the non-linear theories of Volkov and Akulov).

II.1 The world does not seem to be supersymmetric!

The mathematical existence of an algebraic structure does not imply that it has to be an invariance of the fundamental laws of Nature. Incidentally while supersymmetry is commonly believed to "relate fermions with bosons", its algebra (1) does not even require the existence of fundamental bosons – not to speak of the superpartners that were introduced later! Using non-linear realizations of supersymmetry

a fermionic field can be transformed into a composite bosonic field made of fermionic ones; still we shall disregard this possibility, to work in the framework of renormalizable supersymmetric gauge theories [3].

Can Nature be supersymmetric? It does not look like it. Where are the physical fermions and bosons that could be related? Should supersymmetry act at the level of fundamental fields (quarks and leptons, gauge and – presumably – Higgs bosons), or of composite ones (e.g. baryons and mesons)? In any case it can only be, at best, a broken symmetry, otherwise fermions and bosons would be mass-degenerate.

The spontaneous breaking of supersymmetry was first thought not to be possible at all, since any supersymmetric state has vanishing energy and is therefore stable. Still spontaneous breaking of global supersymmetry may be possible in the presence of an abelian $U(1)$ gauge superfield [4], or using several suitably-interacting "chiral superfields" including a gauge-singlet [5], but it remains a rather exceptional situation. The breaking of local supersymmetry, considered later, in principle requires fine-tunings at an extremely high level of accuracy, to maintain a vanishing value of the cosmological constant Λ .

Even with broken supersymmetry one should still find out which fermions and bosons could be associated. One could try to relate, for example, the photon with the neutrino, or the charged W with the electron; or to use a doublet of spin-0 fields associated with a leptonic doublet as Higgs fields responsible for the electroweak breaking; or, also, to relate gluons with quarks. All these ideas were considered in the early days of supersymmetry, but they do not work. One cannot escape the conclusion that it is not possible to use supersymmetry to relate directly known particles

– bosons and fermions – together. Then supersymmetry seemed simply not to be applicable to the real world.

Before describing the way out, which led us to the construction, in 1976-1977, of the Supersymmetric Standard Model, it is useful to begin with a first attempt at a supersymmetric model of "leptons" [6], which led subsequently – through a reinterpretation of the fermions involved as belonging to a new class of particles – to the gauge-and-Higgs electroweak sector of this Supersymmetric Standard Model.

II.2 First attempt at an $SU(2) \times U(1)$ supersymmetric model.

The idea was to try to go as far as possible in attempting to relate known particles together, and construct a theory which could start looking, even partially, like a theory of electroweak interactions [6]. The aim was to:

- i) relate the spin-1 photon with a massless spin- $\frac{1}{2}$ "neutrino",
- ii) and, at the same time, to relate their charged electroweak partners, the spin-1 W 's with spin- $\frac{1}{2}$ "electrons";
- iii) to be able to define a conserved additive "leptonic number" – that we called R – a priori not an easy task in supersymmetric theories, originally constructed in terms of (self-conjugate) Majorana spinors.

We could define such an additive quantum number R by attributing one unit of it to the "electron" and the "neutrino" (and 0 to the $W^\pm$, Z and photon), the supersymmetry generator Q_α carrying one unit of R . This was realized by considering the following set of R -symmetry transformations ² :

2. These transformations originated from similar (Q) symmetry transfor-

$$V(x, \theta, \bar{\theta}) \rightarrow V(x, \theta e^{-i\alpha}, \bar{\theta} e^{i\alpha}) \quad (2)$$

for gauge superfields, and

$$S(x, \theta) \rightarrow e^{in\alpha} S(x, \theta e^{-i\alpha}) \quad (3)$$

for left-handed chiral superfields, with "R-weights" n . A product of chiral superfields has R-weight $n = \sum_i n_i$, and its last ("F") component is R-invariant if and only if $n = \sum_i n_i = 2$.

Using two doublet Higgs superfields

$$S = \begin{pmatrix} S^+ \\ S^- \end{pmatrix} \text{ (left-handed), and } T = \begin{pmatrix} T^+ \\ T^- \end{pmatrix} \text{ (right-handed),} \quad (4)$$

rather than a single one, allowed us to avoid the existence of a massless charged chiral fermion (chiral "chargino") that would have been present otherwise, as well as the appearance of γ_5 anomalies – the whole theory being vectorlike. The ratio of the two Higgs doublet vacuum expectation values defines a mixing angle, originally called δ (and now, β):

$$\tan \delta = \langle T^+ \rangle / \langle S^+ \rangle = v' / v \quad (5)$$

Today one prefers to use left-handed chiral superfields only, S and T being replaced by

$$H = \begin{pmatrix} H^+ \\ H^- \end{pmatrix}, \quad \text{and} \quad \bar{H} = \begin{pmatrix} \bar{H}^+ \\ \bar{H}^- \end{pmatrix}, \quad (6)$$

 mations imposed on an earlier 2-Higgs doublet vectorlike electroweak model already similar to a supersymmetric theory, in which the two Higgs doublets – subsequently to be described by left-handed and right-handed chiral superfields – were exchanged under parity.

both left-handed, and having opposite values of the weak hypercharge, $Y = -1$ ($+1$), with

$$\tan \beta = \langle \bar{H}^0 \rangle / \langle H^0 \rangle = v_2 / v_1 \quad (7)$$

After the electroweak breaking we got two charged Dirac fermions – then called "electron" and "heavy electron" – with the following mixing matrix (in a gaugino-higgsino basis):

$$\begin{pmatrix} 0 & m_W \sqrt{2} \sin \beta \\ m_W \sqrt{2} \cos \beta & 0 \end{pmatrix} \quad (8)$$

(One recognizes the non-diagonal part of what is now the wino mass matrix, β – defined from the ratio of the Higgs-doublet v.e.v.'s – being the same mixing angle that will appear soon in the Supersymmetric Standard Model.) β would be $\pi/4$ for unbroken supersymmetry, the two charged fermions, of mass m_W , forming with the gauge boson $W^\pm$ and a charged Higgs boson (now called $H^\pm$) a massive multiplet of supersymmetry.

Supersymmetry can be spontaneously broken using the D-term of the weak-hypercharge $U(1)$ group, the two charged fermions being split on each side of the W mass. The light "electron" (carrying "lepton number" $R = +1$) is coupled to the massless "neutrino" through a V-A charged current, while the "heavy electron" (carrying $R = -1$) is coupled to the same "neutrino" through a V+A current, the whole theory being vectorlike. This "neutrino" also appears as the massless spin- $\frac{1}{2}$ Goldstone particle associated with the spontaneous breaking of the global supersymmetry.

While having attractive features this model [6] cannot be considered very seriously, in particular since it descri-

bes only one "leptonic" sector, and disregards the quarks. In addition the "electron" and "neutrino" do not have the right electroweak quantum numbers (even if these numbers were not yet experimentally confirmed at the time). These particles will soon be reinterpreted (cf. subsection II.4) as belonging to a new class of particles, to become respectively wino and photino, in the Supersymmetric Standard Model.

II.3 A fruitful track: the way to extended supersymmetry.

In 1974-75 two neutrinos only were known, and we thought of attempting to associate the photon with both ν_e and ν_μ , with a global SU(2) or U(2) symmetry acting on these two neutrinos. (At that time the supersymmetric interaction of an N=1 Yang-Mills multiplet with an adjoint matter multiplet was not yet recognized as having N=2 supersymmetry, and it was thought that extended supersymmetric theories would not be renormalizable.) We started from a (N=1) theory very similar to the previous one, with a superpotential restricted by a continuous R-invariance (exactly as in the first paper of Ref.[5]), and exhibited a global SU(2) symmetry acting in particular on fermion pairs, one in a gauge multiplet and one in an associated matter multiplet, so that their roles could be interchanged [7]. In that way we constructed N=2 supersymmetric gauge theories (also obtained by Salam and Strathdee along similar lines [8]), describing the interactions of N=2 gauge multiplets with massless or massive N=2 matter "hypermultiplets", and studied their symmetry-breaking properties.

By choosing, in addition, massless matter (spin- $\frac{1}{2}$ - spin-0) hypermultiplets in the adjoint representation of a

Yang-Mills group, we discovered in 1976 the N=4 supersymmetric Yang-Mills theory, describing one vector, four Majorana spinors and six real scalars, in the adjoint representation of the gauge group [9]. This theory was subsequently obtained, from (super)string theories, through the dimensional reduction of a supersymmetric Yang-Mills theory in 10 dimensions [10].

But we should not forget our initial purpose of building supersymmetric theories of the real world. Unfortunately N=2 (and even more, N=4) supersymmetric theories do not present sufficient flexibility to be made realistic, at least in the usual framework of renormalizable gauge theories: renormalizable interactions are fixed by the gauge group, and there are no renormalizable superpotential interactions depending on arbitrary (super-)Yukawa coupling constants, that could be directly responsible for the known mass spectrum of quarks and leptons. Although extended supersymmetric grand-unified theories [11] would have very attractive features - especially concerning grand-unification, electroweak and supersymmetry breakings formulated with extra space dimensions (both grand-unification and supersymmetry breaking mass scales m_{GUT} and $m_{3/2}$ may be determined geometrically, from the sizes of compact dimensions [12]) - we now return to the more realistic approach of simple (N=1) supersymmetry.

II.4 The superpartners and the reinterpretation of the first supersymmetric electroweak model.

In an N=2 theory the photon might have been associated with two "neutrinos" and a "scalar photon". If we consider only one supersymmetry generator one neutrino, say ν_μ , would

be associated with a complex scalar. But why such a dissymmetry between neutrinos? Once we abandon the rather utopic idea of associating the photon with two neutrinos, the simplest and most natural possibility is to associate all neutrinos, and more generally leptons and quarks, with new spin-0 particles, "scalar leptons" and "scalar quarks", now known as *sleptons* and *squarks*. This is in fact the only possibility, if we disregard very large gauge groups, which might allow for relations of quarks and leptons with spin-1 bosons, but would still require many new spin-0 particles associated with gauge symmetry breaking.

The superpartners of the gauge bosons should also be considered as new particles. The spin- $\frac{1}{2}$ partner of the photon, which cannot be identified with ν_e , ν_μ , or even ν_τ , should be interpreted as a "photonic neutrino", which I called in 1977 "photino". At the same time the spin- $\frac{1}{2}$ partners of the gluons, an octet of self-conjugate Majorana particles, became the "gluinos", etc.³. The charged fermions associated with the W - that we already encountered in subsection II.2 - are gaugino/higgsino mixtures which should be considered as new particles named winos (or charginos), with the electroweak breaking still induced by the two Higgs doublets considered earlier. (This reinterpretation was made just after the discovery of the manifestations of a new particle [14], not yet known as the τ lepton; this one, as I suggested in 1976, could then have been considered as a light wino candidate, decaying weakly into a ν_τ identified as a photino; i.e., $e^+e^- \rightarrow \tilde{W}^+ \tilde{W}^- \rightarrow \mu^\pm e^\mp$ (+ unobserved $\tilde{\gamma} \tilde{\gamma} \nu \bar{\nu}$) .)

3. At that time colored fermions belonging to octet representations of the SU(3) gauge group were generally believed not to exist, and one could even think of using the absence of such particles as a general constraint to select admissible grand-unified theories [13].

If supersymmetry is to be an invariance of Nature, all known particles should be associated with new superpartners. One may get tempted to reject this idea of a symmetry between bosons and fermions in Nature. Indeed the necessity of associating known bosons with new fermions, and known fermions with new bosons, was often considered as an illustration of the irrelevance of supersymmetry to the description of the real world. The superpartner hypothesis (not a direct consequence of the algebra) constitutes the basis of the "Supersymmetric Standard Model" [1]. R-parity, which may be associated with a reflexion symmetry of the fermionic coordinates in superspace, distinguishes ordinary particles from their superpartners, and forbids unwanted exchanges of the new spin-0 bosons.

III. THE SUPERSYMMETRIC STANDARD MODEL.

Ordinary particles should now be associated with new superpartners: the photon with the photino, gluons with "gluinos", leptons and quarks with "sleptons" and "squarks", etc.. The supersymmetric extension of the standard model involves (at least):

- i) the 8+3+1 gauge superfields of SU(3)xSU(2)xU(1);
- ii) chiral lepton and quark superfields, describing leptons and quarks together with their spin-0 partners, sleptons and squarks (a Dirac fermion f has two spin-0 partners $\tilde{f}$, while a two-component neutrino ν_L has only one);
- iii) a pair of chiral doublet Higgs superfields, describing two Higgs doublets with their associated higgsinos; one is responsible for up-quark masses, the other for down-quark and charged-lepton masses.

III.1 The two doublet Higgs superfields and the particle content of the Supersymmetric Standard Model.

Why two doublet Higgs superfields (cf. eqs.(4-7)), rather than a single one? Introducing them (as done in the early electroweak model of 1974) allowed us to avoid the existence of a massless chiral charged fermion: in modern language, with only one Higgs doublet a linear combination of the charged *Dirac* gaugino with a two-component *chiral* higgsino would have stayed massless. Moreover these two doublets (originally described by *left-handed* and *right-handed* superfields with the same electroweak quantum numbers) involve spin- $\frac{1}{2}$ higgsinos in a vectorlike way, which avoids the introduction of γ_5 anomalies for the standard model gauge group.

These two doublets are precisely those needed to generate lepton and quark masses, through trilinear "superpotential" interactions obtained by multiplying superfields of a definite chirality [1]. H is responsible for charged-lepton and down-quark masses, but cannot provide up-quark masses, generated by $\bar{H}$. With today's notations involving only left-handed superfields, the corresponding superpotential may be written as

$$\mathcal{W} = \epsilon_{ij} [h_e H^i \bar{E}^j L + h_d H^i \bar{D}^j Q + h_u \bar{H}^j \bar{U}^i Q^j] \quad (9)$$

L and Q denoting left-handed doublet lepton and quark superfields; and $\bar{E}$, $\bar{D}$ and $\bar{U}$, left-handed singlet antilepton and antiquark superfields. Actually although I knew about this superpotential in 1976, I wrote it only the following year, to make sure it could be compatible with a *spontaneous* supersymmetry-breaking mechanism (based on an extra- $U(1)$ gauge group) – in preference to the obvious but less attractive possibility of adding soft mass terms breaking explicitly

supersymmetry; those terms would immediately solve the "vacuum stability problem" frequently encountered in supersymmetric theories (how to avoid unwanted stable vacuum states breaking charge and color) by providing large positive mass² for all squarks and sleptons.

Of course if one accepts to introduce by hand extra terms which break *explicitly* – although softly – supersymmetry (such as those discussed later in Ref.[15]) the difficulties associated with supersymmetry-breaking (to be described in subsection III.3) do not appear, and there is no need for the gauging of an extra $U(1)$. One obtains immediately a $SU(3) \times SU(2) \times U(1)$ theory with an acceptable mass spectrum, either by retaining again the old $\mu H\bar{H}$ superpotential term (which would have violated the gauged extra- $U(1)$ symmetry)⁴, which gives the "Minimal Supersymmetric Standard Model". Or by replacing this term by a trilinear coupling $\lambda H\bar{H}N$ between the two Higgs doublets and an extra singlet, N , providing us with a "next to minimal" version of the Supersymmetric Standard Model.

The minimal particle content for the Supersymmetric Standard Model is given in Table 1 (in which further mixings are still possible, after supersymmetry breaking):

4. The direct Higgs superpotential mass term $\mu H\bar{H}$ originally appeared (under a different name $m [D^c D]_F$, using "scalar multiplets" not yet described by chiral superfields) in section 4 of our first electroweak model [6]. It was then replaced, in section 5, by a trilinear coupling $\lambda H\bar{H}N$ between the two doublet Higgs superfields and an extra singlet, N . This allows in particular, with the superpotential $(\lambda H\bar{H}N + s N)$, to generate the electroweak breaking already at the classical level, with all Higgs bosons being heavy, even before (spontaneous or explicit) supersymmetry-breaking.

Table 1: Minimal content of a supersymmetric extension of the Standard Model.

Spin 1	Spin 1/2	Spin 0
gluons g photon γ	gluinos $\tilde{g}$ photino $\tilde{\gamma}$	
$W^\pm$ Z	2 (Dirac) winos $\tilde{W}_I^\pm$ 2 (Majorana) zinos $\tilde{Z}_i$	$H^\pm$ H
	1 (Majorana) higgsino $\tilde{h}^0$	h, A } Higgs bosons
	leptons l quarks q	sleptons $\tilde{l}_L, \tilde{l}_R$ squarks $\tilde{q}_L, \tilde{q}_R$

h and H ⁵ are scalar (CP-even) spin-0 bosons resulting from the mixing of the real parts of the two neutral Higgs fields described by the superfields H and $\bar{H}$. The imaginary parts also mix to give (next to the Goldstone boson eaten away by the Z) a pseudoscalar (CP-odd) particle, A , with "axionlike" couplings to leptons and quarks. This one would also be eliminated if an extra $U(1)$ were gauged to trigger spontaneous supersymmetry breaking. If one uses instead soft explicit supersymmetry-breaking terms (possibly induced by

5. The charged and neutral Higgs bosons $H^\pm$ and H were first called $w^\pm$ and z , since for unbroken supersymmetry they appear as spin-0 partners of the spin-1 $W^\pm$ and Z bosons, respectively. See also footnote 18 in Fig.1 caption.

supergravity) the extra $U(1)$ is broken explicitly (by the $\mu H\bar{H}$ superpotential term and by soft mass terms mixing the two Higgs doublets) and we get the "Minimal" Supersymmetric Standard Model; or, with an extra singlet chiral superfield N [6], a "Next to Minimal" version of it.

III.2 B and L conservation laws, R-parity, and unwanted spin-0 exchanges.

The definition of conserved baryon and lepton numbers – carried by spin-0 squarks and sleptons as well as by spin- $\frac{1}{2}$ quarks and leptons, now becomes trivial. These numbers are conserved as soon as the superpotential is constrained to include only *bilinear* terms in (anti)lepton and (anti)quark superfields (or terms which do not depend on lepton and quark superfields).

In writing the superpotential (9) responsible for quark and lepton masses we explicitly discarded other possible gauge-invariant superpotential terms that are not *bilinear* in lepton and quark superfields⁶ (or independent of them), so as to get a supersymmetric extension of the standard model with *conserved baryonic and leptonic numbers* [1]. This requirement allowed us to avoid direct exchanges of squarks and sleptons between ordinary quarks and leptons. It also follows from the requirement of R-invariance, or even of the discrete R-parity symmetry, which is not a surprise since R-parity is closely related to B and L conservation laws.

6. Such as the terms obtained by replacing, in the superpotential (9), the doublet Higgs superfield H by a leptonic doublet L , or a trilinear $\bar{U}\bar{D}\bar{D}$ quark superpotential term.

Actually R-parity-violating terms, if present, would necessarily imply a breaking of baryon and/or lepton number conservation laws, and therefore in general potential problems with proton decay (or neutrino masses), at least if both B and L violations are simultaneously allowed.

III.3 The difficulties of spontaneous supersymmetry breaking: use soft-breaking terms, or gauge an extra U(1).

Supersymmetry has special features, since the Hamiltonian, which governs the determination of the vacuum state, appears in the anticommutation relations of the algebra. A supersymmetric state has zero energy, and should therefore be stable. For this reason supersymmetry "does not like" to be broken. Nevertheless spontaneous breaking of global supersymmetry is still possible, in very particular situations, using either an abelian U(1) gauge superfield, or a set of suitably-interacting chiral superfields (with for example a continuous R-invariance to restrict the possible terms in the superpotential) [4,5].

Still it is not enough to break spontaneously supersymmetry, since we should do it so as to obtain an acceptable mass spectrum, with most of the superpartners being heavy, while fighting the natural tendency of supersymmetry to get restored (together with those of charge and color symmetries to be spontaneously broken). To illustrate these difficulties let us consider the gauge interactions of the two doublet Higgs superfields H and $\bar{H}$. Supersymmetry can be spontaneously broken thanks to the D-term associated with the weak hypercharge U(1). The massless spin- $\frac{1}{2}$ Goldstone spinor is then identical to the photino, or – in the presence of a direct Higgs superfield mass term $\mu H\bar{H}$ – to a linear combina-

tion of the photino with a neutral higgsino (although in the latter case only one Higgs doublet would acquire a non-vanishing v.e.v.) [6].

Let us now introduce quark and lepton superfields. If squark and slepton fields ($\tilde{f}$) have vanishing v.e.v.'s as they should, and if the "goldstino" is identical to the photino, the boson-fermion mass²-splittings would be proportional to (plus or minus) the electrical charge, and we would get mass relations such as

$$m^2(\tilde{f}_L) + m^2(\tilde{f}_R) = 2 m^2(f) \quad (10)$$

If the goldstino is a photino/higgsino mixture one also generates non-diagonal terms proportional to μm_f , mixing $\tilde{f}_L$ with $\tilde{f}_R$; this still leaves us with the equation

$$m^2(\tilde{f}_1) + m^2(\tilde{f}_2) = 2 m^2(f) \quad (11)$$

relating the mass of a quark or charged lepton (f) with those of its two spin-0 partners $\tilde{f}$. It is impossible to make, for example, both selectrons (or $\tilde{u}$ squarks, or $\tilde{d}$ squarks) heavy: if one mass² is large the other would have to be negative! This is an illustration of the "vacuum stability problem" frequent in supersymmetric theories. Negative mass² for squarks or sleptons signal that we are not at the minimum of the potential, and that squark and/or slepton fields should be translated. One then returns to a stable vacuum state, for which supersymmetry is restored, with charge, and possibly color symmetry, spontaneously broken ⁷ !

7. This may be done by translating, for example, $\tilde{e}_R$ – in which cases the electroweak SU(2) would also remain unbroken – or, alternatively, $\tilde{\nu}_{\mu L}$ and $\tilde{e}_L$. In all cases supersymmetry is restored, and with a wrong gauge symmetry breaking pattern.

As indicated earlier, an obvious way to prevent this and make all squarks and sleptons heavy is to add direct mass terms ⁸ breaking supersymmetry explicitly (although softly). This leads directly to the "minimal" supersymmetric extension of the Standard Model, or to one of its "non-minimal" extensions, as for example if there is an extra singlet chiral superfield N coupled to the two Higgs doublets.

Actually we were initially more ambitious, and attempted to stay, as much as possible, within the framework of spontaneously broken globally supersymmetric theories, which led us to consider the possible introduction of an extra $U(1)$ factor in the gauge group. The (diagonal) mass² terms for squarks and sleptons are in general given by [16]:

$$\begin{cases} m^2(\tilde{f}_L) = m^2(f) - [g \langle D_3 \rangle T_3 + \frac{1}{2} g' \langle D' \rangle Y] + \dots \\ m^2(\tilde{f}_R) = m^2(f) + [g \langle D_3 \rangle T_3 + \frac{1}{2} g' \langle D' \rangle Y] + \dots \end{cases} \quad (12)$$

$\langle D_3 \rangle$ and $\langle D' \rangle$ (associated with the weak isospin and weak hypercharge generators T_3 and Y) originate from the $\frac{1}{2}(D_3^2 + D'^2)$ term in the scalar potential, and ... stand for additional contributions which may arise (spontaneously) from additional neutral gauge symmetry generators, or be added explicitly as soft-breaking terms. (Mixing terms between $\tilde{f}_L$ and $\tilde{f}_R$, in general proportional to m_f , may be also generated spontaneously when the goldstino is partly described by a chiral

8. A common, universal, soft supersymmetry-breaking mass² term for all squarks and sleptons (then called μ^2) was introduced in the first paper of Ref.[1]. (Actually this term was first generated from a limit of a spontaneously broken theory, when the supersymmetry-breaking scale - not yet called $\sqrt{d} = \Lambda_{ss}$ - becomes very large, the Goldstone spinor and its bosonic partner becoming decoupled in this limit; the spin-3/2 gravitino, of mass $m_{3/2} = \kappa d / \sqrt{6}$, would then be heavy.)

superfield - as for a higgsino - but they will not modify the trace of the mass² matrix.)

In the absence of soft-breaking terms, and with $SU(3) \times SU(2) \times U(1)$ as the gauge group (or any group for which neutral generators have equal traces on left-handed and right-handed quark fields, such as $SU(5)$, $SU(5) \times U(1)_{\chi}$, $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ or $SO(10)$) we would always get, at the tree level, undesirable mass relations

$$\Sigma m^2(\tilde{q}) = 2 \Sigma m^2(q) = 2 (m_u^2 + m_d^2) \quad (13)$$

within each quark generation of the standard model (the goldstino being then a linear combination of the spin- $\frac{1}{2}$ partners of the photon and the Z , and possibly also Z' and spin-0 bosons) [1,16]. To generate large tree-level masses for all squarks and sleptons without having to rely on explicit soft-breaking terms we have been led to introduce an extra $U(1)$ gauge group, with - for example - positive (negative) couplings with usual left-handed (right-handed) quark and lepton superfields. The simplest possibility, which generates a common mass² contribution for all squarks and sleptons, is an extra $U(1)$ acting axially on all quarks and leptons ⁹, introduced in 1976. This axial $U(1)$ is similar to the one considered later in the Peccei-Quinn model (where it is only global); or to the gauge group now known as " $U(1)_\psi$ ", which appears for example in the decomposition $E(6) \rightarrow SO(10) \times U(1)$.

The drawback is that the gauging of an extra $U(1)$, with axial couplings to ordinary quarks essential to get a realistic mass spectrum, introduces anomalies, very hard to cancel while keeping an acceptable mass spectrum ¹⁰ (al-

9. More generally the extra- $U(1)$ current may be a combination of this axial current with the weak hypercharge, baryonic and leptonic currents.

though anomalous U(1)'s might now be tolerated, in the superstring framework). Moreover at the time (1976-77) much less was known about weak neutral currents, and it was reasonable to consider an extra U(1) gauge boson of mass $\approx m_Z$. Possible extra-U(1) neutral current effects are now constrained to be small, requiring the extra U(1) to be broken "at a larger scale" than the electroweak scale, using for example large Higgs singlet v.e.v.'s ¹¹ [17].

In any case, however, even the introduction of the extra U(1) to make squarks and sleptons heavy without relying on soft-breaking terms would still leave us, as we shall see now, with the question of massless or light gluinos, that did not appear to be observed experimentally. Again accepting to add soft supersymmetry-breaking gaugino mass terms, as is generally done now, provides an immediate solution to this question.

10. The new superfields that could be introduced to cancel the anomalies associated with the extra U(1) tend again to destabilize the vacuum state considered; but this might be avoided by considering, for example, a mirror sector of heavy quarks and leptons - or exotic fermions like those of an E(6) theory - that would be heavier than their spin-0 partners, in a way compatible with mass sum rules similar to (13) - now extended to include all quarks and leptons - which are valid for "traceless" gauge symmetry generators.

11. One usually thinks of extra U(1)'s Z' gauge bosons as having large masses of the order of a few hundreds of GeV/c² at least. But one may also consider lighter gauge bosons, with a small gauge coupling. A very light and very weakly coupled extra U(1) boson would not decouple, however, but it would behave very much like an axionlike pseudoscalar. Nevertheless it would not necessarily be excluded experimentally: as we indicated in 1980 (both for the spin-1 case and the axion case), the effective strength of its interactions may become arbitrarily small if the extra U(1) is broken "at a large scale" using large Higgs singlet v.e.v.'s ("invisible axion" mechanism, that became popular later) [17].

III.4 The continuous U(1) R-invariance in the Supersymmetric Standard Model, and the question of massless or light gluinos.

In our early supersymmetric model of "leptons" [6] - now reinterpreted as photinos, winos, zinos and higgsinos - a continuous U(1) R-invariance was associated with an additive conserved quantum number carried by the supersymmetry generator. This R-invariance remains a symmetry of the basic structure of the Supersymmetric Standard Model, namely the gauge interactions of the quark, lepton and Higgs superfields, and the superpotential interactions (9) responsible for quark and lepton masses [1]. It acts as follows:

$$V(x, \theta, \bar{\theta}) \rightarrow V(x, \theta e^{-i\alpha}, \bar{\theta} e^{i\alpha}) \quad (14)$$

for gauge superfields,

$$S(x, \theta) \rightarrow e^{i\alpha} S(x, \theta e^{-i\alpha}) \quad (15)$$

for left-handed (anti)quark and (anti)lepton superfields, and

$$H, \bar{H}(x, \theta) \rightarrow H, \bar{H}(x, \theta e^{-i\alpha}) \quad (16)$$

for the two doublet Higgs superfields H and $\bar{H}$. All trilinear terms selected in the superpotential (9) (although not a direct Higgs superfield mass term $\mu H\bar{H}$) have R-weight = 2 and correspond to R-invariant interactions. But, while continuous R-invariance allows for large masses for squarks and sleptons, winos and zinos, in particular, it acts *chirally* on the gluinos and photino and would in general require them to remain massless, if it were to survive supersymmetry-breaking ¹².

12. The $\mu H\bar{H}$ superpotential term, which includes a direct higgsino mass term and obviously breaks the continuous R-invariance, could not origi-

Even if (global) supersymmetry is spontaneously broken, and even if the continuous R-symmetry is not present, we still in general don't get a large mass for gluinos, since: i) no gluino mass term is present in the supersymmetric Lagrangian density; ii) none may be generated spontaneously, at the tree approximation (gluino couplings involve colored spin-0 fields, which cannot be translated); iii) a gluino mass would violate the continuous R-symmetry discussed above, which acts chirally on gluinos; in global supersymmetry it may only be generated at higher orders [18], from mass or interaction terms which do not respect this continuous R-symmetry.

Therefore the experimental searches for supersymmetric particles first concentrated on massless or light gluinos, starting with work done in collaboration with G. Farrar, in 1978 [19]. Soon we concluded that massless gluinos did not seem to exist (cf. subsection IV.1), which made more acute the question of the breaking of the continuous R-invariance down to its discrete subgroup, R-parity, that would allow for gluino masses.

III.5 Supergravity requires the breaking of continuous R-symmetry down to R-parity (allowing for large gluino masses).

Fortunately gluino masses may result directly from supergravity, as already observed in 1977 [20]. Gravitational interactions require, within local supersymmetry, that

nally be used for that purpose, since it also breaks explicitly the extra U(1) gauge symmetry that we used to trigger spontaneous supersymmetry breaking.

the spin-2 graviton be associated with a spin-3/2 partner [21], the gravitino. Since the gravitino is the fermionic gauge particle of supersymmetry it must acquire a mass, $m_{3/2}$ ($= \kappa d/\sqrt{6} \approx d/m_{\text{Planck}}$), as soon as the local supersymmetry gets spontaneously broken. This mass could be small or large, depending on the magnitude of the supersymmetry-breaking scale parameter, $\sqrt{d} = \Lambda_{\text{SS}}$ (see also footnote (8)). The mechanism by which the gravitino gets its mass has not been conclusively identified yet, although different ideas have been proposed. This mass should be considered as an arbitrary parameter, which might well determine the superpartner mass scale, and be of the order of m_W (or even up to a few TeV/c^2).

Since the gravitino is a (self-conjugate) Majorana fermion its mass breaks the continuous R-symmetry, which acts chirally on it [20], forcing us to abandon the continuous U(1) R-invariance, reduced to a discrete subgroup of R-parity transformations. We can no longer distinguish between $R = +1$ and $R = -1$ particles, but only between "R-even" and "R-odd" ones, i.e. between particles with R-parities $+1$ and -1 . R-parity is defined as $+1$ for ordinary particles, and -1 for their superpartners. Its connection with baryon and lepton numbers originates from the fact that we did not want to allow all possible gauge-invariant terms in the superpotential, and chose to select only terms that were bilinear in lepton and quark superfields (or independent of them) [1]. This connection of R-parity with B and L can be made obvious since for usual particles, the "fermion number" can be defined as $3B + L$, so that $(-1)^{2 \text{ spin}}$ coincides with $(-1)^{3B+L}$; this leads to a simple redefinition of R-parity in terms of the spin S and of a "matter-parity", as follows [19]:

$$\text{R-parity} = (-1)^R = (-1)^{2S} (-1)^{3B+L} \quad (17)$$

which may also be rewritten as $(-1)^{2S} (-1)^{3(B-L)}$. This shows that R-parity may be present even if baryon and lepton numbers are separately violated, as long as their difference (B-L) remains conserved, even only modulo 2.

The conservation of baryon and lepton numbers necessarily implies R-parity conservation. R-parity might still be violated by additional interactions introduced in the superpotential; but such violations, if allowed, are generally paid by unwanted processes¹³, if R-odd products of three quark-or-lepton superfields, in particular, are allowed in the superpotential.

In a general way, and irrespectively of the supersymmetry-breaking mechanism considered, one normally expects superpartners not to be too heavy, otherwise the corresponding new mass scale could contaminate the W mass scale, and would create a new hierarchy problem in the electroweak theory. Superpartner masses are therefore generally expected to be of the order of m_W , or $\approx$ TeV scale at most. This natural expectation is independent of the consideration of other large scales, like the grand-unification scale or the Planck scale. One hopes, in addition, that supersymmetry could help solving the hierarchy problems associated with the two latter scales, provided, again, that superpartner masses are $\lesssim$ TeV scale.

13. Like a much too fast proton decay $p \rightarrow \pi^0 e^+$ mediated by R-odd $\tilde{d}_R$ squark exchanges, if B and L violations are allowed simultaneously; or too large neutrino masses, ..., if L-violations are allowed so that ordinary neutrinos can mix with higgsinos and gauginos.

More specifically in the framework of supergravity it is also natural to assume that the gravitino mass $m_{3/2}$ could fix the magnitude of the supersymmetry-breaking in all boson-fermion multiplets; squarks and sleptons, as well as gluinos, could then have masses of the same order as the gravitino mass $m_{3/2}$, itself also expected in the same ($\approx m_W$ to TeV/c^2) mass scale region¹⁴. The required soft supersymmetry-breaking terms needed to make the superpartners heavy can indeed be generated from supergravity, with an additional "hidden sector" of particles coupled with gravitational strength (see for example Ref.[3] and references therein).

IV. SUPERPARTNER SEARCHES AND THE PHENOMENOLOGY OF SUPERSYMMETRY.

The main characteristic features essential in the phenomenology of supersymmetric theories, identified in 1977, follow from R-invariance or simply R-parity conservation, as illustrated for example in Fig.1:

- i) the new particles should be produced in pairs, as in $e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-$ (or $e^+e^- \rightarrow \gamma \tilde{\gamma} \tilde{\gamma}$, etc.);
- ii) superpartners should decay, usually very fast, into lighter ones, for example $\tilde{l}^\pm \rightarrow l^\pm \tilde{\gamma}$, or $\tilde{q} \rightarrow q \tilde{g}$, etc.;
- iii) superpartner decays should ultimately give the "lightest supersymmetric particle", or LSP; this one (presumably a photino, or more generally a "neutralino", although other possibilities may be considered) would be massive and

14. The possibility of having a heavy gravitino of mass $\approx m_W$ (which is equivalent to a large "supersymmetry-breaking scale" $\sqrt{d} = \Lambda_{ss} = (m_W m_{\text{Planck}})^{1/2}$), with $m_{\tilde{g}, \tilde{l}} = m_{3/2} = m_W$, was already anticipated in 1979 (footnote 4 in Ref.[22]), before such models were explicitly constructed, three years later.

stable, in the case of a conserved R-parity; it is expected to be only weakly interacting with matter, through squark (or selectron) exchanges.

Experimental searches for gluinos and photinos in hadronic interactions started in 1978, soon followed by searches for smuons and selectrons in e^+e^- annihilations. Most searches rely in particular on the "missing energy-momentum" carried away by the emitted photinos (or neutralinos); those are also natural candidates for non-baryonic dark matter in our Universe.

IV.1 First searches for gluinos.

Gluinos, which might have been massless or light in a significant class of supersymmetric theories, could have been copiously produced in strong-interaction reactions, and were the first of the new particles searched for experimentally [19]. The pair-production of gluinos was expected to lead, after the decays, to a pair of photinos (or goldstinos/gravitinos).

Photinos would have rather weak interactions with matter, essentially through squark exchanges (cf. Fig. 1c), with cross-sections $\approx \alpha^2 s / m_{\tilde{q}}^4$ (or $\alpha \alpha_s s / m_{\tilde{q}}^4$, for photinos having enough energy to reexcite a gluino in the final state) [1,23]. As a result photinos would most of the time remain undetected, carrying away missing energy-momentum – the famous "missing energy" signature of supersymmetry – although one can also look for their reinteractions in beam-dump experiments.

Gluinos may combine with quarks, antiquarks and gluons to give new color-singlet hadronic states called R-hadrons (R-baryons $\tilde{g}qqq$ being *bosons*, and R-mesons $\tilde{g}q\bar{q}$ *fermions*).

Searches for light gluinos were first discussed by G. Farrar and the author [19] using the results of beam-dump experiments, or the search for missing energy in a fixed-target calorimetry experiment [24] performed at Fermilab with a 400 GeV/c proton beam ($\sqrt{s} \approx 27$ GeV). The results indicated that R-hadrons had to be heavier than about $1\frac{1}{2}$ or 2 GeV/c², pointing in the direction of massive gluinos. Gluinos are necessarily massive, anyhow, as soon as gravitation is introduced, as pointed out in 1977; they could naturally be heavy, like the gravitino, if the "supersymmetry-breaking scale" $\sqrt{d}$ is very large.

Further beam-dump experiments at CERN and Fermilab provided limits on the production cross-sections of short-lived gluinos, and therefore on their masses; these limits depend on the squark masses $m_{\tilde{q}}$ (which govern photino interaction cross-sections) [25]. They implied that gluinos had to be heavier than about 2 to 3 GeV/c², for squarks lighter than 200 GeV/c². These constraints have been very significantly extended by other experiments (although the possible existence of light gluinos is still evocated occasionally).

Today $p\bar{p}$ colliders, with much higher center of mass energies, provide more powerful tools to search for gluinos and squarks, using the same general principles [26]. Once produced these particles should decay, presumably in agreement with R-parity conservation, according for example to $\tilde{q} \rightarrow q \tilde{g}$, $\tilde{q} \rightarrow q \tilde{\gamma}$, $\tilde{g} \rightarrow q \bar{q} \tilde{\gamma}$, ..., ultimately leading to photinos (or more generally neutralinos) in the final state. Fermilab results now imply, under reasonable hypotheses, that gluinos should be heavier than about 100 GeV/c², an impressive improvement upon the first limits, indicating that the supersymmetry-breaking gluino mass term should be at least as large as the W mass.

Then one also expects large mass terms for the SU(2) and U(1) gauginos. The photino is in general no longer expected to remain a pure eigenstate of the mass matrix (since these gaugino mass terms should presumably be different, at our energies), and the "Lightest Supersymmetric Particle" – presumably one of the neutralinos – is now generally expected to be relatively heavy.

IV.2 First searches for sleptons and photinos in e^+e^- annihilations.

Even without having to produce superpartners directly we could already get a lower mass limit, in 1979, from the consideration of the anomalous magnetic moment of the muon: spin-0 muons should presumably be heavier than about 15 GeV/c² (with a light photino), otherwise they would have given a too large additional contribution ($> 2 \cdot 10^{-8}$ in magnitude) to the muon anomaly $a_\mu = \frac{1}{2} (g_\mu - 2)$ [1,16]. But direct limits on slepton masses were soon obtained from e^+e^- annihilation experiments.

The general method to search for the production and decays of sleptons (and squarks) in e^+e^- annihilations was described in 1977: pair-production through a virtual photon or Z-boson in the s-channel, or also, in the case of selectrons, through a photino or zino exchange in the t-channel. Sleptons (or squarks) could then decay into the corresponding lepton (or quark) by emission of a photino (or gluino); (cf. Figs.1a and 1b) [1]. The pair-production of sleptons in e^+e^- annihilations would proceed as follows, in agreement with R-parity conservation:

$$e^+ e^- \rightarrow \tilde{l}^+ \tilde{l}^- \rightarrow l^+ l^- \tilde{\gamma} \tilde{\gamma} \quad (18)$$

It would lead to a non-coplanar lepton pair with "missing energy". From earlier SPEAR data taken at ≈ 7.2 GeV/c² G. Farrar and I deduced in 1979 that selectrons and muons should be heavier than $3\frac{1}{2}$ GeV/c² [27]. Systematic searches for these particles started at PETRA in 1980, and before the end of that year lower limits on selectron and smuon masses were of 16 and 15 GeV/c², respectively (for degenerate sleptons with a massless or light photino) [28]. Bounds on charged slepton masses soon increased up to 20 GeV/c² and more [29].

Other limits (65 GeV/c², for degenerate selectrons with a light photino) were obtained later at PETRA and PEP by searching, as suggested in 1982, for the radiative production of a pair of photinos, $e^+e^- \rightarrow \gamma \tilde{\gamma} \tilde{\gamma}$, which could be induced by selectron exchanges in the t-channel [30].

More recently sleptons and squarks might have been copiously produced in Z decays at LEP. Summing on the two spin-0 particles $\tilde{f}$ (assumed mass-degenerate) associated with a given (Dirac) fermion f , we would have had:

$$\Gamma (Z \rightarrow \tilde{f} \tilde{f}) = \frac{1}{2} \beta^3 \Gamma (Z \rightarrow f \bar{f}) \quad (19)$$

with $\beta = v_f/c$ (and even if R-parity turned out not to be an exact symmetry of the whole Lagrangian). For light sleptons and squarks the Z width might have been increased by up to 50% ! And the contribution to the invisible Z decay width of a stable $\tilde{\nu}$ might have been as large as $\approx 50\%$ of the contribution of one additional neutrino flavor! This constrains an invisible sneutrino $\tilde{\nu}$ to be heavier than 37 GeV/c², and requires pairs of degenerate squarks to be heavier than 38-39 GeV/c². The best limits on charged sleptons (45 GeV/c², provided the LSP is lighter than 38-41 GeV/c²)

come from the search for non-coplanar lepton pairs with missing energy-momentum, originating from $e^+e^- \rightarrow Z \rightarrow \tilde{l}^+ \tilde{l}^- \rightarrow l^+ l^- + 2$ neutralinos, as described earlier [31].

IV.3 Searches for winos and Higgs bosons.

Winos are mixtures of a charged Dirac gaugino with a charged Dirac higgsino (described by our two doublet Higgs superfields). Their expected decay modes depend on the mass spectrum. They could, for example, decay into a photino (or a neutralino), plus a quark or a lepton pair

$$\tilde{W}^\pm \rightarrow \tilde{\gamma} + l^\pm \nu \text{ (or } q \bar{q}')$$
(20)

somewhat like the decay of a heavy lepton into its neutrino (this is not surprising, since these particles first emerged from an attempt at a description of "leptons", and we even thought, in 1976, of the τ -lepton as a possible wino candidate). Their mass matrix reads:

$$\begin{pmatrix} m_2 & m_W \sqrt{2} \sin \beta \\ m_W \sqrt{2} \cos \beta & \mu \end{pmatrix}$$
(21)

One wino often remains lighter than the W (and might thus be found at LEP II). Both winos may also be heavier, when m_2 (direct gaugino mass term) and μ (direct or spontaneously-induced higgsino mass term), which supplement the non-diagonal mass terms of eq.(8) mixing gauginos with higgsinos, are present simultaneously [32]. LEP experiments now constrain winos to be heavier than 45-47 GeV/c², and give also restrictions on neutral higgsinos [31].

Since we used two Higgs doublets rather than a single one the spectrum includes a charged Higgs boson $H^\pm$ (cf. subsection III.1 and Table 1). In our first models with supersymmetry-breaking spontaneously induced from an extra $U(1)$ gauge group this charged Higgs (then called $w^\pm$) was lighter than the W ; but with soft (gravity-induced) supersymmetry-breaking terms it now tends to be heavier. Early PETRA experiments searching for charged Higgs bosons (or technipions) constrained them to be heavier than about 15 GeV/c² – not a severe restriction on supersymmetric models, given that the charged Higgs mass is naturally related to the W mass. Searches went on at LEP, disregarding present theoretical prejudice that the charged Higgs should presumably be heavier than the W .

This charged Higgs boson $H^\pm$ (partial width $\Gamma(Z \rightarrow H^+H^-) \approx 24 \text{ MeV } \beta^3$, where $\beta = v_H/c$) may have dominant decay modes into $\tau^+\nu$, or $c\bar{s}$, depending on $\tan \beta = v_2/v_1$. For large $\tan \beta$ the charged Higgs (essentially a member of the first doublet), decays mostly into $\tau \nu$ (or conversely, for small $\tan \beta$, mostly into $c\bar{s}$ or $\bar{c}s$). LEP searches for $Z \rightarrow H^+H^- \rightarrow ((\tau\nu) + (\tau\nu))$, or $((\tau\nu) + \text{hadrons})$, or hadrons-only now constrain it to be heavier than 41-45 GeV/c² [31].

Our two Higgs doublets also describe two complex neutral Higgs fields. Their real (scalar, CP-even) and imaginary parts (pseudoscalar, CP-odd) mix separately (with mixing angles often denoted by α and β , respectively), to provide us with two scalars, h and H , and one pseudoscalar, A (cf. Table 1). The partial width for the associated pair-production of neutral Higgs bosons is $\approx 83 \text{ MeV } \beta^3$ (as for sneutrinos), before mass-splittings and mixing angles are taken into account. Then one gets (in the absence of further mixings with other spin-0 fields, such as an extra singlet)

$$\Gamma(Z \rightarrow h A) = \frac{1}{2} \cos^2(\beta - \alpha) \bar{B}^3 \Gamma_{\nu\bar{\nu}} \quad (22)$$

and also, for the production of a virtual Z:

$$\Gamma(Z \rightarrow Z^* h) = \sin^2(\beta - \alpha) \Gamma(Z \rightarrow Z^* h_{\text{standard model}}) \quad (23)$$

These complementary methods strongly restrict the existence of such Higgs bosons or even exclude them completely (at least in the minimal model, and with $\tan\beta > 1$), for masses smaller than 44 (21) GeV/c^2 [33]. LEP limits on the new particles are summarized in Table 2.

Table 2: LEP limits on sleptons and squarks, winos and Higgs bosons.

$m(\tilde{e}, \tilde{\mu}, (\tilde{\tau}))$	$> 45 \text{ GeV}/c^2$	(for neutralino LSP < 41 (38) GeV/c^2)
$m(\tilde{\nu})$	$> 33 \text{ GeV}/c^2$	(37 for an invisible $\tilde{\nu}$)
$m(\tilde{u}, \tilde{d})$	> 38 (39) GeV/c^2	(two deg. squarks of charge $2/3$ ($-1/3$))
$m(\text{winos})$	$> 45 \text{ GeV}/c^2$	
$m(\text{charged Higgs } H^\pm)$	$> 41 \text{ GeV}/c^2$	
$m(\text{neutral Higgs } h, A)$	$> 44, 21 \text{ GeV}/c^2$	(for $\tan\beta > 1$)

V. FUTURE PROSPECTS.

In 16 years of searches for "supersymmetric particles" none has been found, and the lower mass limits have now increased from less than a few GeV/c^2 to around 100 GeV/c^2 or more for gluinos, and from 15 GeV/c^2 in 1980 for the selectrons and smuons, up to 45 GeV/c^2 at LEP.

Up to what point should this search go on, and when can we finally expect to detect the much-desired superpartners? We still have chances to make this discovery at LEP 2, which could detect, for example, a *wino lighter than the W* (especially since the two wino masses are often split on each side of the W mass), and, possibly, charged sleptons or other new particles. Detailed analysis of $p\bar{p}$ scattering events at Fermilab may also reveal the existence of squarks and gluinos. Otherwise we may have to wait for future colliders like the Large Hadronic Collider at CERN, or a very-high-energy linear e^+e^- collider.

In any case the mass scale at which these new particles should be found is normally expected to be of the order of the electroweak scale (or up to a few TeV/c^2 at most), otherwise the new scale associated with superpartners would create a hierarchy problem in the electroweak theory (independently of other possible scales like the grand-unification or Planck scales). The remarkable renormalization properties of supersymmetric theories also led to the hope of a solution for the hierarchy problem of grand-unified theories, while supersymmetry seems essential to the construction of consistent string theories, considered as potential candidates for a unified description of all particles and interactions, including gravity.

In the framework of grand-unification we now have an indirect indication that we may be on the right track. Superpartners and Higgs bosons would have a crucial influence on the evolution of the three $SU(3) \times SU(2) \times U(1)$ gauge couplings, and are essential to obtain their convergence at high energy – around 10^{16} GeV or so – with the measured values of $\alpha_s(m_Z) \approx .12$ and $\sin^2\theta \approx .23$. This convergence [34], relying on the field content of the Supersymmetric

Standard Model – including its two Higgs doublets and all the superpartners, at their expected mass scale of around 100 GeV to 1 TeV – may be taken, optimistically, as an indication in favor of the existence of these superpartners ¹⁵. It may be considered as a unification test of the Supersymmetric Standard Model – even non-minimal – rather than a specific prediction of a particular grand-unified supersymmetric model.

Even if superpartners were relatively heavy and managed to escape direct detection for some time, we could still search for signs of supersymmetry by looking for the two-Higgs doublet structure associated with the electroweak breaking. We also expect the existence of Higgs bosons with not-too-heavy masses, if the theory is to remain perturbative up to very high energies ¹⁶.

The Supersymmetric Standard Model is now by itself a standard theory. But the origin of the breaking of the supersymmetry still remains unclear. The usual attitude is to parametrize our ignorance, by describing the effects of

15. At least for the two higgsino doublets and the gauginos, which play an essential role to get a correct low-energy value for $\sin^2\theta$, and a sufficiently large value for the grand-unification scale, respectively. Sleptons and squarks form complete families of the SU(5) group and have essentially no sizeable effect on the convergence (or non-convergence) of the couplings, and on the grand-unification scale.

16. In the presence of extra singlets coupled to the two Higgs doublets, Higgs bosons might all be very heavy, even at the tree approximation; but this would require a rather strongly interacting Higgs sector (very much as in ordinary gauge theories, including the standard model itself), preventing one to compute perturbatively up to very high energies.

supersymmetry-breaking in terms of a (not-so-small) number of arbitrary parameters. This breaking may be related with an unknown "hidden sector" of supergravity – which brings back the difficult question of the extreme smallness of the cosmological constant. Supersymmetry-breaking may also appear as an effect of extra compact space dimensions, with superpartner masses fixed by the compactification scale M/Lc , and $L \lesssim 10^{-16}$ cm ¹⁷ [12]. R-parity may then be given a new geometrical interpretation related with this compactification (in addition to its connection with a reflexion symmetry of the spinorial coordinate θ in superspace). This led us, in a far more speculative way, to contemplate the possibility of discovering new space dimensions at future particle colliders.

Returning to our well-established four spacetime dimensions, we expect the existence of a well-identified set of new particles. We traced our way, from unsuccessful attempts to relate known bosons and fermions, passing beyond the general belief that supersymmetry, although very attractive for field-theory, was irrelevant to the description of the real world, to a view of this world according to which half of the particles at least, distinguished by their odd R-parity character, would still be unknown (with maybe one of them constituting a large part of the Universe).

17. R-even fields would be continuous, while R-odd fields would change signs, when one goes over a closed loop around one of the compact dimensions. Then the gravitino mass is geometrically quantized in terms of the size of this dimension (e.g., for the lowest-lying gravitino, $m_{3/2} = \pi M/Lc = 1/2R$), and one would have, for example, $m^2(\text{winos}) = m_W^2 + [(2n+1)\pi/L]^2$. But model-building and phenomenology still remain unclear.

In view of all the implications of this idea, physicists should not be discouraged by more than 15 years of searches, which explored the region of smaller superpartner masses. They should pursue actively the search for the missing half of the particle world, to extend to superspace our familiar notion of spacetime and disclose the algebraic structure of supersymmetry as a fundamental invariance of the laws of the world, beyond general relativity.

VI. REFERENCES

1. P. Fayet, Phys.Lett. 64B (1976) 159; 69B (1977) 489; "Unification of the Fundamental Particle Interactions", Proc. Erice Conf. (Plenum, N.Y., 1980) p.587.
2. Yu. A. Gol'fand and E.P. Likhtman, ZhETF Pis.Red. 13 (1971) 452 [JETP Lett. 13 (1971) 323]; D.V. Volkov and V.P. Akulov, Phys.Lett. 46B (1973) 109; J. Wess and B. Zumino, Nucl.Phys. B70 (1974) 39; B78 (1974) 1.
3. For review articles on supersymmetry and supergravity, see for example:
P. Fayet and S. Ferrara, Phys. Reports 32C (1977) 249;
P. van Nieuwenhuizen, Phys. Reports 68C (1981) 189;
H.P. Nilles, Phys. Reports 110 (1984) 1;
H. Haber and G. Kane, Phys. Reports 117 (1985) 75;
P. Fayet, "Properties of SUSY Particles" (Erice Workshop, 1992) ed. Cifarelli and Khoze (World Sc. 1993) p.1.
4. P. Fayet and J. Iliopoulos, Phys.Lett. 51B (1974) 461.
5. P. Fayet, Phys.Lett. 58B (1975) 67;
L. O'Raikeartaigh, Nucl.Phys. B96 (1975) 331.
6. P. Fayet, Nucl.Phys. B90 (1975) 104.
7. P. Fayet, Nucl.Phys. B113 (1976) 135.
8. A. Salam and J. Strathdee, Nucl.Phys. B97 (1975) 293.
9. P. Fayet (1976), unpublished; Nucl.Phys. B149 (1979) 137.
10. F. Gliozzi, J.Scherk and D. Olive, Nucl.Phys. B122 (1977) 253;

- L. Brink, J. Scherk and J.H. Schwarz, Nucl.Phys. B121 (1977) 77.
11. P. Fayet, Nucl.Phys. B246 (1984) 89.
12. P. Fayet, Nucl.Phys. B263 (1986) 649; Proc. of the Second Nobel Symposium on El. Particle Physics, Marstrand, Sweden (1986), Physica Scripta T15 (1987) 46.
13. M. Gell-Mann, P. Ramond and R. Slansky, Rev.Mod.Phys 50 (1978) 721.
14. M.L. Perl et al., Phys.Rev.Lett. 35 (1975) 1489; Phys.Lett. 63B (1976) 466.
15. L. Girardello and M.T. Grisaru, Nucl.Phys. B194 (1982) 65.
16. P. Fayet, Phys.Lett. 84B (1979) 416.
17. P. Fayet, Phys.Lett. 95B (1980) 285; 96B (1980) 83; Nucl.Phys. B187 (1981) 184; Proc. of the 17th Renc. de Moriond (1982), p. 483.
18. P. Fayet, Phys.Lett. 78B (1978) 417.
19. G.R. Farrar and P. Fayet, Phys.Lett. 76B (1978) 575; 79B (1978) 442.
20. P. Fayet, Phys.Lett. 70B (1977) 461.
21. S. Ferrara, D.Z. Freedman and P. van Nieuwenhuizen, Phys.Rev. D13 (1976) 3214;
S. Deser and B. Zumino, Phys.Lett. 62B (1976) 335.
22. P. Fayet, Phys.Lett. 84B (1979) 421.
23. P. Fayet, Phys.Lett. 86B (1979) 272.
24. J.P. Dishaw et al., Phys.Lett. 85B (1979) 142.
25. CHARM collaboration, Phys.Lett. 121B (1983) 429;
R.C. Ball et al., Phys.Rev.Lett. 53 (1984) 1314;
WA66 collaboration, Phys.Lett. 160B (1985) 212.
26. UA1 collaboration, Phys.Lett. B198 (1987) 261;
UA2 collaboration, Phys.Lett. B235 (1990) 363;
CDF collaboration, Phys.Rev.Lett. 62 (1989) 1825; 69 (1992) 3439.
27. G.R. Farrar and P. Fayet, Phys.Lett. 89B (1980) 191.
28. H. Spitzer, Proc. of the 15th Rencontre de Moriond at Les Arcs (France) (1980) 157;
D. Cords, Proc. of the 20th Int. Conf. on High Energy Physics, Madison (1980) 590;
D.P. Barber et al., Phys.Rev.Lett. 45 (1980) 1904.
29. See e.g. H. Behrend et al., Z.Phys. C35 (1987) 181.
30. P. Fayet, Phys.Lett. 117B (1982) 460;
C. Hearty et al., Phys.Rev. D39 (1989) 3207.

31. The ALEPH Collaboration, Phys. Reports 216 (1992) 253;
L3 Collaboration, Phys. Reports 236 (1993) 1.
32. P. Fayet, Phys.Lett. 133B (1983) 363.
33. L3 Collaboration, Phys. Lett. B294 (1992) 457;
ALEPH Collaboration, Phys. Lett. B313 (1993) 312.
34. S.Dimopoulos, these proceedings, and references therein.

VII. FIGURE CAPTION

Fig.1 Some characteristic processes in the search for the new superpartners (adapted from Ref.[1] ¹⁸):

- a) pair-production of sleptons and squarks in e^+e^- annihilations: $e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-$ (or $\tilde{q} \tilde{q}$); photino and zino exchanges can also contribute, in the case of selectrons;
- b) possible decay modes of sleptons and squarks: $\tilde{l}^\pm \rightarrow l^\pm \tilde{\gamma}$ (or $\tilde{q} \rightarrow q \tilde{g}$, or $q \tilde{\gamma}$);
- c) scattering of photinos on quarks and electrons.

18. In our early papers we denoted a fermion (lepton or quark) by ψ_i , and by s_i and t_i the two spin-0 fields associated with its left-handed and right-handed components - now denoted by $\tilde{l}_L$ or $\tilde{q}_L$, and $\tilde{l}_R$ or $\tilde{q}_R$, respectively; the corresponding chiral superfields were denoted by S_i and T_i , left-handed and right-handed, respectively. S (left-handed) and T (right-handed) were the two electroweak doublet Higgs superfields, possibly coupled to an extra singlet N . These superfields interact with $SU(3) \times SU(2) \times U(1)$ gauge superfields V_a , $\vec{V}$ and V' (V'' denoting an extra $U(1)$ gauge superfield introduced to trigger spontaneous supersymmetry breaking, having in the simplest case axial couplings to leptons and quarks).

In these papers the photino and gluinos were denoted by λ_γ and λ_a (and the goldstino/gravitino by λ_G). The standard model Z was called Z' , and the extra- $U(1)$ one, Z'' ; the latter, not needed in the presence of soft supersymmetry-breaking terms, would then be replaced by the (CP-odd) pseudoscalar A (cf. Table 1). $l^\pm$ and $L^\pm$ are the two winos, and l'^0 and l''^0 (Dirac) neutralinos. The charged and neutral Higgs bosons $w^\pm$, z' and z'' would now be called $H^\pm$, H and h ; the complex spin-0 boson n is described by the additional neutral chiral superfield N coupled to our two Higgs doublets.

Fig.1