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# Chapter 1

## The Higgs Bosons and The MSSM

This chapter is devoted to introduce the the Minimal Supersymmetric extension of the Standard Model (MSSM) whit focus on its Higgs sector. In section... introduction is given based on [3],

## 1.1 The Standard Model of Particle Physics and its Limitations

The Standard Model (SM) of particle physics is a theory aimed to describe and quantitatively predict the phenomenology of fundamental interaction. At “microscopic” level all the phenomenology of matter and radiation can be understood in terms of three classes of fundamental interactions, which are the strong, the electromagnetic and the weak interactions, the gravitational force is instead negligible in atomic and nuclear physics (quantum effects in gravity are expected to become important at energies corresponding to the Planck mass  $E \sim M_{\text{planck}}c^2 \sim 10^{19}$  GeV). All these interactions (with the exception of gravity) are described by a local relativistic quantum field theory. To each particle, described as pointlike, is associated a field with suitable (depending on the particle spin) transformation properties under the Lorentz group (the relativistic space-time coordinate transformations). The description of all these particle interactions is based on a common principle: “gauge” invariance. A gauge symmetry is invariance under transformations that rotate the basic internal degrees of freedom but with rotation angles that depend on the space-time point.

The SM is a gauge field theory based on the symmetry group  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ . This group has  $8 + 3 + 1 = 12$  generators with a non trivial commutator algebra. The electromagnetic and weak interactions (EW) are described by the  $SU(2)_L \otimes U(1)_Y$  symmetry group, while the  $SU(3)_c$  is the colour group of the theory of strong interactions (QCD). To each generator of the symmetry group is associated a vector boson which act as mediator of the corresponding interactions. Eight gluons are associated to the  $SU(3)_c$  colour generators, while for  $SU(2)_L \otimes U(1)_Y$  there are four gauge bosons  $W^\pm$ ,  $Z^0$  and  $\gamma$ . Of these, only the gluons and the photon are massless since the symmetry induced by the other three generators is spontaneously broken. In the SM the spontaneous symmetry breaking is realized by the Higgs mechanism, the Higgs particle has been recently found at the LHC with  $m_H \sim 125$  GeV representing one of the major milestones of particle physics. The Higgs boson acts as mediator of a new class of interactions that, at tree level, are coupled in proportion to the particle masses.

The fermionic (all of spin 1/2) matter fields of the SM are quarks and leptons. Quarks are subject to all SM interactions, each type of quark is a colour triplet and carries electroweak charges, in particular electric charges  $+2/3$  for up-type quarks and  $-1/3$  for down-type quarks. Leptons are colourless but have electroweak charges, in particular electric charges  $-1$  for charged leptons  $e$ ,  $\mu$  and  $\tau$  (opposite sign charge is intended for respective anti-particle) and charge 0 for neutrinos  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ . Quarks and leptons are grouped in three “generations” with equal quantum numbers but different masses.

Precision tests of the SM have been performed over a wide range of energies in experiment in the last several decades, Precision tests [8] of the standard electroweak theory performed at LEP, SLC and Tevatron [7], has confirmed the couplings of quark and leptons to the weak gauge bosons  $W^\pm$  and  $Z$  are indeed precisely those prescribed by the gauge symmetry. The accuracy of a few per-mille for these tests implies that, not only the tree level, but also the structure of quantum corrections

Names	Supermultiplets	Spin 1/2	Spin 0
quark, squarks ( $\times 3$ families)	$Q$	$(u_L \ d_L)$	$(\tilde{u}_L \ \tilde{d}_L)$
	$\bar{u}$	$u_R^\dagger$	$\tilde{u}_R^*$
	$\bar{d}$	$d_R^\dagger$	$\tilde{d}_R^*$
leptons, sleptons ( $\times 3$ families)	$L$	$(\nu \ e_L)$	$(\tilde{\nu} \ \tilde{e}_L)$
	$\bar{e}$	$e_R^\dagger$	$\tilde{e}_R^*$
higgsinos, Higgs	$H_u$	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	$(H_u^+ \ H_u^0)$
	$H_d$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(H_d^0 \ H_d^-)$

Table 1.1: This table is based on [4] and summarize the chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars and the spin-1/2 are left-handed two-component Weyl fermions.

has been verified. Several other experimental results [6] rare decays and the anomalous magnetic moment of the muon provide a test for low-energies of the standard model.

## 1.2 The Minimal Supersymmetric Standard Model

Supersymmetry (SUSY) was first introduced since it offer a natural way to solve the hierarchy problem....[] This is achieved by introducing a symmetry transformation that relates bosons with fermions. The SUSY generators  $\mathcal{Q}$  transforms fermion into bosons and vice versa:

$$\mathcal{Q}|\text{Fermion}\rangle = |\text{Boson}\rangle, \quad \mathcal{Q}|\text{Boson}\rangle = |\text{Fermion}\rangle \quad (1.1)$$

This is suggesting that in a supersymmetric extension of the SM [?] each of the known fundamental particles is in either a chiral or gauge “supermultiplet” and must have a superpartner with spin differing by 1/2 unit. Fermions since the left-handed and right-handed component transform differently under gauge transformations also their superpartner should maintain this property, the name of the superpartner of the quarks and leptons are made by adding an “s” to the SM name, standing for scalar. Accordingly, the gauge bosons related to the generator of the group  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$  should also have a spin 1/2 partner, whose name will be made by adding a “ino” at the end of the SM name. The symbol of superpartners is defined by adding a ( $\tilde{\phantom{x}}$ ) to the SM symbol.

The Minimal Supersymmetric extension of the Standard Model (MSSM) [?], is defined by requiring the minimal gauge group (i.e., the SM one) and the minimal particle content: three generation of fermions (without right-handed neutrinos), gauge bosons and two Higgs doublet, each with its superpartners. Tables 1.1 and 1.2 summarize chiral and gauge supermultiplets in the MSSM.

Names	Spin 1	Spin 1/2
gluon, gluino	$g$	$\tilde{g}$
W bosons, winos	$W^\pm \ W^0$	$\tilde{W}^\pm \ \tilde{W}^0$
B boson, bino	$B^0$	$\tilde{B}^0$

Table 1.2: This table is based on [4] and summarize the gauge supermultiplets in the Minimal Supersymmetric Standard Model.

### ***R*-parity conservation**

The MSSM also requires a discrete and multiplicative symmetry called *R*-parity [?], this symmetry assures baryon and lepton number conservation and it is defined as follows:

$$R_p = (-1)^{2s+3B=L} \quad (1.2)$$

where  $L$  and  $B$  are lepton and baryon numbers and  $s$  stands for the spin quantum number. *R*-parity quantum numbers has value +1 for ordinary SM particles and  $-1$  for their superpartners. This symmetry was first introduced to overcome the problem of instability of the proton, lepton and baryon number violation leads, in many cases, to unstable proton with life-time shorter than the experimental lower limit. However the conservation of *R*-parity has also other important phenomenological consequences, SUSY particle are always produced in pairs and in their decay there is always an odd number of SUSY particle, and the lightest SUSY particle is stable, providing a good candidate for dark matter.

### **The Soft SUSY Breaking**

In case the Supersymmetry is an exact symmetry of nature, the bosonic fields and the corrispective fermion fields should have the same mass and quantum numbers, except for the spin. However, the particle spectrum of SUSY has not yet been observed, suggesting that these particle should have an higher mass than their SM superpartners. To achieve SUSY-breaking in a way which does not reintroduce the quadratic divergences to the Higgs mass squared, a so called “soft-SUSY-breaking” term is introduced [?], this term explicitly break SUSY introducing ad hoc the mass terms for Higgs, gauginos and sferions, furthermore trilinear coupling terms between sfermions and Higgs bosons are introduced. In general, if intergenerational mixing and complex phases are allowed, the soft-SUSY-breaking terms will introduce a huge number of unknown parameters  $\mathcal{O}(100)$  [?]. However, in absence of phases and mixing, and if obey to a set of boundary conditions [?], only few new parameters are introduced.

## 1.3 The Higgs Sector in The MSSM

## 1.4 Higgs Phenomenology in The MSSM





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