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Hidden Supersymmetry

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Abstract

Inspired by the concept of complementarity, we present a illustrative model for the weak interactions with unbroken gauge symmetry and unbroken supersymmetry. The observable particles are bound states of some more fundamental particles. Supersymmetry is broken at the macroscopic scale of the observable particles by a discrete symmetry but remains exact at the scale of the fundamental particle and is thus hidden. This provides a link between theories at very high energies and the observed particle physics. Supersymmetric particles are confined in usual matter.

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1 Introduction

In seminal papers [1, 2], 't Hooft has shown that in a gauge theory with a Higgs boson in the fundamental representation of the gauge group there is no fundamental difference between the theory in the Higgs phase, i.e, with a gauge symmetry broken by means of the Higgs mechanism and the theory in the confinement phase i.e, a theory with confined gauge charges. This property is known as the complementarity principle [3]. The fundamental difference between the electroweak theory and QCD is that in the electroweak sector one has a large parameter which allows perturbative calculations.

Recently we have used this complementarity to build an alternative to the standard model using a $SU(2)_L \otimes U(1)_Y$ gauge group with $SU(2)_L$ confinement [4]. We have clarified how to incorporate quantum electrodynamics in that kind of models and studied the physical consequences of the assumption that the electroweak interactions might be described by the confinement phase. In that case all phenomena in particle physics are described by exact gauge theories. If nature is such that its fundamental Lagrangian has the maximal number of allowed symmetries, it is natural to assume that supersymmetry could also be an exact symmetry of this Lagrangian. Supersymmetry is a crucial aspect in particle physics, it is a desirable feature of many high energy theories like some variants of grand unified theories. It is the missing link between some theories at very high energies and low energy particle physics.

It is thus meaningful to design mechanisms that explain why supersymmetry is unobserved. A possibility is that supersymmetry is broken. This leads to models such as the minimal supersymmetric standard model (MSSM). We propose an alternative point of view. If the electroweak interactions are described by a confining theory, the microscopic theory can be supersymmetric but this symmetry is then hidden at the macroscopic scale of fermions and electroweak bosons. In other words we will break supersymmetry at the macroscopic scale without breaking it at the scale of fundamental particles thus providing a link between some theories at very high and low energy particle physics.

In composite models, supersymmetry is not necessary to solve the hierarchy problem because the Higgs boson is not a fundamental particle but it remains important to have a supersymmetric theory to reach the unification of the coupling constants at the unification scale.

We then consider a supersymmetric extension of the model for the electroweak interactions proposed in [4] with broken supersymmetry at the fundamental level.

2 A supersymmetric toy model

We shall consider a illustrative model with the gauge group $SU(2)_L$ and unbroken $N=1$ supersymmetry. The situation in a gauge theory with unbroken supersymmetry is very similar to that of the confinement phase in a non-supersymmetric theory. We assume that there is a $SU(2)_L$ confinement: all physical particles are $SU(2)_L$ singlets. We have the following particle spectrum: the right-handed fermions e_R, u_R, d_R and their superpartners $\tilde{e}_R$, $\tilde{u}_R$, $\tilde{d}_R$. The right-handed particles are the usual right-handed leptons and quarks of the standard model and their superpartners, whereas the left-handed doublets are bound states of some more elementary particles. The fundamental $SU(2)_L$ fields (D-quarks) are:

leptonic D-quarks $\quad l_i = \begin{pmatrix} l_1 \\ l_2 \end{pmatrix}$ (fermions)

hadronic D-quarks $\quad q_i = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}$ (fermions, $SU(3)_c$ triplets)

scalar D-quarks $\quad h_i = \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$ (bosons).

Notice that in order to cancel the anomalies we would have to introduce a second scalar doublet. We discard this problem as our aim is only to present a toy model to emphasize our idea. We then have the superpartners

leptonic D-squarks $\quad \tilde{l}_i = \begin{pmatrix} \tilde{l}_1 \\ \tilde{l}_2 \end{pmatrix}$ (bosons)

hadronic D-squarks $\quad \tilde{q}_i = \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix}$ (bosons, $SU(3)_c$ triplets)

scalar D-squarks $\quad \tilde{h}_i = \begin{pmatrix} \tilde{h}_1 \\ \tilde{h}_2 \end{pmatrix}$ (fermions).

We shall refer to the theory involving the D-quarks and the D-squarks as the microscopic theory. At the macroscopic level i.e, the theory of bound states, a large number of $SU(2)_L$ invariant bound states can be identified. We see that bound states of different particles can have the same quantum numbers. For example, the neutrino can be identified with the bound state $\bar{h}l$ but also with the bound state $\bar{\tilde{h}}\tilde{l}$. It will thus be a superposition of both bound states. This can be applied to the rest of the known particles. The left-handed fermions, normalized in the appropriate way, are defined as follows. We have the leptons

$$\text{left-handed neutrino } \nu_L = \frac{1}{F}\left((\bar{h}l) + (\bar{\tilde{h}}\tilde{l})\right) \quad (1)$$
$$\text{left-handed electron } e_L = \frac{1}{F}\left((\epsilon^{ij}h_i l_j) + (\epsilon^{ij}\tilde{h}_i\tilde{l}_j)\right)$$

where F is a numerical, to be specified, normalization factor. The quarks are also bound states

$$\text{left-handed up quark } u_L = \frac{1}{F}\left((\bar{h}q) + (\bar{\tilde{h}}\tilde{q})\right) \quad (2)$$
$$\text{left-handed down quark } d_L = \frac{1}{F}\left((\epsilon^{ij}h_i q_j) + (\epsilon^{ij}\tilde{h}_i\tilde{q}_j)\right).$$

The Higgs and electroweak bosons are bound states of scalar D-quarks and their superpartners:

$$\text{Higgs field } \phi = \frac{1}{2F}\left((\bar{h}h) + \beta(\bar{\tilde{h}}\tilde{h})\right) \quad (3)$$
$$\text{electroweak boson } W^3_\mu = \frac{2i}{gF^2}\left((\bar{h}D_\mu h) + \beta(\bar{\tilde{h}}D_\mu\tilde{h})\right)$$
$$\text{electroweak boson } W^-_\mu = \frac{\sqrt{2}i}{gF^2}\left((\epsilon^{ij}h_i D_\mu h_j) + \beta(\epsilon^{ij}\tilde{h}_i D_\mu\tilde{h}_j)\right),$$

where D_μ is the covariant derivative of the gauge group $SU(2)_L$ involving the gauge bosons B^a_μ and g is the gauge coupling of this group. The second charged W boson W^+ is defined as $(W^-)^\dagger$. A simple dimensional analysis shows that a constant β with dimension -1 has to appear. This constant is a priori unknown but the only scale of the theory being F, we could impose $\beta = 1/F$. This apparently arbitrary choice is not a drawback for the theory as we will see that only the terms containing a scalar D-quark doublet will be relevant.

The problem is to know whether a particle and its superparticle will belong to the same supermultiplet, i.e, if they have the same mass. It is a difficult question as dynamical effects can contribute to the masses. For example, the masses of the electroweak bosons are to a large extent dominated by dynamical effects. Once we have introduced a second Higgs doublet, we have the same gauge group and the same particle contain as in the MSSM, dynamical supersymmetry breaking is thus possible. There are two possibilities: either the masses of, for example, an electroweak boson and of the corresponding superparticle are identical and supersymmetry is unbroken at the macroscopic level or they are different because of dynamical effects and supersymmetry is dynamically broken. This possibility can't be excluded, but in the sequel we assume that these particles indeed form a supermultiplet. Thus, an electron is the superpartner of a selectron. Lattice simulations could test the dynamical behavior of such a model.

All the particles we have identified up to this point are those appearing in the standard model. We can also identify the bounds states corresponding to the macroscopic superparticles. For example, we have

$$\text{selectron } \tilde{e} = \frac{1}{F}\left((\epsilon^{ij} h_i \tilde{l}_j) + \beta(\epsilon^{ij}\tilde{h}_i l_j)\right)$$

for the left-handed selectron.

The complementarity principle was established in the framework of a non-supersymmetric theory with a single Higgs boson doublet. This principle requires that the coupling constants between the bounds states and the electroweak bosons are the same in the Higgs phase and in the confinement phase. In the case of a non-supersymmetric model [4], 't Hooft proposed that the confinement is due to vortices [1]. This means that we have a confinement with a weak coupling constant which avoids the problems due to chiral symmetry breaking [5].

In a supersymmetric model the situation is more complex since the theory is richer. Nevertheless the situation in such a theory is very similar to that of the confinement phase in a non-supersymmetric gauge theory. The question is whether our microscopic model which is supersymmetric will have a supersymmetric macroscopic spectrum. A lattice study of the vacuum structure and of the dynamical behavior of our model would be useful to answer this question. As long as this as not been done some place is left for speculation.

A discrete symmetry could explain why nature selects, at least at low energy, only the particles. We introduce a mechanism similar to the so-called R-parity. We assign a new quantum number to the particles. We call this new quantum number S-parity. The D-quarks are assigned S-parity +1, whereas the D-squarks are assigned S-parity -1. We then assume that the bound states appearing in nature have S-parity +1.

This selection rule shifts the masses of the superparticles to very high energies. In other words we break supersymmetry at the macroscopic level by imposing a discrete symmetry but it remains intact at the microscopic level. It is thus clear that superparticles corresponding to the left-handed particles, to the Higgs sector and to the electroweak bosons will not be observable at least at low energy. In that case, we expect that a confining theory describes the weak interactions correctly. Imposing this selection rule which is motivated by the apparent absence of superparticles in nature at low energy is not trivial as it would be in the case of the MSSM because the fundamental D-squarks are confined in usual matter. It would not be very surprising if this S-parity was broken in nature, as there are already many examples of broken discrete symmetries. But, at this stage it remains a speculation, which could be tested on the lattice.

That scenario is useful in the case of a grand unified theory. If there is a deconfinement phase at the scale of a few TeV, supersymmetry is realized above that scale and the coupling constants unification takes place at the unification scale, but supersymmetry remains hidden at low energy under this deconfinement phase. Two scenarios are conceivable, the mass scale of the superparticles is below the deconfinement scale, in which case one will observe superparticles but the theory is not explicitly supersymmetric until one reaches the deconfinement scale. Another possibility is that the mass scale for the superparticles is above the deconfinement scale in which case the particle spectrum would suddenly become supersymmetric above the deconfinement scale. This feature allows to test our idea.

Even if supersymmetry was broken by dynamical effects, it might still be necessary, if the mass splitting was not sufficiently large, to introduce this S-parity for phenomenological reasons.

3 Back to known particles

It remains to show that the definitions for the fields indeed describe the observed particles. We use the unitary gauge for the scalar doublet

$$h_i = \begin{pmatrix} F + h_{(1)} \\ 0 \end{pmatrix}. \tag{4}$$

The parameter F is a real number. If F is sufficiently large we can perform a $1/F$ expansion for the fields defined previously, we then have

$$\begin{aligned}
\nu_L &= l_1 + \frac{1}{F}\left(h_{(1)} l_1 + \bar{\tilde{h}}\tilde{l}\right) \approx l_1 \\
e_L &= l_2 + \frac{1}{F}\left(h_{(1)} l_2 + \epsilon^{ij}\tilde{h}_i \tilde{l}_j\right) \approx l_2 \\
u_L &= q_1 + \frac{1}{F}\left(h_{(1)} q_1 + \bar{\tilde{h}}\tilde{q}\right) \approx q_1 \\
d_L &= q_2 + \frac{1}{F}\left(h_{(1)} q_2 + \epsilon^{ij}\tilde{h}_i \tilde{q}_j\right) \approx q_2 \\
\phi &= h_{(1)} + \frac{F}{2} + \frac{1}{2F}\left(h_{(1)} h_{(1)} + \beta\bar{\tilde{h}}\tilde{h}\right) \approx h_{(1)} + \frac{F}{2}
\end{aligned} \tag{5}$$

$$
\begin{aligned}
W_\mu^3 &= \left(1 + \frac{h_{(1)}}{F}\right)^2 B_\mu^3 + \frac{2i}{gF}\left(1 + \frac{h_{(1)}}{F}\right)\partial_\mu h_{(1)} \\
&\quad + \frac{2i\beta}{gF^2}\left(\bar{\tilde{h}} D_\mu \tilde{h}\right) \approx B_\mu^3 \\
W_\mu^- &= \left(1 + \frac{h_{(1)}}{F}\right)^2 B_\mu^- + \frac{\sqrt{2}i\beta}{gF^2}\left(\epsilon^{ij}\tilde{h}_i D_\mu \tilde{h}_j\right) \approx B_\mu^- .
\end{aligned}
$$

As also done by 't Hooft [1, 2], we assume that the only particles which are stable enough to be observable at presently accessible energies are those containing the scalar doublet h, those are the only fields who survive to the expansion, and we consider the terms suppressed by a factor $1/F$ as being irrelevant. Therefore the spectrum of this theory is, for the left-handed sector, identical to the spectrum of the standard model. Nevertheless we are not able to hide the superpartners of the right-handed particles at this stage. Supersymmetry is apparently broken in the left-handed sector but in fact it remains unbroken at the microscopic level of the theory.

4 The MSSM

In this section, we assume that the complementarity principle remains valid for supersymmetric theories once soft breaking terms have been introduced. The model in the confinement phase corresponding to the minimal supersymmetric standard model can easily be obtained by requiring that supersymmetry is broken by usual means at the level of the fundamental D-quarks and D-squarks. A second Higgs doublet k and the corresponding superparticle $\tilde{k}$ can be introduced without any difficulty, and we basically have to replace h and $\tilde{h}$ by $s = h + i\sigma_2 k^*$ and $\tilde{s} = \tilde{h} + i\sigma_2\tilde{k}^*$ in the definitions of the fermions, superfermions, electroweak bosons and of their superpartners. The gauge is fixed in such a way that s takes the form $s = (F + h_{(1)} + k_{(1)}, 0)$, where $F = F_1 + F_2$, F_1 corresponding to the scalar doublet h and F_2 to the scalar doublet k. We then have

$$
h = \begin{pmatrix} F_1 + h_{(1)} + i\chi^0 \\ -\phi^- \end{pmatrix}, \quad k = \begin{pmatrix} -\phi^+ \\ F_2 + k_{(1)} + i\chi^0 \end{pmatrix}. \tag{6}
$$

We can define the five Higgs bosons

$$
\begin{aligned}
CP \text{ even Higgs boson } \phi_1 &= \frac{1}{2F_1}\left(\bar{h}h\right) = h_{(1)} + \frac{F_1}{2} + \mathcal{O}\left(\frac{1}{2F_1}\right) \qquad (7) \\
CP \text{ even Higgs boson } \phi_2 &= \frac{1}{2F_2}\left(\bar{k}k\right) = k_{(1)} + \frac{F_2}{2} + \mathcal{O}\left(\frac{1}{2F_2}\right)
\end{aligned}
$$

$$
\begin{aligned}
CP \text{ odd Higgs boson } i\chi &= \left(\frac{1}{2F}(\bar{s}h + \epsilon^{ij} s_i k_j) - \frac{1}{2F_1}(\bar{h}h) - \frac{1}{2F_2}(\bar{k}k)\right) \\
&= i\chi + \mathcal{O}\left(\frac{1}{2F_1}\right) + \mathcal{O}\left(\frac{1}{2F_2}\right) \\
\text{charged Higgs boson } \phi^+ &= \frac{-1}{F}\left(\bar{s}k\right) = \phi^+ + \mathcal{O}\left(\frac{1}{F}\right) \\
\text{charged Higgs boson } \phi^- &= \frac{-1}{F}\left(\epsilon^{ij} s_i h_j\right) = \phi^- + \mathcal{O}\left(\frac{1}{F}\right).
\end{aligned}
$$

The superpartners of these Higgs bosons can be obtained in a similar way. The model presented in [4] is thus compatible with a supersymmetric extension provided that both F_1 and F_2 can be chosen to be large. This model has the same vertices as the MSSM and the same particle contain. As in the case of the non-supersymmetric model, we expect that radial and orbital excited versions of the known particles will appear.

5 Conclusions

We have considered a toy model with $SU(2)_L$ confinement and hidden supersymmetry in the left-handed sector. Supersymmetry is broken at the macroscopic level by a discrete symmetry. The first step towards a realistic model is to include a second Higgs doublet. It can be done without major difficulties as has been shown in the last section.

This model can be extended to a model with a $SU(3)_c \otimes SU(2)_R \otimes SU(2)_L \otimes U(1)_Y$ gauge group with two Higgs doublets for each $SU(2)$ sector. Once this extension has been done, we can hide supersymmetry completely at the microscopic level for the $SU(2)_R \otimes SU(2)_L$ sector, assuming a $SU(2)_R \otimes SU(2)_L$ confinement. Supersymmetry would have to be broken by usual means for the two remaining gauge groups. The spectrum of the macroscopic theory at low energy is then that of the standard model with ten Higgs fields, i.e. five for each $SU(2)$ sector, 8 gluinos and a photino.

This model provides the missing link between low energy particle physics and very high energy theories like grand unified theories. Usual models with supersymmetry breaking are not able to explain a small cosmological constant [6]. In our approach, supersymmetry is not broken in the $SU(2)_L$ sector at the microscopic level. Thus the contribution of the energy of the fundamental vacuum of that sector to the cosmological constant is vanishing. Our mechanism could therefore help to explain a small or vanishing cosmological constant.

Note that this model would nicely fit into a supersymmetric $SO(10)$ grand unified theory, which thus could be the fundamental theory of D-quarks and

D-squarks. It turns out that such a theory would be very similar to the standard model if there is a confinement in the weak interactions sector.

Finally, we described a supersymmetric extension of the model proposed in Ref. [4] for the electroweak interactions with $SU(2)$ confinement. We have shown that this model is compatible with a supersymmetric extension provided that the complementarity principle remains valid for supersymmetric theories once soft breaking terms have been introduced.

A detailed study of the vacuum structure of supersymmetric $SU(2)$ gauge theories and of their dynamical behavior by lattice simulations would allow to determine whether these scenarios can be realized in nature.

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