

## Chapter 2

# Supersymmetry and the MSSM

The Standard Model is a very successful theory in predicting the experimental observations through the latest years. With a possible discovery of the Higgs boson, the SM will be a theory of almost everything. However questions arise when the Standard Model is seen as part of a larger unified theory. The masses of the gauge bosons in SM are derived by the vacuum expectation value of the Higgs boson which it was found in the previous chapter to be

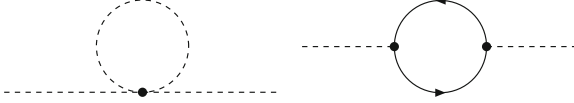
$$v = 246 \text{ GeV} \quad (2.1)$$

The mass of the  $W/Z$  and Higgs depends on this value. A first question is what is happening if loops are included in the diagrams. One example is the Higgs self interaction diagram in Fig. 2.1 on the left.

This diagram will correct the Higgs mass in higher orders by a factor of

$$\lambda \int^{\Lambda} d^4k \frac{1}{k^2 - m_h^2} \quad (2.2)$$

which seems to be quadratically divergent. However, the SM is a renormalizable theory. This means that the Lagrangian term  $-\mu^2$  can be picked so that it depends on the cut-off  $\Lambda$  and if  $\Lambda \rightarrow \infty$ , the renormalized coefficient has the desired value. The problem, however, arises when we see the SM as a part of a larger theory that appears in a scale  $\Lambda$  where the SM needs to be modified. One example is what happens at the Planck scale where quantum gravity becomes important. If the integral in Eq. 2.2 stops at a finite scale  $\Lambda$  the correction term to the mass is positive and proportional to  $\lambda \Lambda^2 \phi^\dagger \phi$ . Therefore if there is new physics at a higher scale the SM is going to collapse. This problem is known as the hierarchy problem [1]. One important step in solving the hierarchy problem is to consider the one loop correction to the Higgs mass but via a fermion loop this time (Fig. 2.1 on the right). This term is:



**Fig. 2.1** Scalar (*left*) and fermion (*right*) loop corrections to the Higgs mass

$$\left[ -g^2 \int^\Lambda \frac{d^4 k}{\not{k} \not{k}} \right] \phi^\dagger \phi \approx -g^2 \Lambda^2 \phi^\dagger \phi \quad (2.3)$$

Combining this term with the one derived from the scalar loop gives:

$$(\lambda - g^2) \Lambda^2 \phi^\dagger \phi \quad (2.4)$$

So if  $g^2 = \lambda$  the quadratic divergence disappears. Therefore if for each scalar there was a fermion partner with  $g^2 = \lambda$  the divergences would not occur any more. The existence of such a particle partner imposes a new symmetry between fermions and bosons known as Supersymmetry [2]. To define Supersymmetry (SUSY) we need a set of generators for the symmetry that can turn a bosonic state to a fermionic state and vice versa. That implies that the generators themselves must carry spin of 1/2. The simplest selection of SUSY generators is a 2-component Weyl spinor  $Q$  and its conjugate  $\bar{Q}$  such that:

$$Q|\text{boson}\rangle = |\text{fermion}\rangle \quad Q|\text{fermion}\rangle = |\text{boson}\rangle \quad (2.5)$$

The algebra of the generators can be written in terms of the anti-commutators as:

$$Q_\alpha, Q_\beta = \bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}} = 0 \quad (2.6)$$

$$[Q_\alpha, P_\mu] = 0 \quad (2.7)$$

$$Q_\alpha, \bar{Q}_{\dot{\beta}} = 2\sigma_{\alpha\dot{\beta}}^\mu P_\mu \quad (2.8)$$

where  $P_\mu$  is the translation generator (momentum) and  $\alpha, \beta$  take values of 1,2. From the commutation relations it can be shown that:

$$P^\mu P_\mu Q|b\rangle = P^\mu P_\mu|f\rangle = m_f^2|f\rangle \quad (2.9)$$

but also

$$P^\mu P_\mu Q|b\rangle = Q P^\mu P_\mu|b\rangle = m_b^2 Q|b\rangle = m_b^2|f\rangle \quad (2.10)$$

Therefore the masses of the boson and the fermions must be the same. This has not been observed experimentally which leads to the conclusion that if SUSY exists it must be broken so that the masses of the bosons and the corresponding fermions must be different.

## 2.1 The Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Standard Model (MSSM) is a straightforward supersymmetric extension of the SM. It is designed to satisfy the phenomenological constraints imposed by the experimental observations. SUSY transformations do not act in the  $SU(3)$ ,  $SU(2)$ ,  $U(1)$  degrees of freedom. For example a lepton doublet cannot have the Higgs boson as a super-partner since the Higgs doublet doesn't carry lepton number which needs to be conserved. Therefore, the spectrum of SM particles must be doubled in the MSSM. There are two types of super-multiplets in SUSY theories: Chiral super-multiples that contain one fermion and a complex scalar boson and gauge supermultiplets that contain one vector boson and one fermion. All fermions in the SM are parts of chiral super-multiplets. Their scalar super-partners are called squarks and sleptons and are coupling to the electroweak interactions exactly as the nominal SM particles. The SM vector boson fields are members of gauge super-multiplets and their fermionic super-partners are known as gauginos (gluinos, winos, binos). Photinos and zinos are defined as linear combinations of winos and binos, exactly as in the SM case. For the Higgs sector two Higgs doublets are needed and their corresponding fermion super-partners (Higgsinos). The Higgs sector is described in detail in the next section.

In SUSY, particles are assigned a quantum number known as R-parity defined as:

$$R = (-1)^{3B+L+2S}, \quad (2.11)$$

where  $B$  is the baryon number,  $L$  is the lepton number and  $S$  is the spin.  $R$  is  $+1$  for usual SM particles and  $-1$  for SUSY particles. The  $R$  parity is introduced to forbid couplings in the theory that allow the baryon and lepton numbers to not be conserved. Such couplings would allow decay of the proton. Conservation of  $R$  parity introduces additional phenomenological constraints such as the fact that the lighter supersymmetric particle (LSP) is stable. This is interesting in the sense that LSP could be a very good candidate for dark matter. In addition, the production of supersymmetric particles in colliders must conserve the  $R$  parity therefore they are always produced in pairs.

## 2.2 The Higgs Sector in the MSSM

In the MSSM, the Higgs sector is described by a model consisting of two Higgs doublets.

$$\Phi_1 = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \quad (2.12)$$

The  $\Phi_1$  doublet has hypercharge of  $-1$  and gives masses to the down-type quarks and charged leptons while the  $\Phi_2$  doublet gives masses to the up-type quarks. In the

MSSM two doublets are needed to cancel out anomalies in triangle diagrams with three bosons and a triangle loop. Those diagrams cancel in the SM due to the equal number of quark and lepton generations. In the same manner, two Higgs doublets are needed to cancel out the anomalies in the triangle loops with higgsinos in the loop. Each Higgs doublet has a different vacuum expectation value. Translating the fields at their minima gives the following mass eigenstates:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \sqrt{2} \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \text{Re} \phi_1^{0*} - v_1 \\ \text{Re} \phi_2^0 - v_2 \end{pmatrix} \quad (2.13)$$

$$A = \sqrt{2}(\sin \beta \text{Im} \phi_1^{0*} + \cos \beta \text{Im} \phi_2^0), \quad (2.14)$$

$$H^- = (H^+)^* = -\phi_1^- \sin \beta + \phi_2^- \cos \beta \quad (2.15)$$

Therefore in the MSSM the Higgs sector consists of two scalar bosons  $h, H$ , a pseudo-scalar  $A$  and a pair of charged Higgs bosons  $H^\pm$ . The angle  $\beta$  is related to the vacuum expectation values of the two Higgs doublets as

$$\tan \beta = \frac{v_1}{v_2} \quad (2.16)$$

At tree level, the MSSM Higgs sector is described only by two parameters which can be the mass of the pseudo-scalar  $A$  and the  $\tan \beta$ . The masses of the other neutral bosons are given by:

$$m_h^2 = \frac{1}{2}(m_A^2 + m_Z^2 - \sqrt{(m_A^2 - m_Z^2)^2 + 4m_Z^2 m_A^2 \sin^2(2\beta)}) \quad (2.17)$$

$$m_H^2 = \frac{1}{2}(m_A^2 + m_Z^2 + \sqrt{(m_A^2 - m_Z^2)^2 + 4m_Z^2 m_A^2 \sin^2(2\beta)}) \quad (2.18)$$

while the mass of charged Higgs in tree level is given by

$$m_{H^\pm}^2 = m_A^2 + M_W^2 \quad (2.19)$$

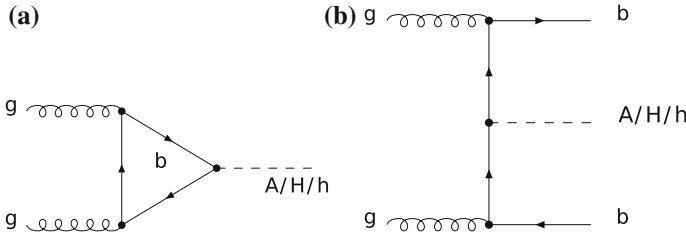
To make reliable phenomenological predictions, loop corrections have to be included that depend on the masses of the SUSY particles. Therefore specific benchmark scenarios are chosen for the MSSM based on the SUSY parameters. This thesis uses the  $m_h^{\text{max}}$  scenario [3] which is defined by:

$$\begin{aligned} M_{\text{SUSY}} &= 1 \text{ TeV}, \quad X_t = 2M_{\text{SUSY}}, \quad \mu = 200 \text{ GeV}, \\ M_{\tilde{g}} &= 800 \text{ GeV}, \quad M_2 = 200 \text{ GeV}, \quad A_b = A_t, \end{aligned} \quad (2.20)$$

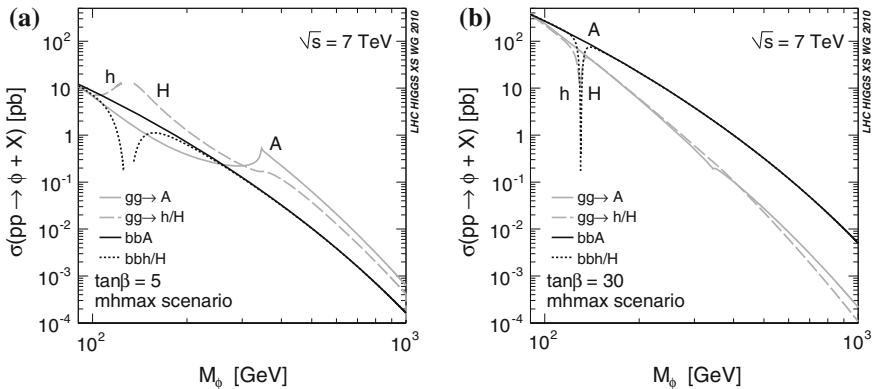
where  $M_{SUSY}$  denotes the common soft-SUSY-breaking squark mass of the third generation,  $X_t = A_t - \mu/\tan\beta$  the stop mixing parameter,  $A_t$  and  $A_b$  the stop and sbottom trilinear couplings, respectively,  $\mu$  the Higgsino mass parameter,  $M_{\tilde{g}}$  the gluino mass, and  $M_2$  the SU(2)-gaugino mass parameter.  $M_1$  is fixed via the GUT-relation  $M_1 = 5/3 M_2 \sin\theta_w/\cos\theta_w$ .

### 2.3 MSSM Higgs Production in Proton Collisions

The two doublet structure of the Higgs sector in the MSSM is responsible for some very interesting phenomenological effects that do not appear in the SM. The dominant production mechanisms are gluon fusion and associated production of  $b$  quarks (Fig. 2.2). For large values of  $\tan\beta$ ,  $\mathcal{O}(10)$ , the couplings to the down-type fermions is enhanced practically for the heaviest ones ( $b$ ,  $\tau$ ) resulting in higher branching ratios for the  $\phi \rightarrow \tau^+\tau^-$  and  $\phi \rightarrow b\bar{b}$  final states that are almost constant as a function of  $m_A$  at the values of 10 % and 90 % respectively.



**Fig. 2.2** Dominant MSSM Higgs production mechanisms in proton collisions. **a** Gluon fusion **b** Associated production with  $b$  quarks



**Fig. 2.3** Production cross section for different MSSM Higgs bosons and production mechanisms [4]. **a**  $\tan\beta = 5$  **b**  $\tan\beta = 30$

In addition, the top loop in the gluon fusion is augmented by an enhanced bottom loop resulting in enhancement of the gluon fusion cross section by a factor proportional to  $\tan \beta^2$ . Moreover, due to the increased  $b$  couplings, the associated production with  $b$  quarks becomes a dominant mechanism. The presence of  $b$  quarks in the final state makes possible to identify them and enhance sensitivity against the  $Z \rightarrow \tau\tau$  background. Figure 2.3 shows the production cross section for two different values of  $\tan \beta$ . The enhancement of the cross section at higher  $\tan \beta$ , the high branching ratio to di-tau final state and the presence of the associated production with  $b$  quarks makes the MSSM Higgs search extremely promising at the LHC.

## References

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Heavy Neutral Particle Decays to Tau Pairs  
Detected with CMS in Proton Collisions at  $\sqrt{s} =$   
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