Signals of Gauge-Higgs Unification

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Abstract

1. Introduction (the SM "forces").
2. Yukawa and Higgs parameters in the MSSM.
   - Higgs self-coupling,
   - Raditive Yukawa couplings.
3. Higgs parameters and extra-dimensions
   - Higgs quartic coupling in 6D Gauge models.
   - Realistic Yukawas?
4. Conclusions

1 Introduction

The SM of the strong and electroweak interactions has met with extraordinary succes; it has been tested at the level of quantum corrections.

These corrections give some hints about the nature of the SM Higgs sector, pointing towards the existence of a relatively light Higgs boson $m_{\phi_{SM}} \simeq v$.

However, an understanding of all the SM parameters is still lacking. This motivates the search for model/ideas beyond the SM where such description could be achieved.

The SM parameters include:

1. *Dimensionless gauge parameters*, i.e. those associated with the gauge symmetries (g_1, g_2, g_3 and θ_{QCD}).

2. The *dimensionfull parameter* of the Higgs potential μ^2, which fixes the electroweak scale.

3. *Non-gauge dimensionless parameters*, not associated with a known symmetry, i.e. the quartic Higgs coupling (λ) and the Yukawa matrices (Y_f, $f = u, d, l, \nu$).

Then, how many "forces" are included in the SM?

From the point of view of QFT, the parameters λ and Y_f describe new interactions, i.e. they induce the Higgs self-coupling and the Higgs-fermion vertices. However, these "forces" are not associated with a gauge symmetry.

As a "conservative" program to look for extensions of the SM, one could attempt to find a framework where all the SM interactions are expressed in terms of gauge couplings.

(This could arise either because there are extra symmetries that allow to express them in terms of the known gauge coupings or because they come from a new gauge interaction.)

In fact, one of the simplests attempts to solve the problem of quad. divs. in the SM, through an accidental cancellation, does show a relationship between the quartic Higgs coupling and the Yukawa and gauge constants, namely:

$$4M_\phi^2 = 4m_t^2 - 2m_W^2 - m_Z^2 \quad (1)$$

$$\lambda = y_t^2 - \frac{1}{8}[3g^2 + g'^2] \quad (2)$$

Unfortunately, this relation implies a Higgs mass $m_\phi = 316$ GeV, that seems already excluded.

== We need Extra-dimensions!! (Fermionic or Bosonic)

2 Yukawa and Higgs parameters in the MSSM

The minimal implementation of SUSY in fundamental particle physics (MSSM) has met with mixed succes. On the positive side one could count:

1. The stabilization of the Higgs mass,
   Radiative EWSB
2. Unification of the gauge coupling constants,
3. Dark matter candidate.

Whereas the non-observation (yet) of the superpartners, and the corresponding mechanisms of SUSY breaking / transmition that makes them heavy enough, are among the unpleasant aspects.

However, by its own virtues SUSY also solves the problem of the Higgs self coupling (through the D-terms), which should be counted almost at the same level as the gauge coupling unification.

Furthermore, SUSY also offers some new avenues to discuss the problem of the Yukawa couplings within the MSSM.

2.1 The quartic Higgs coupling in the MSSM

Although the gauge and Higgs particles are placed in different multiplets in the MSSM, the auxiliary fields ($D-$terms) are required in order to have equal bosonic and fermionic d.o.f., and this open the window to incorporate Higgs bilinears into the vector multiplet,

$$V^a = (\lambda^a, v^a_\mu, D^a) \tag{3}$$

$$D^a = \sum g\phi^\dagger T^a \phi \tag{4}$$

Then, a quartic term appears in the Higgs potential:

$$V = \frac{g^2}{4}[(H_u^\dagger \tau^i H_u)^2 + (H_d^\dagger \tau^i H_d)^2] + \frac{g'^2}{4}[(H_u^\dagger H_u)^2 + (H_d^\dagger H_d)^2] \tag{5}$$

However, the resulting natural value for the Higgs mass, $m_h \simeq m_Z$, is getting into conflict with current Higgs mass bounds ($m_h \geq 115$ Gev), and something should come to the rescue:

- Radiative corrections can make $m_h \simeq 130$ GeV,

- New gauge contributions to the Higgs mass...

The possiblity to express the scalar quartic couplings as gauge constants, is valid not only for the Higgs boson, but also for all the scalar superpartners (squarks and sleptons), and is independent of the SUSY soft-breaking.

The quartic couplings among squarks and Higgs bosons contribute to sfermion masses, and could be tested by meassuring the mass-difference among scalars that only differ by their gauge quantum numbers, for instance:

$$m^2_{\tilde{u}_L} - m^2_{\tilde{d}_L} = \cos 2\beta m^2_W = m^2_{\tilde{\nu}} - m^2_{\tilde{l}} \qquad (6)$$

2.2 Radiative fermion masses

SUSY also has the elements as a QFT, that may allow to express the Yukawa parameters in terms of gauge couplings, i.e. there are certain types of “Yukawa interactions” that are given in terms of gauge couplings.

Within the MSSM, these couplings can be used to generate the true Yukawa parameters. Namely:

Then the Yukawas can be obtained as a loop effect:

A succesfull program along these lines requires:

1. Elements of M_{LR}^2 , and SUSY parameters, that generate the correct textures and are not in conflict with current FCNC bounds.

   Such large corrections can indeed be found in the MSSM, e.g. Diaz-Cruz, Murayama and Pierce, PRD65 (2002); J. Ferrandis, hep-ph/0404068

2. A SUSY breaking scheeme that generates the correct patern of soft-breaking terms.

   A model with U(2) flavor symmetry has been proposed recently, J. Ferrandis and Haba, hep-ph/0404077

For d-type squarks and sleptons:

$$M_{LR}^2 = v[A_f \cos\beta - \mu Y_f \sin\beta] \qquad (7)$$

Table 1. Soft-parameters required to generate SM fermion masses, for $\tan\beta = 5$.

Fermion	$\frac{Am_\lambda}{\tilde{m}^2}$	$\frac{m_\lambda}{\tilde{m}}$	$\frac{A}{\tilde{m}}$
e	3.5×10^{-3}	$O(1)$	3.5×10^{-3}
μ	$\simeq 1$	$O(1)$	$O(1)$
u	5×10^{-4}	$\simeq 0.5$	$O(10^{-3})$
c	$\simeq 0.5$	$\simeq 0.5$	$O(1)$
d	$\simeq 10^{-3}$	$\simeq 0.5$	$O(10^{-3})$
s	5×10^{-2}	$\simeq 0.5$	$O(1)$

3 Higgs parameters with extra-dimensions

The non-observation of the light Higgs boson, as well as the superpartners, have re-introduced some fine-tunning problems in the MSSM.

This “Little Hierachy problem”, has motivated the search for alternatives to the SUSY approach to EWSB (and the quartic Higgs coupling).

An interesting scenario within the extra-dimensional (XD) new approach to address the SM problems, consists in identifying the Higgs boson as a component of an XD gauge field.

Prominsing models could be obtained with an appropriate choice of the number of XD, compactification mechanism and gauge group. For instance:

1. SUSY models in 5D could be made realistic.
2. Non-SUSY models in 5D have a problems to generate the quartic Higgs coupling, and usually predict a too light Higgs boson.
3. Non-SUSY models in 6D or higher could work.

To illustrate the idea of symmetry breaking in XD, we shall consider first a gauge theory in 5D, with a gauge group G, which is compactified on a S^1/Z_2 orbifold.

The 5D gauge boson is: $A_M = T^A A_M^A$ $[M = (\mu, 5)]$.

1. Gauge symmetry can be broken by the orbifold boundary conditions (O.B.C.):
   $A_\mu(x_\mu, y) \to A_\mu(x_\mu, -y) = +PA_\mu(x_\mu, y)P^{-1}$,
   $A_5(x_\mu, y) \to A_5(x_\mu, -y) = -PA_5(x_\mu, y)P^{-1}$,
2. P acts on gauge space as an “inner automorphism”, such that the gauge symmetry is broken: $G \to H$.
3. Thus, O.B.C. split the group generators into two sets, $T^A = [T^a, T^k]$, T^A G, T^a H. Since A_μ^a has even Z_2- parity, it has zero modes in the spectrum.
4. On the other hand, A_μ^k has odd Z_2- parity, and does not have zero modes in the spectrum.
5. Furthermore, A_5^a (odd-odd) has zero modes, and its v.e.v. can break $H \to H'$.

Although 5D SUSY models are interesting in their own, with the aim of exploring true alternatives to SUSY, we shall discuss some aspects of the non-SUSY 6D models.

Consider a gauge theory in 6D, with a gauge group G, which is compactified on a T^2/Z_2 orbifold.

The 6D gauge lagrangian is:

$$\mathcal{L}_6 = -\frac{1}{2} F_{MN} F^{MN} \tag{8}$$

where $F_{MN} = \partial_M A_N - \partial_N A_M - i g_6 tr[A_M, A_N]$.

The XD coordinates x_5, x_6 can be grouped in a complex one: $z = \frac{1}{\sqrt{2}}(x_5 + i x_6)$.

The 4D lagrangian for the zero modes becomes:

$$\begin{aligned} \mathcal{L}_4 &= \int dz d\bar{z} \mathcal{L}_6 \qquad (9) \\ &= -\frac{1}{2} F^0_{\mu\nu} F^{0\mu\nu} + 2tr|D_\mu A^0_z|^2 - g_4^2 tr[A^0_z, A^0_{\bar{z}}] \end{aligned}$$

Further: $g_4 = g_6/V^{1/2}$, $D_\mu A^0_z = \partial_\mu A^0_z - i g_4 [A^0_\mu, A^0_z]$.

The zero-modes $A^0_{z,\bar{z}}$ can be identified as the Higgs bosons, and the last term in eq.(9) correspond to a Higgs quartic coupling.

Some 6D models proposed in the literature and their main advantages / problems include:

1. SU(3) model

   Predicts $m_h = 2m_W$ *for a particular compactification, but gives* $\sin^2\theta_W = 3/4$.

2. String inspired U(3)xU(3) model.

   Gives a correct value for $\sin^2\theta_W$*, but contains two anomalous* $U(1)$ *simmetries.*

3. G_2 model with fermions at fixed points.

   Predicts $\sin^2\theta_W = 1/4$*, and with fermions at the orbifold fixed points, Yukawas could be generated by Wilson lines, but not yet a realistic construction.*

4 CONCLUSIONS

1. SUSY offers a simple solution to express the Higgs self-coupling in terms of gauge coupling constants.
2. Yukawas could be generated raditively within the MSSM.
3. 6D models have the potential to become an alternative to the MSSM, but so far no realistic model has been constructed.