Contents

Chapter 1

The Higgs Bosons and the MSSM

This chapter is devoted to introduce the theoretical background to the experimental search presented in this thesis. A brief overview of the Standard Model of particle physisics is given in Section 1.1 based on Reference [1]. Among all the extesion of the Standard Model, the Minimal Supersymmetric extension of the Standard Model (MSSM) is a theoretically favoured scenario as one of the most predictive framework beyond the Standard Model, it is introduced in Section 1.2 with focus on its Higgs sector and is based on References [2, 3]. Finally, a review of the MSSM Higgs bosons phenomenological aspects, which are relevant to the presented search, is given in Section 1.3 based on Reference [4].

1.1 The Standard Model of Particle Physics

1.1.1 Introduction

A detailed description of the Standard Model of particle physics may be found in Ref. [5], only a brief overview is given in what follows.

The Standard Model (SM) of particle physics is a theory aimed to describe and quantitatively predict the phenomenology of foundamental interactions. At "microscopic" level the spectrum of all interactions between matter and radiation can be understood in terms of three classes of foundamental forces: the strong, the electromagnetic and the weak forces. These interactions are described by a local relativistic quantum field theory, where to each particle is associated a field with suitable transformation properties under the Lorentz group. The theory is based on the principle of gauge invariance, which means invariance under a symmetry transformations that operates on basic internal degrees of freedom and depends on the space-time coordinate. The gravitational force is negligible in atomic and nuclear physics, in fact, quantum effects of gravity are expected at energies corresponding to the Planck mass $E \sim M_{planck}c^2 \sim 10^{19}$ GeV.

The SM is a gauge field theory based on the symmetry group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. The group has $8 + 3 + 1 = 12$ generators with a non trivial commutator algebra. The electromagnetic and weak interactions [6–8] 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) [9]. To each generator of the symmetry group is associated a vector boson which act as mediator of the correspondig interactions. Eight gluons are associated to the $SU(3)_c$ colour generators, while for four gauge bosons $W^{\pm}$, Z^0 and γ are associated to the generators of $SU(2)_L \otimes U(1)_Y$. Only the gluons and the photon are massless since the symmetry induced by the other three generators is spontaneusly broken. In the SM the spontaneus symmetry breaking is realized by the Higgs mechanism [10–14]. The Higgs boson acts as mediator of a new class of interactions that, at tree level, are coupled in proportion to the particle masses. An Higgs boson, with properties that resemble the one of the SM, has recently been discovered at the LHC with $m_H \sim 126$ GeV [15,16] and represents one of the major mailstone of particle physics.

The fermionic 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, μ and τ (opposite sign charge is intended for respective anti-particle) and charge 0 for neutrinos ν_e, ν_μ and ν_τ. Qarks and leptons are grouped in three "generations" with equal quantum numbers but different masses.

1.1.2 Precision Test and Limitation of the SM

Precision tests of the SM has been performed over a wide range of energies in experiment in the last several decades, Precision tests [20] of the standard electroweak theory performed at LEP, SLC and Tevatron [19], 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 has been verified. Several other experimental results [18] including rare decays and the anomalus magnetic moment of the muon provide a test for low-energies of the standard model. The recent discovery of a Higgs boson with mass in perfect agreement with the prediction of the SM [21].

In spite of this success, the Standard Model is conceptually unsatisfactory for quite few deficiencies and is widely belived to be an effective theory valid only at the present accessible energies. Beside the fact that it does not include gravitational force, it does not explaint the pattern of fermion masses and in its simplest version does not include neutrino masses, it ha at least other three conceptual problems which indicates the need for physics Beyond the Standard Model (BSM):

- Calculating the radiative correction to the Higgs boson mass, quadratic divergencies of the order of the cut-off scale Λ occur, where Λ defines the energy beyond which the theory ceases to be valid and new physics should appear [**?**]. If the cut-off is choosen to be $\sim M_{Planck}$, then an unnatural fine tunig should occur to cancell these divergencies leaving the Higgs boson with a mass of the order of the electroweak breaking scale, M_{EW}. A question that has no satisfactory answer in the SM is how these cancellations can occur and why $\Lambda >> M_{EW}$, these problems are called the fine-tuning and hierarchy problem [22–24].

- The SM does not have a candidate which can explain the large contribution of non-barionic, non-luminous matter to the density of the Universe [25–27]. To be a Dark Matter candidate a particle should be stable, massive and should interact only via very weak interactions.

- Another unsatisfactory aspect of the SM is that does not provide the unification of the electroweak and strong interactions, their couplings do not meet at high energies. Considering the successfull unification of electromagnetic and weak interaction, the existence of Grand Unified Theory (GUT) has been suggested [28, 29], which predicts the unification of all the three gauge coupling strenght at the GUT energy scale, $\Lambda_{GUT} \simeq 10^{16}$ GeV and describes the three forces within a single gauge group with just one coupling constant.

Among all the extension of the SM, Supersymmetry is a theoretically favoured scenario as the most predictive framework beyond the Standard Model. As discussed in Section 1.2, it gives a natural answer to the hierarchy problem, provides a suitable candidate for Dark Matter and predicts unification of the three gauge couplings at GUT energy scale.

Names	Supermultiplets	Spin 1/2	Spin 0
quark, squarks	Q	$(u_L\ d_L)$	$(\tilde{u}_L\ \tilde{d}_L)$
(× 3 families)	$\bar{u}$	$u_R^\dagger$	$\tilde{u}_R^*$
	$\bar{d}$	$d_R^\dagger$	$\tilde{d}_R^*$
leptons, sleptons	L	$(\nu\ e_L)$	$(\tilde{\nu}\ \tilde{e}_L)$
(× 3 families)	$\bar{e}$	$e_R^\dagger$	$\tilde{e}_R^*$
higgsinos, Higgs	H_1	$(\tilde{H}_1^0\ \tilde{H}_1^-)$	$(H_1^0\ H_1^-)$
	H_1	$(\tilde{H}_2^+\ \tilde{H}_2^0)$	$(H_2^+\ H_2^0)$

Table 1.1: This table is based on [2] 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.

1.2 The Minimal Supersymmetric Standard Model

1.2.1 Introduction to the MSSM

Supersymmetry (SUSY) [30–32] was first introduced since as a natural way to solve the hierarchy problem. The SUSY generators $\mathcal{Q}$ transforms fermion into bosons and vice versa:

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

This is suggesting that in a supersymmetric extesion of the SM each of the known foundamental particles is in either a chiral or gauge “supermultiplet” and must have a superpartner with spin differing by 1/2 unit. In this way, the quadratic divergent loop contribution to the Higgs mass of the SM particles are canceled by the loop contribution of the corresponding partners. Since the left-handed and right-handed components of fermions 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 ($\tilde{}$) to the SM symbol.

The Minimal Supersymmetric extension of the Standard Model (MSSM) [33–38], 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. This guys will mix to form neutralino and chargino....

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 [2] 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 barion and lepton number conservation and it is defined as follows:

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

where L and B are lepton and barion 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 barion 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 fenomenological 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.

1.2.2 The Higgs Sector in the MSSM

In the MSSM two doublets of complex scalar field of opposite hypercharge are required to break the electroweak symmetry, this requirement is motivated by the needs to generate masses separately to isospin up-type fermion and down-type fermions [?] and to cancel chiral anomalies that otherwise would spoil the renormalizability of the theory [?]. The two Higgs doublet then are:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ with } Y_{H_1} = -1, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \text{ with } Y_{H_2} = +1 \tag{1.3}$$

In analogy with the SM, a similar Higgs mechanism is employed in the MSSM [?], requiring that the minimum of the Higgs potential breaks $SU(2)_L \otimes U(1)_Y$ group while preserving the electromagnetic symmetry $U(1)_Q$. the to break electroweak symmetry. The neutral components of the two Higgs field acquire vacuum expectation values:

$$\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}}, \qquad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}} \tag{1.4}$$

Three of the original eight degrees of freedom of the scalar fields are absorbed by the $W^{\pm}$ and Z bosons, building their lomgitudinal polarizations and acquire masses. The remaning degrees of freedom correspond to five scalar Higgs bosons: two CP-even and neutral h and H, a neutral pseudoscalar boson A and a pair of charged bosons $H^{\pm}$. At tree level, besides the masses of these particle, two additional parameter define the system: the mixing angle in the neutral CP-even sector α and the ratio between the two vacuum expectation value $\tan\beta = v_1/v_2$. However, the supersymmetric structure of the theory impose strong constraint on the Higgs spectrum, out of the six parameters which describe the MSSM Higgs sector, M_h, M_H, M_A, $M_{H^{\pm}}$, β and α, only two are actually independent at tree level, a common choice is $\tan\beta$ and M_A. At tree level these relation impose a strong hierarchical structure on the mass spectrum: the h boson is the lightest with $M_h < M_Z$, $M_A < M_H$ and $M_{H^{\pm}}^2 = M_A^2 M_W^2$. Furthermore, the following relation holds between the mixing angles, which is particularly important for the Higgs couplings:

$$\cos^2(\beta - \alpha) = \frac{M_h^2(M_Z^2 - M_h^2)}{M_A^2(M_H^2 - M_h^2)} \tag{1.5}$$

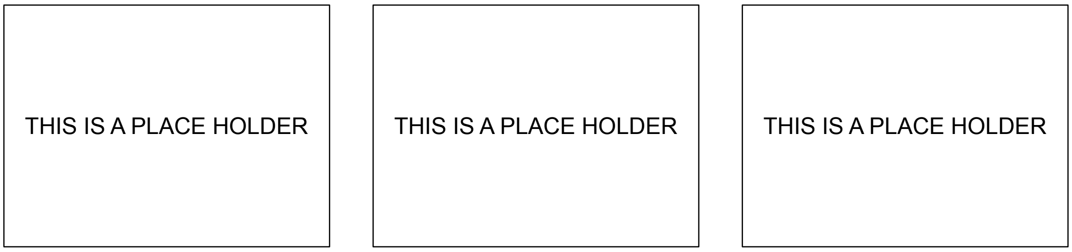
These relations, however, are broken by large radiative corrections to the Higgs masses [?], which cause the costraint on the mass of h to move from the tree level value of M_Z to $M_h \lesssim 140$ GeV. Another restriction, coming from GUT assumptions gives $1 \lesssim \tan\beta \lesssim m_t/m_b$ [?].

1.3 Neutral Higgs Bosons Phenomenology in the MSSM

1.3.1 MSSM Higgs Couplings with SM Particles

The phenomenology of the MSSM Higgs bosons is enclused in their couplings with standard model and supersymmetric particles, a short overview of the former, based onthe review [3], is given in this section.

The Feynman diagram for the possible couplings between MSSM Higgs bosons and vector bosons are shown in Figure 1.3.1, where is possible to identify threelinear



(a) (b) (c)

Figure 1.1: Feynman diagrams for the couplings between one Higgs boson and two gauge bosons (a), two Higgs bosons and one gauge boson (b) and two Higgs bosons and two gauge bosons (c). Based on [3].

couplings $V_\mu V_\nu H_i$ among one Higgs boson and two gauge bosons and $V_\mu H_i H_j$ among one gauge boson and two Higgs bosons, as well as the couplings between two Higgs bosons and two gauge bosons $V_\mu V_\nu H_i H_j$. Among these couplings, the most relevat for MSSM Higgs phenomenology is the trilinear couplings between two gauge bosons and one Higgs boson $V_\mu V_\nu H_i$, in this case, since the photon is massless, there are no Higgs-$\gamma\gamma$ and Higgs-$Z\gamma$ couplings at tree level, CP-invariance also forbids WWA, ZZA and $WZH^\pm$ couplings, for this case only the following couplings remains:

$$Z_\mu Z_\nu h \ : \ ig_z M_Z \sin(\beta-\alpha) g_{\mu\nu}, \qquad Z_\mu Z_\nu H \ : \ ig_z M_Z \cos(\beta-\alpha) g_{\mu\nu} \tag{1.6}$$
$$W_\mu^+ W_\nu^- h \ : \ ig_w M_W \sin(\beta-\alpha) g_{\mu\nu}, \quad W_\mu^+ W_\nu^- H \ : \ ig_w M_W \cos(\beta-\alpha) g_{\mu\nu} \tag{1.7}$$

The couplings of the neutral CP-even Higgs bosons h and H with pair of vector bosons are prortional to $\sin(\beta-\alpha)$ and $\cos(\beta-\alpha)$ respectively, where $\cos(\beta-\alpha)$ is fixed at tree level following equation (1.6). An interesting fenomenological consequence is that, calling G_{VVh} and G_{VVH} a general coupling between two vector bosons and one of the neutral CP-even Higgs bosons the following equation holds:

$$G^2_{VVh} + G^2_{VVH} = g^2_{VVH_{SM}} \tag{1.8}$$

this means that the couplings with vector bosons for h and H respectively increase and decrease with $\tan\beta$, for large value of $\tan\beta$, h has SM-like couplings with vector bosons and H decouple from them. For an overview of all the other couplinq between vector boson and Higgs bosons, charged Higgs, trilinear and quartic coupling between Higgs bosons and couplings to SUSY particles refer to [3].

The MSSM Higgs bosons couplings with isospin up-type u, and down-type d fermions also depend on $\tan\beta$ and may be written as follows:

$$\begin{aligned} G_{huu} &\propto m_u[\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)], & G_{hdd} &\propto m_u[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)] \\ G_{Huu} &\propto m_u[\cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha)], & G_{Hdd} &\propto m_d[\cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha)] \\ G_{Auu} &\propto m_u\cot\beta, & G_{Add} &\propto m_d\tan\beta \end{aligned}$$

Then the couplings with down-type (up-type) fermions of either the h or H boson is enhanced (suppressed) by a factor $\tan\beta$, depending on the magnitude of $\cos(\beta-\alpha)$ or $\sin(\beta-\alpha)$, while the coupling of A boson with down-type (up-type) fermions are directly enhanced (suppressed) by $\tan\beta$.

1.3.2 MSSM Higgs Benchmark Scenarios

In the MSSM the Higgs sector is fully determined at tree level by two free parameter by convention chosen to be M_A and $\tan\beta$, meaning that the Higgs bosons masses, decay branching fraction and production cross section are all determined. However, radiative corrections contribute significantly to the Higgs masses [?], these physical quatintity becomes dependent on several other parameters. The main corrections arises from the top-stop quark sector, and fro large $\tan\beta$ also from the bottom-sbottom quark sector, and in general dependent on the SUSY-breacking scale M_{SUSY}, the trilinear Higgs Yukawa couplings.

Due to the large number of free parameters, a complete scan of the MSSM parameter space is impractical in experimental analysis and phenomenological studies. Several benchmark scenarios has been proposed [4], where the SUSY parameters, entering via radiative corrections, are fixed to particular benchmark values which exibit interesting features of the MSSM Higgs phenomenology, while the parameters M_A and $\tan\beta$ are left free to vary, and usually results are presented in a $M_A - \tan\beta$ plane.

One of the most interesting benchmark scenarios is the m_h^{max} benchmark scenario [?], where the parameter that contributes to radiative corrections are fixed such that the mass of the light CP-even Higgs boson, M_h, is maximal under the variation of M_A and $\tan\beta$. This scenario allows to set conservative lower bounds on M_A, $M_H^{\pm}$ and $\tan\beta$ [?]. This scenario was used in the past to set limits at LEP, Tevatron and LHC [41–44], however, given the recent discovery of a Higgs boson with mass $\tilde{1}25.5$ GeV, this scenario tend to predict a too high mass for M_h, resulting to be, for large part of the parameter space, inconsistent with this observation by roughly two σ. The mass of M_h is bounded to be $M_h < 135$ GeV.

An interesting up-to-date benchmark scenario is the $m_h^{mod\pm}$ benchmark scenario, where departing from the parameter configuration of the m_h^{max} the amount of mixing in the stop sector is reduced and has the feature of predict that the lightest CP-even Higgs boson should have a mass $M_h \simeq 125.5 \pm 3$ GeV. The low-M_H benchmark scenario is complementary to the $m_h^{mod\pm}$, in this scenario, the observed Higgs boson is instead interpreted as the heavy CP-even Higgs boson of the MSSM, implying that h and A should have relatively small mass. For an overview of the interesting benchmark scenario refer to [4].

The m_h^{max} benchmark scenario has been used throughout this thesis, since it provides a model that can be compared with past exclusion limits and it has been shown that experimentally, the resolution to the Higgs mass in the $\tau\tau$ decay mode is not enough to distinguish between the m_h^{max} scenario and an updated scenario in which $M_h \simeq 125.5 \pm 3$ GeV for all the points in the parameter space. More over it is a “general purpose” scenario in which exclusion limits can be assesed from low to very large value of M_A, which is not the case otherwise due to the Higgs masses hierarchy.

1.3.3 Neutral MSSM Higgs Bosons Production and Decay at LHC

For large region of the MSSM parameter space a SM-like Higgs boson is expected, usually identified with the lightest CP-even Higgs boson, h. Given the Higgs bosons couplings discussed in Section 1.3.1 tourns out that, in this case, H and A, tend to be degenerate in mass and decouple from gauge bosons. Furthermore the coupling of the latter two Higgses with down (up) type fermions are enhanced (suppressed) by $\tan\beta$, therefore, for large $\tan\beta$ bottom-quark and τ lepton will play a more important role than in the SM case either for production and decay.

The production of the neutral CP-even MSSM Higgs bosons at hadron colliders proceeds via the same processes as for the SM Higgs production. However, the pseudoscalar A instead cannot be produced in association with gauge bosons or in vector boson fusion (VBF) at tree-level, as this coupling is forbidden due to CP-invariance. At the LHC one of the most relevant production mechanisms for the MSSM Higgs bosons is gluon-gluon fusion, $gg \to A/H/h$. In addition, the production in association with b-quarks becomes important for large value of $\tan\beta$. Those are the two production mechanism that are considered in this analysis, Figure 1.3 shows the Feynman-diagram for those processes, while Figure 1.4 shows the production cross section of the neutral MSSM Higgses via these two processes in the m_h^{max} scenario.

The decays of the neutral MSSM Higgs bosons (in the assumption that all supersymmetric particle are heavy enough) are the same as for the SM one with the already cited exception of A. Figure 1.4 shows the decay branching fractions for H and A as a function of the mass, the decay into tau pair is the most important after $b\bar{b}$ and the one used in this thesis.

1.3.4 Current Status of the Seacrh for Neutral MSSM Higgs Bosons

The measure of the couplings of the found SM-like Higgs boson can shed light on the Higgs sector and determine if this boson is fully responsable for the generation of all the SM particles masses. There are then two approaches to explore the Higgs sector: one, is to use the measured Higgs couplings with SM particles to set constraint on new physics, while the other is to directly search for additional Higgses in a well defined model, like in this case the MSSM.

In case the SM-like Higgs boson is interpreted as the light CP-even Higgs boson of the MSSM, the couplings of the Higgs boson to vector bosons (k_V), up-type fermions (k_u) and down-type fermions (k_d), can be expressed as a ratio to the corresponding SM expectation and this allow to set exclusion limits in the $m_A - \tan\beta$ plane [45]. Figure 1.5 shows the exclusion limits in a “simplified MSSM” model [?] via fits to the measured rates of Higgs boson production and decay.

The current latest constraint on $m_A - \tan\beta$ by direct search of neutral MSSM Higgs bosons are instead shown in Figure **??** and are part of the work of this thesis.

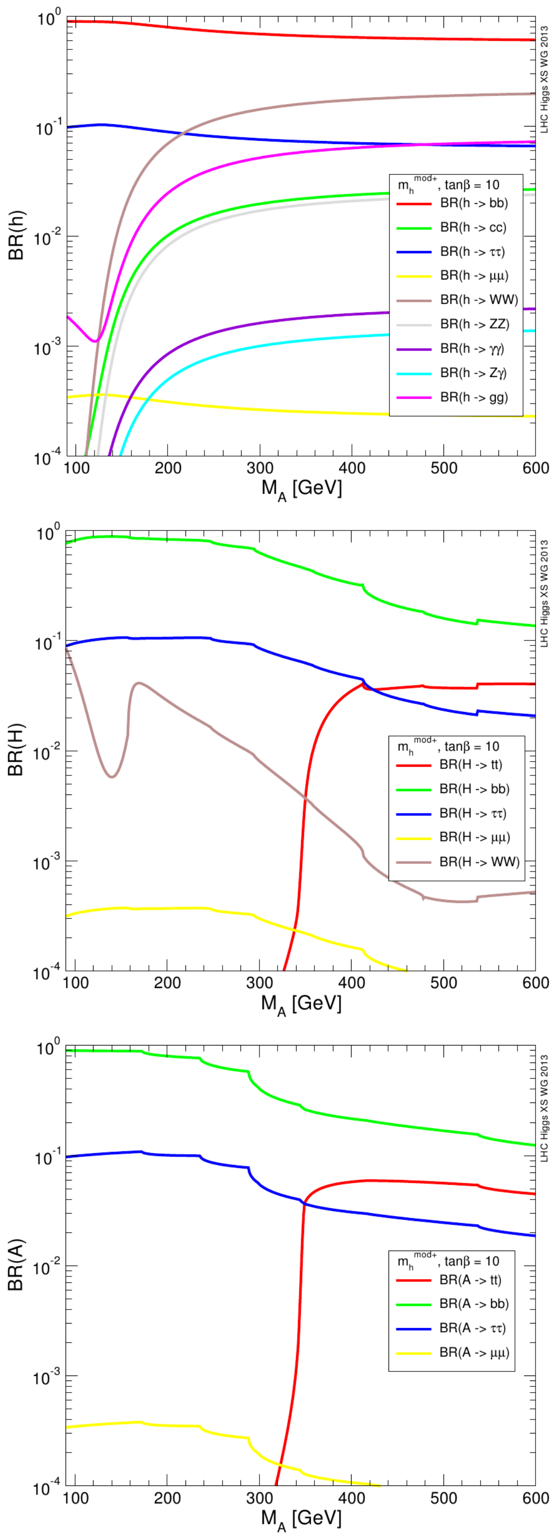


Figure 1.2: Branching fraction for the MSSM neutral higgses $h/H/A$ in the m_h^{max} scenario.

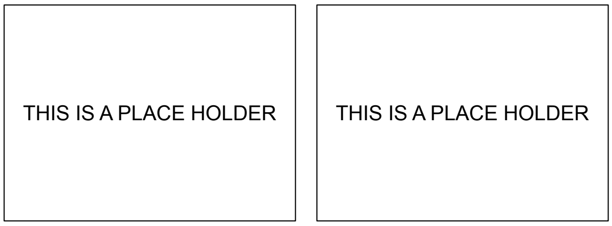


Figure 1.3: Feynman diagram for b-associated production and gluon-gluon fusion for MSSM neutral Higgs.

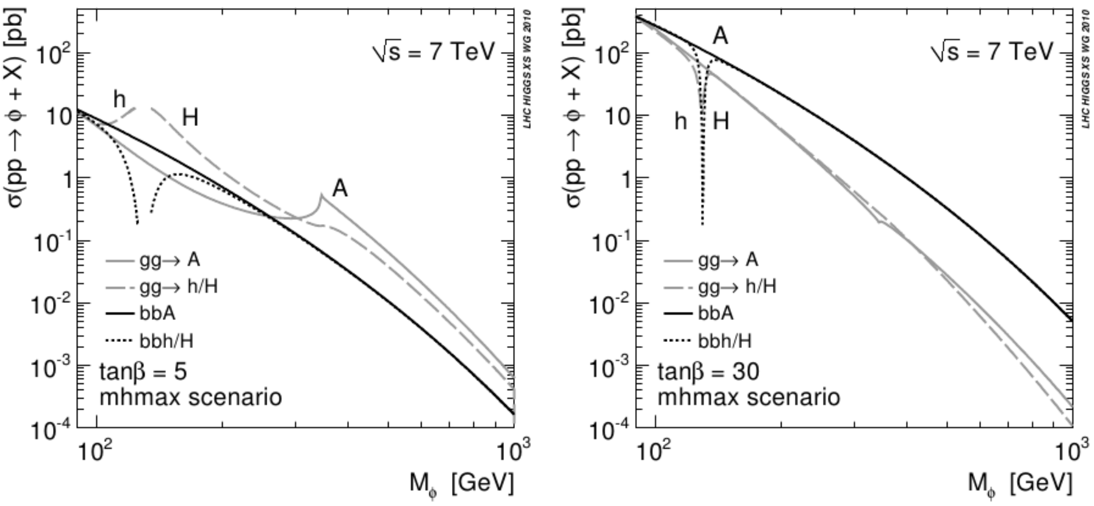


Figure 1.4: Production cross section for the $h/H/A$ MSSM neutral Higgs bosons via b-associated production and gluon-gluon fusion production mode. The calculation are for the m_h^{max} scenario and for $\tan\beta = 5$ (left) and $\tan\beta = 30$ (right).

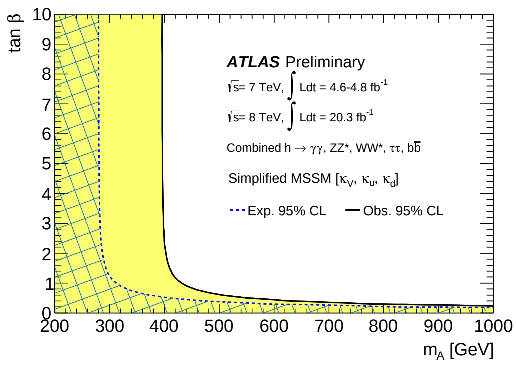


Figure 1.5: Regions of the $m_A - \tan\beta$ plane excluded in a simplified MSSM model via fits to the measured approximately to 95% CL (2σ), are indicated for the data and expectation assuming the SM Higgs sector. The light shaded and hashed regions indicate the observed and expected exclusions, respectively. The SM decoupling limit is $m_A \to \infty$. See Reference [45].

Bibliography

[1] G. Altarelli, *"Collider Physics within the Standard Model: a Primer,"* arXiv:1303.2842 .

[2] S. P. Martin, *"A Supersymmetry primer,"* In *Kane, G.L. (ed.): Perspectives on supersymmetry II* 1-153 [hep-ph/9709356].

[3] A. Djouadi, *The Anatomy of Electroweak Symmetry Breaking Tome II: The Higgs Bosons in the Minimal Supersymmetric Model*, Phys. Rep. 459 (2008) 1.

[4] S. Heinemeyer *et al.* [LHC Higgs Cross Section Working Group Collaboration], "Handbook of LHC Higgs Cross Sections: 3. Higgs Properties," arXiv:1307.1347 [hep-ph].

[5] Michael E. Peskin, Dan V. Schroeder, *An Introduction To Quantum Field Theory*, Westview Press, 1995.

[6] S. L. Glashow, Partial Symmetries of Weak Interactions, Nuc. Phys. 22 (1961) 579.

[7] A. Salam, Weak and Electromagnetic Interactions, Conf. Proc. C 680519 (1968) 367. Originally printed in Svartholm: Elementary Particle Theory, proceedings of the Nobel Symposium held 1968 at Lerum, Sweden.

[8] S. Weinberg, A Model of Leptons, Phys. Rev. Lett. 19 (1967) 1264.

[9] H. Fritsch, M. Gell-Mann, and H. Leutwyler, Advantages of the Color Octet Gluon Picture, Phys. Lett. B 47 (1973) 365.

[10] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev. Lett. **13** (1964) 321.

[11] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, Phys. Lett. **12** (1964) 132.

[12] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, Phys. Rev. Lett. **13** (1964) 508.

[13] P. W. Higgs, *Spontaneous Symmetry Breakdown without Massless Bosons*, Phys. Rev. **145** (1966) 1156.

[14] T. W. B. Kibble, Symmetry Breaking in NonAbelian Gauge Theories, Phys. Rev. 155 (1967) 1554.

[15] The ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Physics Letters B **716** (2012) 1–29.

[16] The CMS Collatoration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Physics Letters B **716** (2012) 30–61.

[17] W. Hollik, *"Electroweak theory,"* hep-ph/9602380.

[18] The Review of Particle Physics, J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012) and 2013 partial update for the 2014 edition.

[19] The ALEPH, CDF, D0, DELPHI, L3, OPAL and SLD Collaborations, the LEP Electroweak Working Group, Tevatron Working Group and SLD Electroweak and Heavy Flavour Working Groups, *Precision Electroweak Measurements and Constraints on the Standard Model*, arXiv:1012.2367. Updated for 2012 winter conferences, March 2012.

[20] G. Altarelli and M. W. Grunewald, *"Precision electroweak tests of the standard model,"* Phys. Rept. **403-404** (2004) 189 [hep-ph/0404165].

[21] The Gfitter Group, M. Baak, et al., Updated Status of the Global Electroweak Fit And constraints on New Physics, Eur. Phys. J. C 72 (2012) 2003. Updated for 2012 winter conferences, March 2012, http://gfitter.desy.de.

[22] S. Weinberg, Gauge Hierarchies, Phys. Lett. B 82 (1979) 387.

[23] M. Veltman, The InfraredUltraviolet Connection, Acta Phys. Polon. B 12 (1981) 437.

[24] C. Smith and G. Ross, The Real Gauge Hierarchy Problem, Phys. Lett. B 105 (1981) 38.

[25] F. Zwicky, Spectral Displacement of Extra Galactic Nebulae, Helv. Phys. Acta 6 (1933) 110.

[26] E. W. Kolb and M. S. Turner, The Early Universe, Front. Phys. 69 (1990) 1.

[27] The WMAP Collaboration, D. N. Spergel et al., First Year Wilkinson Microwave Anisotropy Probe (wmap) Observations: Determination of Cosmological Parameters, Astrophys. J. Suppl. 148 (2003) 175.

[28] H. M. Georgi and S. L. Glashow, Unity of All ElementaryParticle Forces, Phys. Rev. Lett. 32 (1974) 438.

[29] J. C. Pati and A. Salam, Lepton Number as the Fourth Color, Phys. Rev. D 10 (1974) 275.

[30] P. Fayet, Phys. Lett. B 64, 159 (1976).

[31] P. Fayet, Phys. Lett. B 69, 489 (1977), Phys. Lett. B 84, 416 (1979).

[32] G.R. Farrar and P. Fayet, Phys. Lett. B 76, 575 (1978).

[33] S. Martin, in Perspectives on Supersymmetry, Ed. G.L. Kane, World Scientific, Singa- pore, 1998, hep-ph/9709356.

[34] For reviews on the MSSM, see: P. Fayet and S. Ferrara, Phys. Rep. 32 (1977) 249; H.P. Nilles, Phys. Rep. 110 (1984) 1; R. Barbieri, Riv. Nuovo Cim. 11N4 (1988) 1; R. Arnowitt and Pran Nath, Report CTP-TAMU-52-93; J. Bagger, Lectures at TASI-95, hep-ph/9604232.

[35] H. E. Haber and G. Kane, Phys. Rep. 117 (1985) 75.

[36] M. Drees and S. Martin, CLTP Report (1995) and hep-ph/9504324.

[37] D.J.H. Chung, L.L. Everett, G.L. Kane, S.F. King, J. Lykken and L.T. Wang, Phys. Rept. 407 (2005) 1.

[38] M. Drees, R.M. Godbole and P. Roy, Theory and Phenomenology of Sparticles, World Scientific, Spring 2004.

[39] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.

[40] G. S. Guralnik, C.R. Hagen and T. W. B. Kibble Phys.Rev.Lett. **13** (1964) 585.

[41] ALEPH, DELPHI, L3 and OPAL Collaboration, *Search for neutral MSSM Higgs bosons at LEP*, Eur. Phys. J. **C47** (2006) 547.

[42] *Combined CDF and D0 upper limits on MSSM Higgs boson production in tau-tau final states with up to 2.2 fb^{-1} of data*, `arXiv:1003.3363 [hep-ex]`.

[43] The CMS Collaboration, S. Chatrchyan et al., `arXiv:1104.1619 [hep-ex] [hep-ex]`.

[44] The ATLAS Collaboration , *Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, `arXiv:1211.6956 [hep-ex]`.

[45] The ATLAS Collaboration , *Constraints on New Phenomena via Higgs Boson Coupling Measurements with the ATLAS Detector.* ATLAS-CONF-2014-010.

[46] S. Heinemeyer, O. Stål and G. Weiglein, *Interpreting the LHC Higgs search results in the MSSM*, Phys.Lett. **B710** (2012) 201–206, `arXiv:1112.3026 [hep-ph]`.

[47] A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, *The Higgs sector of the phenomenological MSSM in the light of the Higgs boson discovery*, JHEP **1209** (2012) 107, `arXiv:1207.1348 [hep-ph]`.

[48] The ATLAS Collaboration, G. Aad et al., *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[49] M. L. Mangano et al., *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, JHEP **07** (2003) 001.

[50] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, Eur. Phys. J. **C53** (2008) 473, `arXiv:0706.2569`.

[51] S. Frixione and B. R. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP **06** (2002) 029, `hep-ph/0204244`.

[52] B. P. Kersevan and E. Richter-Was, *The Monte Carlo Event Generator AcerMC 2.0 with Interfaces to PYTHIA 6.2 and HERWIG 6.5*, `arXiv:0405247v1 [hep-ph]`.

[53] G. Corcella et al., *HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, JHEP **01** (2001) 010.

[54] J. M. Butterworth, J. R. Forshaw, and M. H. Seymour, *Multiparton Interactions in Photoproduction at HERA*, Z. Phys. **C72** (1996) 637.

[55] T. Binoth, M. Ciccolini, N. Kauer, and M. Kramer, *Gluon-induced W-boson pair production at the LHC*, JHEP **12** (2006) 046.

[56] A. S. et al., *Higgs boson production in gluon fusion*, JHEP **02** (2009) 029.

[57] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009) 007.

[58] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, "New generation of parton distributions with uncertainties from global QCD analysis," JHEP **0207** (2002) 012 [hep-ph/0201195].

[59] H. -L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin and C. -P. Yuan, "New parton distributions for collider physics," Phys. Rev. D **82** (2010) 074024 [arXiv:1007.2241 [hep-ph]].

[60] M. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, *Suggestions for benchmark scenarios for MSSM Higgs boson searches at hadron colliders*, Eur. Phys. J. **C26** (2003) 601–607, `hep-ph/0202167`.

[61] The ATLAS Collaboration, *ATLAS Monte Carlo Tunes for MC09*, ATL-PHYS-PUB-2010-002.

[62] S. Jadach, J. H. Kuhn and Z. Was, *TAUOLA - a library of Monte Carlo programs to simulate decays of polarized τ leptons*, Comput. Phys. Commun. **64** (1990) 275.

[63] E. Barberio, B. V. Eijk and Z. Was, *Photos - a universal Monte Carlo for QED radiative corrections in decays*, Comput. Phys. Commun. **66** (1991) 115.

[64] The GEANT4 Collaboration, S. Agostinelli et al., *GEANT4 - a simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003) 250.

[65] The ATLAS Collaboration, G. Aad et al., *The ATLAS Simulation Infrastructure*, ATLAS-SOFT-2010-01-004, submitted to Eur. Phys. J. C., `arXiv:1005.4568`.

[66] The ATLAS Collaboration, *Estimation of $Z/\gamma^* \to \tau\tau$ Background in VBF $H \to \tau\tau$ Searches from $Z \to \mu\mu$ Data using an Embedding Technique*, ATL-PHYS-INT-2009-109.

[67] The ATLAS Collaboration, *Search for the Standard Model Higgs boson in the $H \to \tau\tau$ decay mode with 4.7 f b1 of ATLAS detector*, Tech. Rep. ATLAS-CONF-2012-014, CERN, Geneva, Mar, 2012.

[68] The ATLAS Collaboration, *Search for the Standard Model Higgs boson $H \to \tau\tau$ decays with the ATLAS detector*, ATL-COM-PHYS-2013-722.

[69] T. S. et al., Z *physics at LEP 1*, CERN 89-08 **3** (1989) 143.

[70] The ATLAS Collaboration, Inner Detector: Technical Design Report, CERN/LHCC/97-016/017 (1997).

[71] The ATLAS Collaboration, G. Aad et al., The ATLAS Experiment at the CERN Large Hardon Collider, 2008 JINST 3 S08003.

[72] A. Bazan, T. Bouedo, P. Ghez, M. Marino and C. Tull, "The Athena data dictionary and description language," eConf C **0303241** (2003) MOJT010 [cs/0305049 [cs-se]].

[73] The ATLAS Collaboration, *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics*, CERN-OPEN-2008-020, `arXiv:0901.0512`.

[74] T. Cornelissen et al., Concepts, Design and Implementation of the ATLAS New Tracking, ATLAS Note ATL-SOFT-PUB-2007-007 (2007).

[75] Kalman, R. E. (1960). *"A New Approach to Linear Filtering and Prediction Problems"*. Journal of Basic Engineering 82 (1): 3545. doi:10.1115/1.3662552

[76] The ATLAS Collaboration, Performance of primary vertex reconstruction in proton-proton collisions at $s = sqrt(7)$ TeV in the ATLAS experiment. ATLAS-CONF-2010-069.

[77] R. Fruhwirth, W. Waltenberger, P. Vanlaer, *Adaptive vertex fitting*, J. Phys. G34 (2007).

[78] The ATLAS Collaboration, *Characterization of Interaction-Point Beam Parameters Using the pp Event-Vertex Distribution Reconstructed in the ATLAS Detector at the LHC*, ATL-CONF-2010-027.

[79] The ATLAS collaboration, *Expected electron performance in the ATLAS experiment*, ATL-PHYS-PUB-2011-006

[80] The ATLAS Collaboration, *Electron reconstruction and identification efficiency measurements with the ATLAS detector using the 2011 LHC proton-proton collision data*, CERN-PH-EP-2014-040, arXiv:1404.2240

[81] The ATLAS Collaboration, G. Aad et al., *Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data*, Eur.Phys.J. C72 (2012) 1909.

[82] S. Hassini, et al., *A muon identification and combined reconstruction procedure for the ATLAS detector at the LHC using the (MUONBOY, STACO, MuTag) reconstruction packages*, NIM A572 (2007) 7779.

[83] The ATLAS Collaboration, G. Aad et al., *Preliminary results on the muon reconstruction efficiency, momentum resolution, and momentum scale in ATLAS 2012 pp collision data*, ATLAS-CONF-2013-088, CERN, 2013,

[84] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet user manual*, Eur.Phys.J. C72 (2012) 1896.

[85] W. Lampl et al., *Calorimeter Clustering Algorithms : Description and Performance*, ATL-LARG-PUB-2008-002.

[86] M. Cacciari, G. P. Salam, and G. Soyez, *The anti-kt jet clustering algorithm*, JHEP 04 (2008) 63.

[87] E. Abat, J. Abdallah, T. Addy, P. Adragna, et al., *Combined performance studies for electrons at the 2004 ATLAS combined test-beam*, JINST 5 (2010) P11006.

[88] ATLAS Collaboration, *Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV*, Submitted to EPJ (2011) , arXiv:1112.6426

[89] The ATLAS Collaboration, *Pile-up corrections for jets from proton-proton collisions at ATLAS in 2011*, ATLAS-CONF-2012-064, July, 2012.

[90] M. Cacciari and G. P. Salam, *Pileup subtraction using jet areas*, Phys.Lett. B659 (2008) 119.

[91] The ATLAS Collaboration, G. Aad et al., *Jet energy resolution in proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2010 with the ATLAS detector*, Eur.Phys.J. C73 (2013) 2306

[92] The ATLAS collaboration, *Jet energy scale and its systematic uncertainty in proton-proton collisions at $\sqrt{s} = 7$ TeV with ATLAS 2011 data*, ATLAS-CONF-2013-004

[93] The ATLAS Collaboration, *Data-Quality Requirements and Event Cleaning for Jets and Missing Transverse Energy Reconstruction with the ATLAS Detector in Proton-Proton Collisions at a Center-of-Mass Energy of* $\sqrt{s} = 7$ *TeV*, ATLAS-CONF-2010-038.

[94] G. Piacquadio, C. Weiser, *A new inclusive secondary vertex algorithm for b-jet tagging in ATLAS*, JPCS 119 (2008) 032032

[95] The ATLAS Collaboration, G. Aad et al., *Commissioning of the ATLAS high-performance b-tagging algorithms in the 7 TeV collision data, ATLAS-CONF-2011-102*, CERN, 2011, ATLAS-CONF-2011-102.

[96] The ATLAS Collaboration, *Measuring the b-tag efficiency in a ttbar sample with 4.7* fb^{-1} *of data from the ATLAS detector* ATLAS-CONF-2012-097.

[97] The ATLAS Collaboration, *Calibration of b-tagging using dileptonic top pair events in a combinatorial likelihood approach with the ATLAS experiment* ATLAS-CONF-2014-004.

[98] The ATLAS Collaboration, *Reconstruction and Calibration of Missing Transverse Energy and Performance in Z and W events in ATLAS Proton-Proton Collisions at* $\sqrt{s}$*=7 TeV*, ATLAS-CONF-2011-080.

[99] ATLAS Collaboration, G. Aad et al., Performance of missing transverse momentum reconstruction in proton-proton collisions at 7 TeV with ATLAS, Eur.Phys.J. C72 (2012) 1844.

[100] TheATLAS Collaboration, *Performance of the Reconstruction and Identification of Hadronic tau Decays in ATLAS with 2011 Data*, ATLAS-CONF-2012-142.

[101] The ATLAS Collaboration, G. Aad et al., *Performance of the ATLAS trigger system in 2010*, Eur.Phys.J. C72 (2012) 1849.

[102] The ATLAS Collaboration, G. Aad et al., *Performance of the ATLAS muon trigger in 2011*, ATLAS-CONF-2012-099, CERN, 2012.

[103] The ATLAS Collaboration, G. Aad et al., *Performance of the ATLAS electron and photon trigger in p-p collisions at* $\sqrt{s} = 7$ *TeV in 2011*, ATLAS-CONF-2012-048, CERN, 2012.

[104] M. Dobbs and J.B. Hansen, *The HepMC C++ Monte Carlo Event Record for High Energy Physics*, Computer Physics Communications, ATL-SOFT-2000-001.

[105] The ATLAS Collaboration, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data* , Phys. Lett. B 726 (2013), pp. 120-144.

[106] The ATLAS Collaboration, *Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC*, Phys. Lett. B 726 (2013), pp. 88-119.

[107] The CMS Collaboration, *"Evidence for the direct decay of the 125 GeV Higgs boson to fermions,"* arXiv:1401.6527 [hep-ex].

[108] The CMS Collaboration, *Higgs boson width from on- vs. off-shell production and decay to Z-boson pairs* , arXiv:1405.3455.

[109] A. Elagin, P. Murat, A. Pranko, and A. Safonov, *A New Mass Reconstruction Technique for Resonances Decaying to di-tau*, `arXiv:1012.4686 [hep-ex]`. * Temporary entry *.

[110] T. A. Collaboration, *Search for neutral MSSM Higgs bosons decaying to $\tau\tau$ pairs in proton-proton collisions at with the ATLAS detector*, Physics Letters B **705** (2011) no. 3, 174 – 192.

[111] The ATLAS Collaboration, *Data-driven estimation of the background to charged Higgs boson searches using hadronically-decaying tau final states in ATLAS,* ATLAS-CONF-2011-051.

[112] The ATLAS Collaboration, *Measurement of the $Z \to \tau\tau$ cross section with the ATLAS detector*, Phys. Rev. D **84** (2011) 112006.

[113] T. A. Collaboration, *Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, JHEP , `arXiv:1211.6956`.

[114] Atlas statistics forum, *ABCD method in searches*, link

[115] The ATLAS Collaboration, *Search for Neutral MSSM Higgs Bosons H to $\tau\tau$ to $l\tau_h$ with the ATLAS Detector in 7 TeV Collisions*, ATL-COM-PHYS-2012-094.

[116] The ATLAS Collaboration, *Search for neutral Higgs Bosons in the decay mode $H \to \tau\tau \to ll{+}4\nu$ in proton proton collision at $\sqrt{7}$ TeV with the ATLAS Detector*, ATL-COM-PHYS-2011-758.

[117] The Atlas Collaboration, *Measurement of the ttbar production cross-section in pp collisions at $\sqrt{s} = 8$ TeV using e-mu events with b-tagged jets* . ATLAS-CONF-2013-097.

[118] The ATLAS Collaboration, *Luminosity Determination in pp Collisions at $\sqrt{s} = 7$ TeV using the ATLAS Detector in 2011*, ATLAS-CONF-2011-116.

[119] T. Sjostrand, S. Mrenna and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026.

[120] A. B. et al., *Rivet user manual*, `arXiv:1003.0694 [hep-ph]`.

[121] The ATLAS and CMS Collaborations, *Procedure for the LHC Higgs boson search combination in summer 2011*, ATL-PHYS-PUB-2011-011, ATL-COM-PHYS-2011-818, CMS-NOTE-2011-005.

[122] W. Verkerke and D. P. Kirkby, *The Roofit Toolkit for Data Modeling*, eConf C0303241 (2003) MOLT007, arXiv:physics/0306116

[123] K. S. Cranmer et al., *The Roostats Project*, PoS ACAT2010 (2010) 57.

[124] K. Cranmer, G. Lewis, L. Moneta, A. Shibata, and W. Verkerke, *Histfactory: A Tool for Creating Statistical Models for use with Roofit and Roostats*, CERNOPEN2012016 (2012)

[125] E. G. G. Cowan, K. Cranmer and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, `arXiv:1007.1727 [hep-ex]`.

[126] A. L. Read. *Presentation of search results: the CLs technique.* J. Phys. G: Nucl. Part. Phys., 28, 2002.

[127] A. L. Read. *Modified frequentist analysis of search results (the CLs method).* In Proceedings of the First Workshop on Confidence Limits, CERN, Geneva, Switzerland, 2000.

[128] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, R. Tanaka (Eds.), et al., *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*, `arXiv:1101.0593 [hep-ph]`.

[129] LHC Higgs Cross Section Working Group, S. Dittmaier, C. Mariotti, G. Passarino, and R. Tanaka (Eds.), *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*, CERN-2012-002 (CERN, Geneva, 2012) , `arXiv:1201.3084 [hep-ph]`.

[130] ATLAS collaboration *Performance of the ATLAS Silicon Pattern Recognition Algorithm in Data and Simulation at* $\sqrt{s} = 7\ TeV$, ATLAS-CONF-2010-072

[131] The ATLAS Collaboration, *A measurement of the material in the ATLAS inner detector using secondary hadronic interactions*, arXiv:1110.6191, JINST 7 (2012) P01013

[132] The ATLAS Collaboration, *Validation of the ATLAS jet energy scale uncertainties using tracks in proton-proton collision* $\sqrt{s} = 7\ TeV$, ATLAS-CONF-2011-067

[133] The ATLAS Collaboration, *Track Reconstruction Efficiency in* $\sqrt{s} = 7\ TeV$ *Data for Tracks with* $P_T > 100\ MeV$, ATL-PHYS-INT-2010-112

[134] D. de Florian, G. Ferrera, M. Grazzini and D. Tommasini, *Transverse-momentum resummation: Higgs boson production at the Tevatron and the LHC*, JHEP **1111** (2011) , `arXiv:1109.2109 [hep-ph]`.

[135] Statistical twiki, NuissanceCheck. https://twiki.cern.ch/twiki/bin/view/AtlasProtected/Nuisa