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. [6], 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 [7–9] 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) [10]. 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 [11–15]. 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 [16,17] 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

The Standard Model has been succesfully tested in a vast number of experiments over a wide range of energies during the last few decades. Precision tests of the electroweak theory performed at LEP, SLC and the Tevatron [20], has confirmed

that 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 [19] including rare decays of hadrons provides a test for low-energies of the standard model. The recent discovery of a Higgs boson is also another success of the SM, its mass, spin and couplings are in agreement with expected values from a global fit of electroweak costraints [21]. Among all the parameters of the Standard Model only few of them presents tension with experimental data, the most significant discrepancies are sligthly above three standard deviations and are given by: the anomalus magnetic moment of the muon [22], a_{μ} and the forward-backward asymmetry of top quarks [23], $A_{FB}^{t\bar{t}}$.

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 explain the pattern of fermion masses and in its simplest version does not include neutrino masses, it has at least other three conceptual problems which indicates the need for physics Beyond the Standard Model (BSM):

Hierarchy Problem 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 [24]. If the cut-off is choosen to be $\sim M_{Planck}$, then a fine tunig with an unnaturally high precision , $\mathcal{O}(10^{-30})$, 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 [25–27].

Dark Matter 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 [28–30]. To be a Dark Matter candidate a particle should be stable, massive and should interact only via very weak interactions.

Unification Problem 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 [31, 32], 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.

1.2   The Minimal Supersymmetric Standard Model

1.2.1   Introduction to the MSSM

Supersymmetry (SUSY) [33–35] was first introduced as a natural way to solve the hierarchy problem. The SUSY generators $\mathcal{Q}$ transforms fermion into bosons and vice versa:

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

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. SUSY naturally solve the hierarchy problem since the quadratic divergent loop contribution to the Higgs mass of the SM particles are canceled by the loop contribution of the corresponding partners. 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 (˜) to the SM symbol. The SUSY particles share the same couplings with their SM partner, since the left-handed and right-handed components of fermions transform differently under gauge transformations also their superpartner present this feature.

The Minimal Supersymmetric extension of the Standard Model (MSSM) [36–41], 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 superpartner. Tables 1.1 and 1.2 summarize chiral and gauge supermultiplets in the MSSM. Among the gauge eigenstates summarized in the tables, the superpartner of the Higgs bosons, the *higgsinos* mix with the *wino* and *bino* to give the "ino" mass eigenstates: two charginos $\chi_{1,2}^{\pm}$ and four neutralinos $\chi_{1,2,3,4}^0$.

R-parity conservation

The MSSM requires a discrete and multiplicative symmetry called R-parity [35], 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. The R-parity quantum number has value $+1$ for ordinary SM particles and -1 for their superpartners. This symmetry was first introduced as a simple way 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. The conservation of R-parity has also other important fenomenological consequences: SUSY particles are always produced in pairs and decays always in an odd number of SUSY particles. Furthermore, the lightest SUSY particle, often chosen as one of the neutralinos, is stable and provides a suitable candidate for dark matter.

Names	Supermultiplets	Spin 1/2	Spin 0
quark, squarks	Q	$(u_L \ d_L)$	$(\tilde{u}_L \ \tilde{d}_L)$
($\times$ 3 families)	$\bar{u}$	$u_R^\dagger$	$\tilde{u}_R^*$
	$\bar{d}$	$d_R^\dagger$	$\tilde{d}_R^*$
leptons, sleptons	L	$(\nu \ e_L)$	$(\tilde{\nu} \ \tilde{e}_L)$
($\times$ 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 Ref. [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.

Names	Supermultiplets	Spin 1	Spin 1/2
gluons, gluinos	G_a (a =1,...,8)	g	$\tilde{g}$
W bosons, winos	W_a (a=1,...,3)	$W^\pm \ W^0$	$\tilde{W}^\pm \ \tilde{W}^0$
B boson, bino	B	B^0	$\tilde{B}^0$

Table 1.2: This table is based on Ref. [2] and summarize the gauge supermultiplets in the Minimal Supersymmetric Standard Model.

The Soft SUSY Breaking

In case Supersymmetry is an exact symmetry of nature, the SM particles and their relative superpartners 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, if these particles exist, they 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 to the SUSY lagrangian [42,43], this term explicitly break SUSY introducing the mass terms for Higgs, gauginos and sfermions, as well as trilinear coupling terms between sfermions and Higgs bosons. In general, if intergenerational mixing and complex phases are allowed, the soft-SUSY-breaking terms will introduce a huge number of unknown parameters $\mathcal{O}(100)$ [44]. However, in absence of phases and mixing, and if the soft terms obey a set of boundary conditions [42,43], only few new parameters are introduced $\mathcal{O}(10)$.

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 necessary to generate masses separately for isospin up-type fermion and down-type fermions [34, 45, 46] and to cancel chiral anomalies that otherwise would spoil the renormalizability of the theory [47]. The two Higgs doublet are:

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

In analogy with the SM, a similar Higgs mechanism is employed in the MSSM [36,48] 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 neutral components of the two Higgs field acquire vacuum expectation values:

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

Three of the original eight degrees of freedom of the scalar fields are absorbed by the $W^\pm$ and Z bosons, which acquire their longitudinal polarizations and masses. The remaning degrees of freedom correspond to five scalar Higgs bosons: two CP-even and neutral h and H, a neutral CP-odd boson A and a pair of charged bosons $H^\pm$. Six parameters describes the MSSM Higgs sector: M_h, M_H, M_A, $M_{H^\pm}$, β and α, where the latter represents the mixing angle in the neutral CP-even sector, while $\tan\beta$ is equal to the ratio between the two vacuum expectation values $\tan\beta = v_1/v_2$. At tree level, only two of these parameters are actually independent, a common choice is to keep $\tan\beta$ and M_A as free the parameters of the Higgs sector. At tree level, the supersymmetric structure of the theory impose a strong hierarchical structure on the Higgs bosons mass spectrum: the h boson is the lightest with $M_h < M_Z$, while $M_A < M_H$ and $M_{H^\pm}^2 = M_A^2 M_W^2$. Furthermore, the following
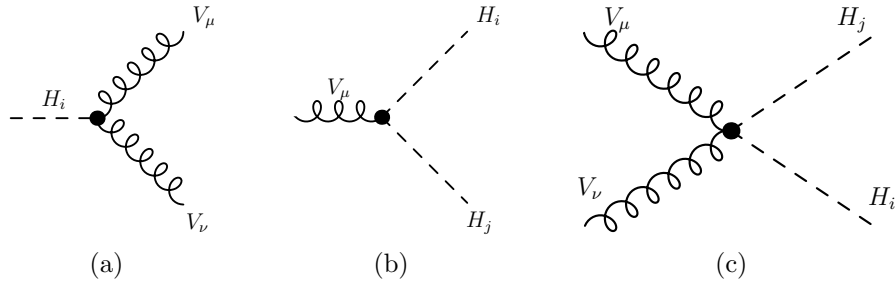
Figure 1.1: Feynman diagrams for the couplings between one Higgs boson and two gauge bosons (a), two Higgs bosons and one gauge boson (b) and two Higgs bosons and two gauge bosons (c). Based on [3].

relation holds between the mixing angles:

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

These relations are broken by large radiative corrections to the Higgs bosons masses [49], 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 $1 \lesssim \tan\beta \lesssim m_t/m_b$ [50].

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 depends on their couplings with standard model and supersymmetric particles, a short overview of the former, based on the Ref. [3], is given in this section.

The possible couplings between MSSM Higgs bosons and vector bosons are: the threelinear 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 $V_\mu V_\nu H_i H_j$. Figure 1.3.1 shows the Feynman diagram relative to these couplings. Among all of them, the most relevat for MSSM Higgs phenomenology is the trilinear couplings between two gauge bosons and one Higgs boson $V_\mu V_\nu H_i$. For 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. Then, in case of $V_\mu V_\nu H_i$ couplings, only the following possibilities 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 $\cos(\beta -$

α) is fixed at tree level following equation (1.5). An interesting fenomenological consequence is that, calling G_{VVh} and G_{VVH} the coupling between two generic vector bosons and one of the neutral CP-even Higgs bosons the following equation holds:

$$G_{VVh}^2 + G_{VVH}^2 = g_{VVH_{SM}}^2 \tag{1.8}$$

The equations (1.7) and (1.8) leads to the fact that the couplings with vector bosons for h (H) increase (decrease) with $\tan\beta$. For relatively large value of $\tan\beta$, h has SM-like couplings with vector bosons while H decouple from them. For an overview of all the other couplings between vector bosons and Higgs bosons, charged Higgs, trilinear and quartic coupling between Higgs bosons and couplings to SUSY particles refer to Ref. [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:

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

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

At tree level, the MSSM Higgs bosons masses, decay branching fraction and production cross section are all determined by two parameters, by convention chosen to be M_A and $\tan\beta$. As it has been pointed out in Section 1.2.2, radiative corrections contribute significantly to the MSSM Higgs bosons masses and the prediction of physics observables becomes dependent on several MSSM parameters. The main corrections arises from the top-stop (s)quark sector and for large $\tan\beta$ also the bottom-sbottom (s)quark sector becomes increasingly important. Furthermore, these corrections are dependent on the SUSY-breaking scale M_{SUSY}, the trilinear Higgs-stop, Higgs-sbottom Yukawa couplings, the electroweak gaugino and gluino mass parameters.

Due to the large number of free parameters, a complete scan of the MSSM parameter space is impractical in experimental analysis and phenomenological studies. To cope with this difficulty several benchmark scenarios has been proposed [4, 52], 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. Usually results are presented in a $M_A - \tan\beta$ plane.

The m_h^{max} benchmark scenario [51] was used in the past searches for neutral MSSM Higgs bosons performed at LEP, Tevatron and LHC [58–61]. In this benchmark scenario the parameters 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 $\tan\beta$. The m_h^{max} scenario allows to set conservative lower bounds on M_A, $M_H^{\pm}$ and $\tan\beta$ [52]. However, given the recent discovery of a Higgs boson with mass ~ 126 GeV, this scenario tend to predict a too high mass for M_h, resulting to be, for large part of the MSSM parameter space, inconsistent with this observation. This scenario is still currently used in the presented analysis since it offer the possibility to compare results with past experiments.

Recently, several benchmark scenarios has been updated [4] to accommodate the experimental constraints on past neutral MSSM Higgs searches and the observation of a SM-like Higgs boson. An interesting updated benchmark scenario is the m_h^{mod} scenario, which has the feature to predict $M_h \simeq 125.5 \pm 3$ GeV for large region of MSSM parameter space. The m_h^{mod} scenario configuration is obtained by reducing the amount of mixing in the stop sector with respect to the m_h^{max} scenario. This can be done for both signs of the MSSM parameter that regulate the stop mixing X_t, giving rise to two complementary scenarios m_h^{mod+} and m_h^{mod-}. The difference between these two scenarios is found to be negligible for experimental searches, the m_h^{mod+} benchmark scenario has been used throughout this thesis as reference scenario.

Other interesting benchmark scenario are the light stop scenario and the light stau scenatio. The first may lead to relevant modification of the gluon fusion production cross section, while the second leads to modification of the di-photon decay branching fraction of the light CP-even MSSM Higgs boson. For an overview of other relevant benchmark scenarios refer to Ref. [4].

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, this role is commonly played by the lightest CP-even Higgs boson, h. Given the Higgs bosons couplings discussed in Section 1.3.1 tourns out that the MSSM Higgs bosons H and A tend to be degenerate in mass and decouple from gauge bosons. Furthermore the coupling of the latter two Higgs bosons with down (up) type fermions are enhanced (suppressed) by $\tan\beta$, therefore, for large $\tan\beta$ bottom-quark and τ lepton will play an important role for the Higgs bosons production and its decays.

The production of the neutral CP-even MSSM Higgs bosons at hadron colliders proceeds via the same processes as for the SM Higgs production. The pseudoscalar A, instead, cannot be produced in association with gauge bosons or in vector boson fusion (VBF) processes 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 fusion, $gg \rightarrow A/H/h$. In addition, the production in association with b-quarks becomes important for large value of $\tan\beta$. These are the only two production mechanism that are considered in the presented analysis. Figure 1.2 shows the Feynman-diagram for these processes, while Figure 1.3 shows the production cross section of the neutral MSSM Higgses via these two processes in the m_h^{max} scenario.

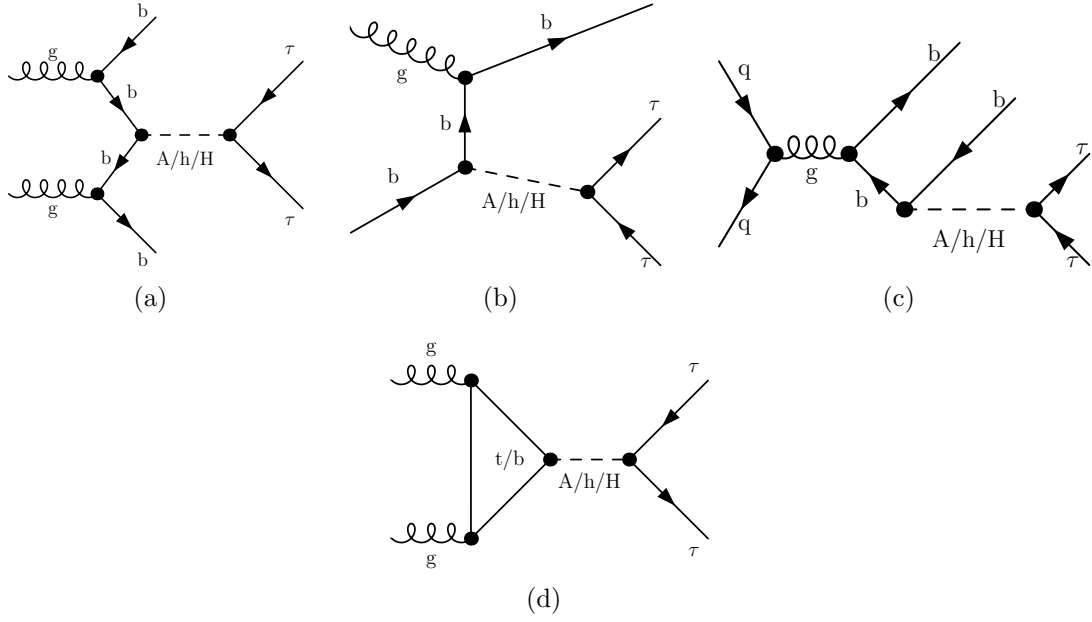The decays of the neutral MSSM Higgs bosons (in the assumption that all

Figure 1.2: Feynman diagram for the production of the neutral MSSM Higgs bosons via b-associated (a,b,c) and gluon fusion (d) processes, subsequent decay in tau lepton pairs is considered.

supersymmetric particle are heavy enough) are the same as for the SM one with the already cited exception of A. Figure 1.3 shows the decay branching fractions in the m_h^{mod+} scenario for h, H and A as a function of the mass of A for two values of $\tan\beta$. The decay into tau lepton pairs is the most important after $b\bar{b}$ and the one used in this thesis.

### 1.3.4   Current Status of the Searh for Neutral MSSM Higgs Bosons

The measure of the couplings of the observed 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 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.

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 function of m_A and $\tan\beta$ and this allow to set exclusion limits in the $m_A - \tan\beta$ plane [53]. Figure 1.5 shows the exclusion limits in a "simplified MSSM" model [54, 55] 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 1.6 and are part of the work of this thesis.
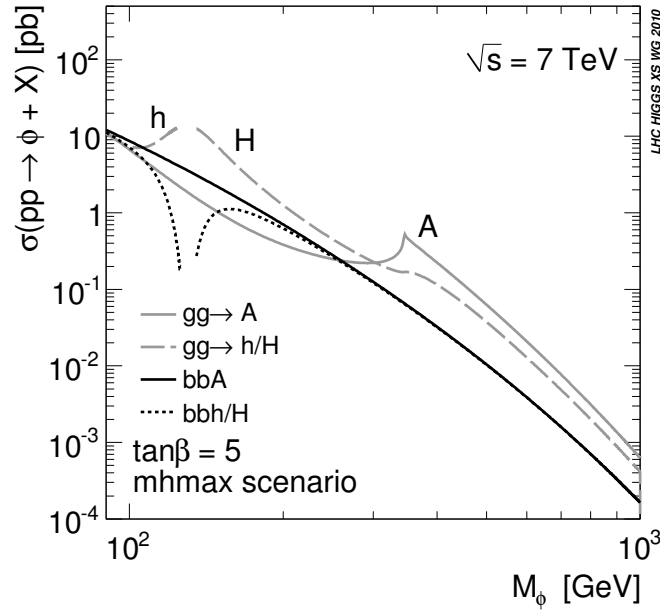
(a)
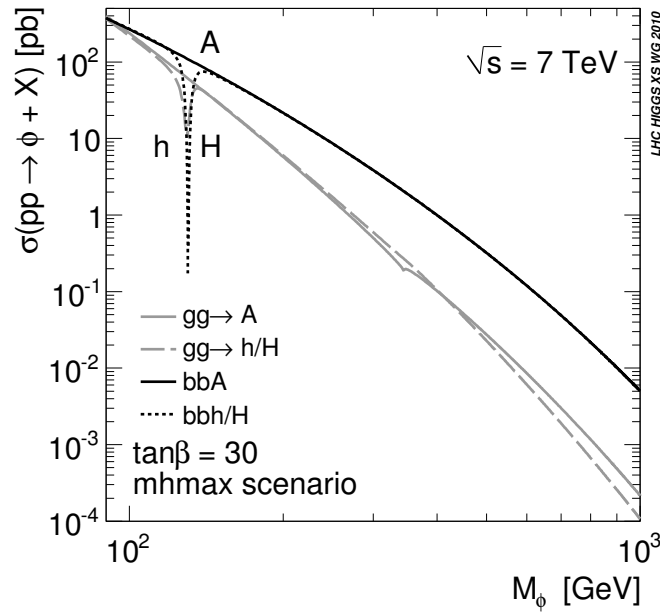
(b)

Figure 1.3: Central predictions for the total MSSM Higgs bosons production cross sections via gluon fusion and Higgs radiation off bottom quarks for $\sqrt{s} = 7$ TeV using NNLO and NLO MSTW2008 PDFs m_h^{max} scenario; (a) $\tan\beta = 5$, (b) $\tan\beta = 30$. Ref. [5].
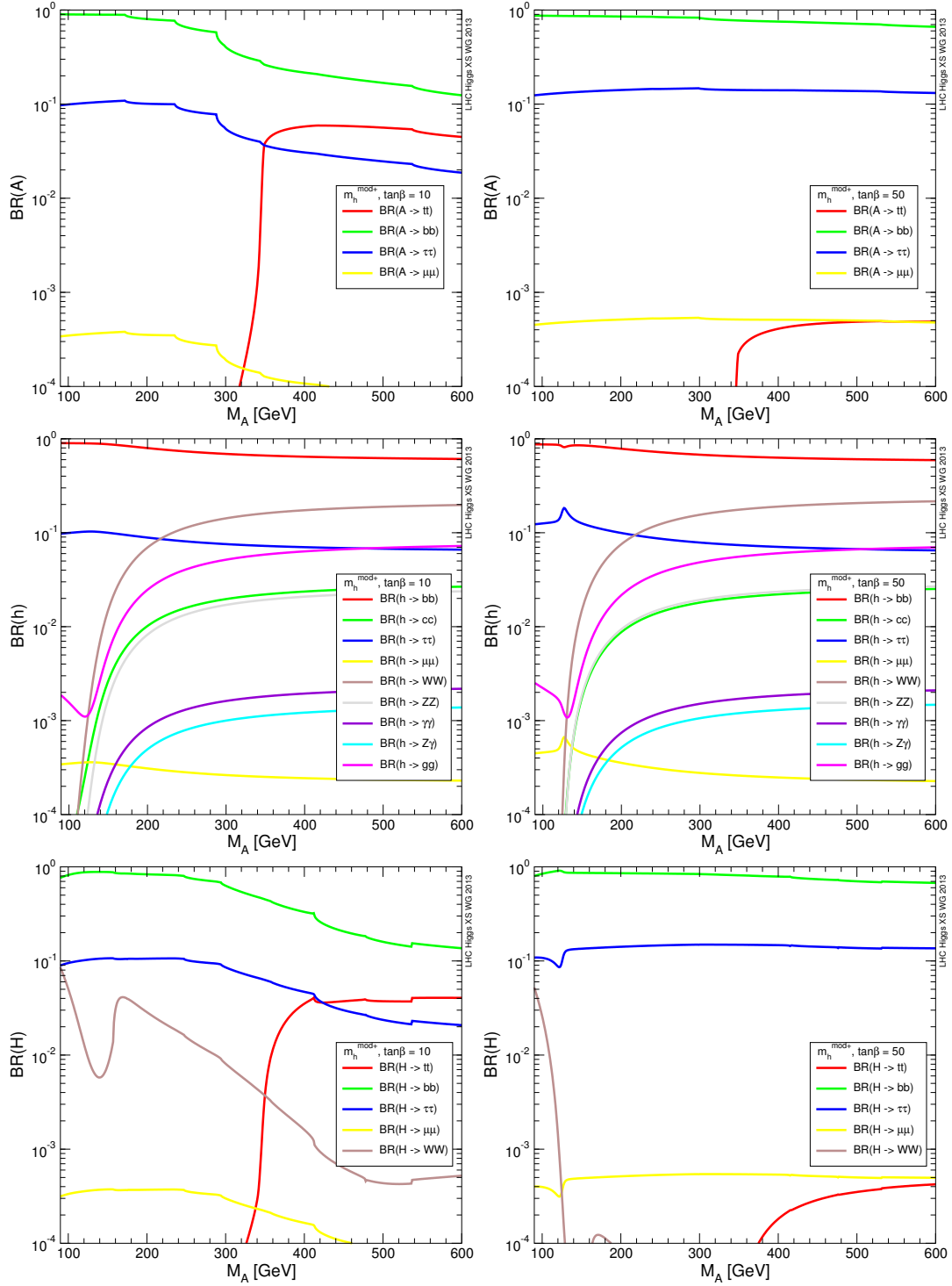
Figure 1.4: Branching fraction for the MSSM neutral higgses $h/H/A$ in the m_h^{mod+} scenario for $\tan\beta = 10$ and $\tan\beta = 50$. Ref. [4].
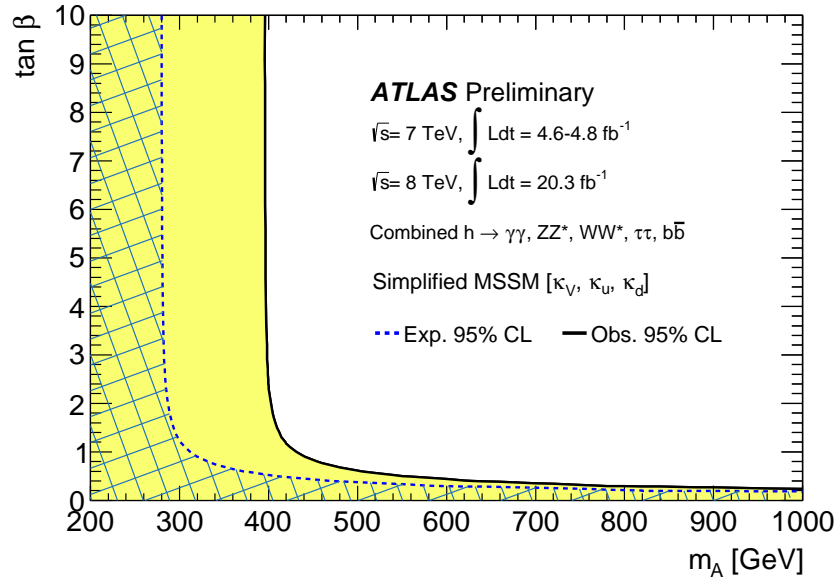
Figure 1.5: Regions of the $m_A - \tan\beta$ plane excluded in a simplified MSSM model via fits to the measured approximately to 95% CL (2σ), are indicated for the data and expectation assuming the SM Higgs sector. The light shaded and hashed regions indicate the observed and expected exclusions, respectively. The SM decoupling limit is $m_A \to \infty$. See Reference [53].

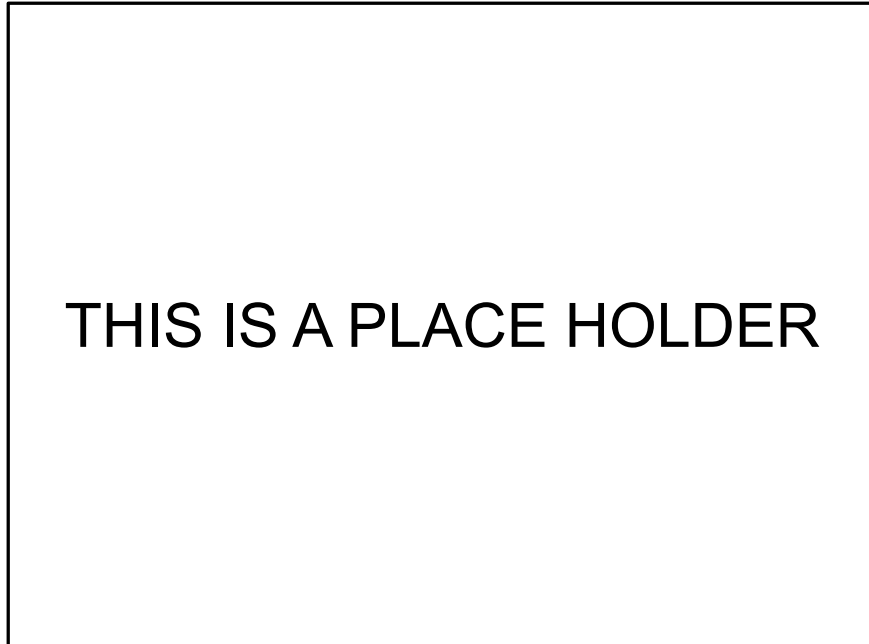Figure 1.6: Limit CMS or ATLAS depending if we manage to publish in time

Chapter 2

Search for neutral MSSM Higgs Bosons in $A/h/H \to \tau^+\tau^- \to e\mu + 4\nu$ decays

In light of the recent discovery of a Higgs boson with mass of ~ 126 GeV at LHC [16, 17], it remains an open question whether this new particle is the only missing piece of the electroweak symmetry breaking sector or whether it is one of several Higgs bosons predicted in some theories that go beyond the SM. The most recent measurements [120–123] of its properties shows this new boson to be, within experimental uncertainties, fully compatible with the SM Higgs boson. Nevertheles, such a new particle can also still be accommodated within several theories beyond the standard model (BSM), among all of them, Supersymmetry is a theoretically favoured scenario as the most predictive framework beyond the Standard Model.

This chapter presents the search for the neutral MSSM Higgs bosons decaying into pairs of tau leptons in the fully leptonic final state, published in Ref. []^1 as a part of the search for the neutral MSSM Higgs bosons in all final states of the tau leptons decay. The search is based on 20.3 fb^{-1} of 8 TeV data recorded by the ATLAS experiment during 2012 at the Large Hadron Collider. The chapter is organized as follows: a brief summary of the MSSM Higgs sector and an introduction to the analysis strategy is given in Section 2.1, while the event selection and categorization are described in Section 2.2. In Section 2.3 the estimation of the background is described and in Section **??** methods to evaluate sys-

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[1]to Sandra: I'll remove this sentence if Conf note wont be ready in time

tematic uncertainties are discussed. Finally, in section **??**, an overview of the statistical methods employed along with the corresponding result of the search are presented.
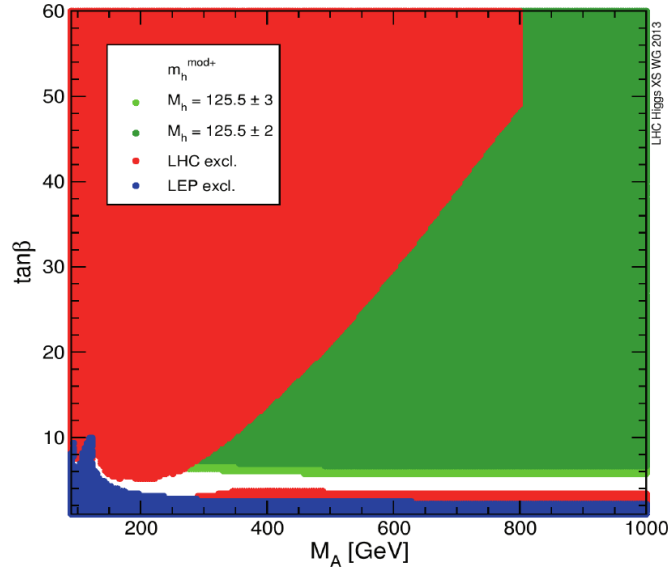
Figure 2.1: Excluded and allowed regions of the $m_A - \tan\beta$ parameter space for the m_h^{mod+} MSSM benchmark scenario. Excluded regions are determined based on direct Higgs boson searches at LEP (blue) and LHC (red). The two green bands correspond to the parameter regions which are compatible with the assumption that the lightest MSSM Higgs boson, h, has a mass respectively of $M_h = 125.5 \pm 2$ (dark green) or 125.5 ± 3 GeV (light green). For more detail see [4].

2.1 Introduction

2.1.1 The Higgs Sector in the MSSM

In the Minimal Supersymmetric extension of the Standard Model (MSSM) [36, 37] the Higgs sector is composed of two Higgs doublets of opposite hyper-charge, resulting in five observable Higgs bosons: two of these are neutral and CP-even (h,H), one is neutral and CP-odd (A) and two are charged ($H^{\pm}$). At tree level their properties such as masses, widths and branching ratios can be predicted in terms of only two parameters, often chosen to be the mass of the CP-odd Higgs boson m_A and the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta$ (for more details see chapter **??**). The MSSM predicts the existence of a Higgs boson with properties that resemble those of a SM Higgs boson in large regions of its parameter space. This is usually the case for the lightest Higgs boson, h, while the other two, H and A, tend to be degenerate in mass and decouple from gauge bosons. On the other hand, the couplings of the latter two Higgs bosons with down (up) type fermions are enhanced (suppressed) proportionally to the value of $\tan\beta$, meaning that for large $\tan\beta$ bottom-quark and τ lepton will play an important role for the Higgs bosons production and its decays.

The two most relevant MSSM Higgs bosons production mechanisms at the LHC are gluon fusion, $gg \to A/H/h$, and the production in association with b-quarks, $pp \to b(b)A/h/H$, the latter becoming increasingly important for large values of

Figure 2.2: To Sandra: the diagrams are will be updated asap.

$\tan\beta$. These two are the only production mechanisms considered in this analysis. Assuming there are no decays into supersymmetric particles since these are too heavy, the favored neutral MSSM Higgs bosons decay mode is the decay into a pair of b-quark and antiquark, $A/h/H \rightarrow b\bar{b}$. This is followed, for the CP-odd A and CP-even H Higgs bosons, by the decay into pairs of τ leptons. Given that it is very difficult to distinguish the former decay from the large $b\bar{b}$ background, the decay mode $A/h/H \rightarrow \tau^+\tau^-$ provides the highest sensitivity in the search for neutral MSSM Higgs bosons.

Searches for neutral MSSM Higgs bosons have been performed at LEP [58], the Tevatron [59] and the LHC [60,61]. In the following the search for the neutral MSSM Higgs bosons in the final state $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ is presented. This search is complementary to the searches in other $\tau^+\tau^-$ final states characterized by the presence of one or two hadronicaly decaying τ leptons. Despite of the fact that the $\tau\tau$ branching ration in $e\mu + 4\nu$ is only 6%, this decay channel provides a sensitivity to the signal comparable to those in other $\tau\tau$ final states, especially for low m_A values. This is mainly due to the high transverse momentum treshold at the trigger level for hadronicaly decaying τ leptons.

As it is impractical for an experimental search to explore the full parameter space of the MSSM, which has many free paramers, several benchmark scenarios are introduced by fixing all except m_A and $\tan\beta$ parameters to values typical for most interesting physics cases. With the recent Higgs boson discovery, benchmark scenarios of the MSSM have been updated to accommodate for new experimental constraints. As an example, Figure 2.1 shows the currently excluded and allowed regions of the MSSM parameter space for the m_h^{mod+} updated benchmark scenario. In this scenario a large region of the $m_A - \tan\beta$ parameter space is compatible with the assumption that the observed Higgs boson correspond to the supersymmetric SM-like Higgs boson, h. A large part of this parameter space is still experimentally unexplored, this is a strong motivation to pursue the search for additional neutral MSSM Higgs bosons.

2.1.2   Signal and Background Processes

Signal events, in which the neutral MSSM Higgs bosons decays trough $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$, are characterized by the presence of one electron and one muon of opposite charge, these are isolated and with relatively high transverse momentum, additionally, four neutrinos contribute to the missing transverse energy of the event. Figure 2.2 shows leading order Feynman diagram for the two signal production mode considered, gluon-gluon fusion and b-associated production. The production modes also contributes to the characterization of the signal topology: the presence or the absence of b-jet in the final state is expected in case of b-associated or gluon-gluon fusion production mode, respectively.

The signal topology just described is common to several other processes, which

Figure 2.3: To Sandra: the diagrams are will be updated asap.

Process	Cross-section (pb) [$\times$ BR]
Signal ($m_A = 150$ GeV, $\tan\beta = 20$, m_h^{max} scenario)	
$gg \to A/h/H \to \tau\tau \to e\mu + 4\nu$)	0.12/0.09/0.13
$pp \to b\bar{b}A/h/H \to \tau\tau \to e\mu + 4\nu$)	0.29/0.03/0.25
Backgrounds	
$W \to \ell$+jets	12.22×10^3
$Z/\gamma^* \to \ell\ell$+jets	5.5×10^3
$t\bar{t} \to \ell\ell + X$	137.3
Single top (t, s and Wt channels) $\to \ell + X$	28.4, 1.8, 22.4
Dibosons WW, WZ and ZZ $\to \ell + X$	20.6, 6.8, 1.55

Table 2.1: The cross sections multiplied by the relevant branching ratios (BR) for signal and the considered backgrounds. the symbol ℓ stands for $\ell = (e, \mu, \tau)$. Signal cross sections are calculated for the m_h^{max} scenario shown for $m_A = 150$ GeV and $\tan\beta = 20$, in this case $m_H = 151$ GeV and $m_h = 129$ GeV.

unfortunately, have higher cross section than the sought signal. The dominant backgrounds for this search are the production of $Z/\gamma^* \to \tau^+\tau^-$ either via Drell-Yan process or in association with jets and the top quark production ($t\bar{t}$ and single top production is intended). Additional significant backgrounds are dibosons production (WW, WZ, ZZ) and events with non-prompt leptons coming solely from hadron decay (QCD multi-jet). Vector bosons production like $W \to \ell\nu$ or $Z \to \ell\ell$ in association with jets (with ℓ here meaning either e or μ) are also considered, however these processes have a limited impact. Figure 2.3 shows few relevant examples of leading order Feynman diagrams for the dominant background processes. The production cross sections times the relevant branching fraction for signal and backgrounds are summarized in Table 2.1.

2.1.3 Analysis Strategy

In this thesis a search for the MSSM $A/h/H \to \tau^+\tau^- \to e\mu + 4\nu$ is presented. The $e - \mu$ final state is chosen out of the three possible fully leptonic final state of a $\tau^+\tau^-$ resonance, the choice is motivated by the fact that it represent the 50% of the the fully leptonic final states and because the $e - e$ and $\mu - \mu$ case are not expected to bring significant sensitivity, in fact in these cases, large background contribution are expected not only from $Z/\gamma^* \to \tau\tau$ but also from $Z \to ee$ and $Z \to \mu\mu$, respectively.

Candidate events are selected based on the topological properties of the Higgs boson production and decay, the events are required to present one electron and one muon, isolated and of opposite charge. The set of events is divided in two orthogonal category which are optimized separately for the two different production mode considered. In the gluon-gluon fusion category (also called *b-vetoed* category),

the absence of a b-tagged jet is required, the main background in this category is $Z/\gamma^* \to \tau\tau$. In contrast, the presence of a b-tagged jet is required for b-associated production category (also called *b-tagged* category), the request of a b-jet suppress the $Z/\gamma^* \to \tau\tau$ background, $t\bar{t}$ and single top production are then the main backgrounds in this category.

The $A/h/H \to \tau\tau \to e\mu+4\nu$ search is performed in the MSSM m_h^{max} benchmark scenario scanning the $m_A - \tan\beta$ plane in the ranges $90 \leq m_A \leq 300$ GeV and $5 < \tan\beta < 60$, the signal prediction for the event yield and kinematical distributions is evaluated by simulation.

The dominant $Z/\gamma^* \to \tau\tau$ background is estimated from data via a signal-depleted control sample. The QCD multi-jet background contribution is also estimated from data since it represent a challenge for MC simulation. The estimation of the contribution of all the other backgrounds is obtained by means of MC simulation. The background model predictions are validated using different signal-depleted control data samples, good agreement is found.

The systematics uncertainties taken into account for simulated signal and backgrounds arise from uncertainties on cross section calculations and on the modeling of the detector response. For backgrounds that are estimated from data, specific uncertainty are evaluated considering the possible uncertainties of the estimation methods.

The final statistical interpretation of the data is based on the comparison of the observed invariant mass distributions with the expected background and signal-plus-background predictions. Exclusion limits are set by means of a binned likelihood ratio test statistic. The limits are interpreted in the MSSM m_h^{max} scenario and evaluated as a function of m_A and $\tan\beta$. Furthermore, the limits are interpreted, in a less model depended way, in terms of the cross section for the production of a generic Higgs boson, ϕ, of mass m_ϕ, via the production mode $pp \to b\bar{b}\phi$ and $gg \to \phi$.

2.1.4 Data and Simulated Event Samples

Data Sample

The presented result are based on proton-proton collision data collected at the LHC during 2012 at a center-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.3 fb^{-1}. The events used in this analysis are recorded using a combination of a single electron and combined electron-muon triggers. Only recorded events in which all the relevant components of the ATLAS detector were fully operational are considered. Additional data quality requirements are applied to the events according to [108], these requirements assures the rejection of events with data corruption due to the LAr and Tile calorimeters and with jet activity in known noisy calorimeter regions.

Signal Samples

Signal production via the gluon fusion process, $gg \to A/H/h$, was simulated with POWHEG [72] and the associated $b\bar{b}A/H/h$ production with SHERPA [73]. The pseudo scalar Higgs boson samples were generated in the mass range from 90 GeV

to 300 GeV and at $\tan\beta = 20$, the same kinematics are assumed for $A/h/H$ Higgs bosons decay products and at other $\tan\beta$ values, appropriate re weighting is applied according to the different cross-sections. The $m_h^{\max}$ MSSM benchmark scenario is assumed.

Background Samples

The production of W and Z/γ^* bosons in association with jets was simulated with the ALPGEN [65] generator. The $t\bar{t}$ process was generated using the POWHEG generator. The single-top (s-channel, Wt) processes were generated using MC@NLO [67], while single-top (t-channel) processes were generated with AcerMC [68]. The production of dibosons (WW, WZ, ZZ) were generated with HERWIG [69]. For all ALPGEN and MC@NLO samples described above, the parton shower and hadronisation were simulated with HERWIG and the activity of the underlying event with JIMMY [70]. Different parton density functions (PDFs) sets are used depending on the generator: CTEQ6L1 [74] is used by ALPGEN and AcerMC while CT10 [75] is used by SHERPA, POWHEG and MC@NLO.

TAUOLA [77] and PHOTOS [78] are used to model the tau lepton decay and additional photon radiation from charged leptons in the leading-log approximation, respectively.

The ATLAS detector response is simulated for all the MC samples using GEANT4 [79, 80], the physics object reconstruction is performed with the same software as for data described in chapter **??**. The effects of the simultaneous recording of several events from the same or neighboring bunch crossings (pile-up) are considered in the simulation.

2.2 Event Selections and Categorization

2.2.1 The "Common" Selections

According to the signal events characteristics, each event either data and MC should satisfy the following selection criteria, these selections are shared by both analysis category and therefore referred in the following as "common selections":

(i) A trigger selection, requiring the presence of an electron with $P_T > 24$ GeV, or alternativaley, an electron with $P_T > 12$ GeV togheter with a muon with $P_T > 8$ GeV.

(ii) At least one reconstructed vertex with more that three associated tracks. This selection is aimed to reject background from cosmic muons.

(iii) Exactly one reconstructed "Tight" electron with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. The electron should have $P_T > 15$ or 25 GeV depending on the trigger that selected the event.

(iv) Exactly one "Combined" muon with $|\eta| < 2.5$ and $P_T > 10$ GeV.

(v) The electron should be isolated with $E_T^{cone}/P_T < 0.08$ and $P_T^{cone}/P_T < 0.06$.

(vi) The muon should be isolated with $E_T^{cone}/P_T < 0.04$ and $P_T^{cone}/P_T < 0.06$

(vii) Muon and electron should be of opposite charge.

(viii) Overlap removal between electron, muon, τ_h and jets is performed.

(ix) The events is rejected if at least one hadronic τ decay is found with $P_T > 15$ GeV.

(x) The invariant mass of the sum of the electron and muon 4-vectors should be greather than 30 GeV.

For details about the definition of physics object used above and their quality requirements refer to chapter **??**.

The two analysis category, *b-tagged* and *b-vetoed*, are defined adding on top of the common selections the request of exactly one b-tagged jet or the absence of b-tagged jet in the event respectively. To be *taggable* a jet should have $P_T > 20$ GeV, $|\eta| < 2.5$ and JVF > 0.5. A jet is considered tagged if passes the selection of the $MV1$ algorithm at 70% of efficiency for b-quark, $\epsilon_b^{t\bar{t}}$. Further selection are applied to each category and optimized separately, these additional selection are described in the following.

2.2.2 b-vetoed Category

The final state of Higgs decaying into tau pair coincide with the one from $Z/\gamma^* \to \tau\tau$ process, this is then an irreducible background for this category. Exploiting the different kinematics of the Higgs decay with respect to other backgrounds is possible to disentangle between them. In the Higgs decaying into $\tau^+\tau^- \to e\,\mu + 4\nu$ the taus are highly boosted and this feature is transferred to the final state leptons, their kinematics then result to be significantly different with respect to process like diboson or $t\bar{t}$. A first difference is that e and μ from the Higgs decay will be more likely "back-to-back", as it is shown in Figure 2.4(a) where the angle between the leptons in the transverse plane $\Delta\phi_{e,\mu} = |\phi_e - \phi_\mu|$ is reported. Furthermore the neutrinos will be more likely collinear with the charged leptons: this feature can be matematically seen as the sum of scalar product between missing energy and the leptons four-vectors in the transverse plane, if the vectors are normalised to unit versors then what remains is a relation only between angles:

$$\hat{E}_T^{miss} \cdot (\hat{P}_T^\mu + \hat{P}_T^e) = cos(\Delta\phi_{E_T,\mu}) + cos(\Delta\phi_{E_T,e}) = \sum_\ell cos(\Delta\phi_{E_T,\ell})$$

collinearity implies this sum to be equal to zero as it is shown in Figure 2.4(b). These two feature can be used to distinguish between $e - \mu$ and E_T^{miss} coming from decay of highly boosted and back-to-back object and the one coming from W decays in top or in dibosons backgrounds, in which the leptons are not necessarily back-to-back and the neutrinos not collinear with them. In b-vetoed category these two variables are sufficient to suppress contribution from dibosons, no other selection is applied in this category because it has been shown to not bring significant improvement. The

Category	Selection
b-vetoed	Exactly zero b-tagged taggable jets
	$\Delta\phi(e-\mu) > 1.6$
	$\sum \cos \Delta\phi > -0.4$
b-tagged	Exactly one b-tagged taggable jet
	$\Delta\phi(e-\mu) > 2$
	$\sum \cos \Delta\phi > -0.2$
	$H_T < 100$ GeV
	$P_{T\mu} + P_{Te} + E_T^{miss} < 100$ GeV

Table 2.2: Summary of the dedicated b-tagged and b-vetoed category selections that are employed after the common selections.

actual selection employed in this category are shown in Table 2.2, while in Table 2.3 the prediction for the number of background and signal events that survises at each selection stage of this category is reported.

2.2.3 b-tagged Category

In the b-tagged category the situation is different, the request of a b-jet enhance backgrounds with b-jet activity as top and single top production. In this category selection on $\Delta\phi(e-\mu)$ and $\sum \cos \Delta\phi$ are employed as described for b-vetoed, since these selections are effective in reducing top and diboson backgrounds. In addition further selection exclusive of this category are employed and are described below.

Given the relatively low jet activity of Higgs events (also in the case of b-associated production), it is possible to separate them from top production which instead is very likely to have two or more highly enegetic jets in the event. Little jet activity is achieved by requesting the sum of the jets P_T in the event to be small, this variable is called H_T and is shown in Figure 2.4(c). The jets used for the calculation of H_T should have $P_T > 30$ GeV, $|\eta| < 4.5$ and JVF > 0.5 (when applicable).

Another feature that distinguish top pair production from Higgs is the higher invariant mass of the former final state (the highest Higgs mass considered for this search is 300 GeV), in the transverse plane all the leptons will tend to have a higher momentum, the sum of electron and muon P_T and E_T^{miss} is then used as a discriminating variable. Figure 2.4(d) shows the distribution of this last analysis variable.

The above described variables defines the b-tagged category, in table 2.2 a summary of all the employed selection variables with their optimized cut values is shown. In Table 2.4 the prediction for the number of background and signal events that survises at each selection stage of this category is reported.
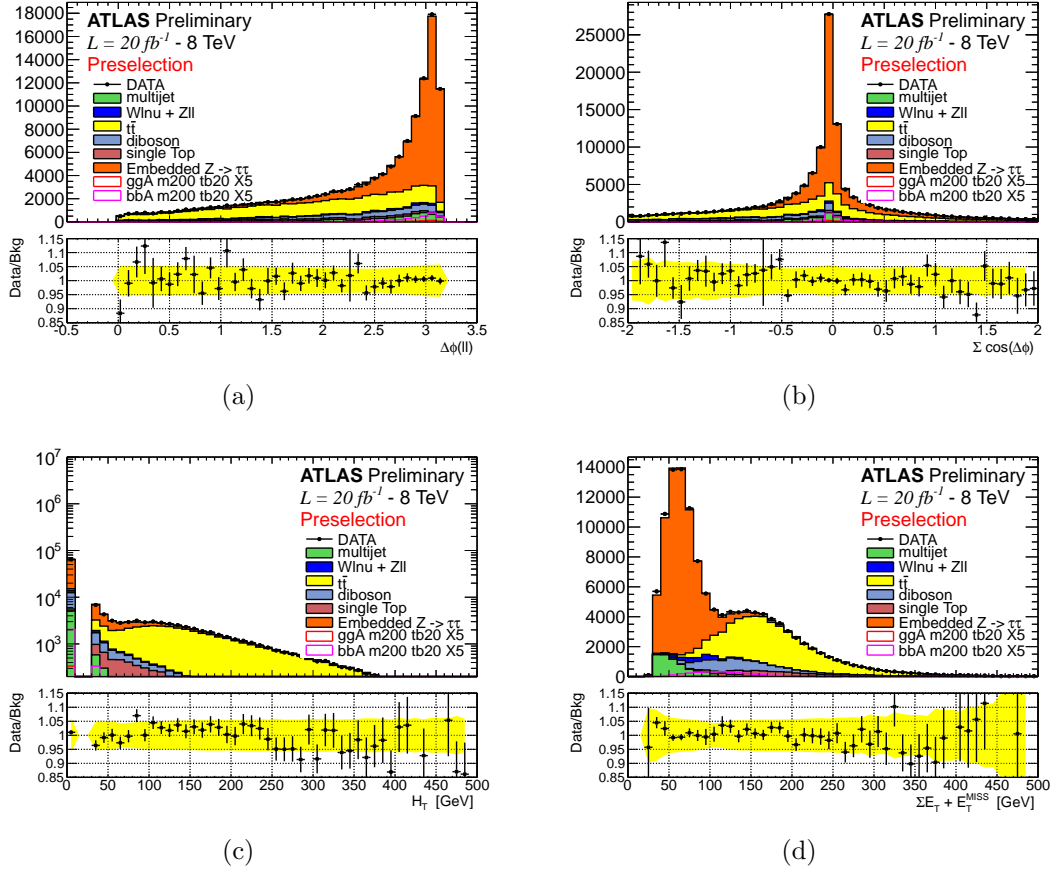
Figure 2.4: Distribution of analysis variable after the selections common to both category, a comparison of the prediction of background model prediction and data is made showing good agreement. The yellow band represents the total systematic uncertainty for the background model prediction.

	Common Selections	n(b-jet)=0	$\Delta\phi(e-\mu) > 1.6$	$\sum\cos\Delta\phi > -0.4$
Data	125886	89155	-	- -
Multi-jet	6693 ± 456	6357 ± 461	5322 ± 438	4137 ± 339
$Z \to \ell\ell$	569 ± 48	564 ± 48	516 ± 47	434 ± 44
$W \to \ell\nu$	1625 ± 155	1604 ± 155	1145 ± 125	714 ± 101
Dibosons	9338 ± 48	9235 ± 48	7358 ± 43	4002 ± 31
$t\bar{t}$	40632 ± 106	7707 ± 46	5044 ± 37	3416 ± 31
Single Top	4449 ± 44	1664 ± 27	1124 ± 22	682 ± 18
$Z/\gamma^* \to \tau\tau$	61503 ± 68	60440 ± 67	58078 ± 65	55303 ± 64
Signal			-	-

Table 2.3: Number of data and background events in the b-vetoed channel.

	n(b-jet)=1	$\Delta\phi$	$\sum\cos\Delta\phi$	$P_{T\mu} + P_{Te} + E_T^{miss}$	H_T
Data	23352	-	-	-	-
Multi-jet 330 ± 40	208 ± 27	135 ± 22	114 ± 17	100 ± 15	
$Z \to \ell\ell$	5.2 ± 1.8	2.3 ± 1.1	2.3 ± 1.1	1.7 ± 1.0	0.9 ± 0.8
$W \to \ell\nu$	20 ± 6	15 ± 6	13 ± 6	10 ± 6	10 ± 6
Dibosons	99 ± 5	63 ± 4	36.4 ± 3.0	14.8 ± 1.8	13.3 ± 1.8
$t\bar{t}$	19810 ± 70	9680 ± 50	6450 ± 50	808 ± 15	350 ± 10
Single Top	2456 ± 33	1223 ± 23	784 ± 18	122 ± 7	99 ± 7
$Z/\gamma^* \to \tau\tau$	952 ± 9	625 ± 7	540 ± 7	482 ± 6	421 ± 6
Signal		-	-	-	-

Table 2.4: Number of data and background events in the b-tagged channel.

2.2.4 Mass Reconstruction with MMC Technique

Acurate invariant mass reconstuction of a di-τ resonace is a challenging task due to the presence of neutrinos from the τ leptons decay. In case of leptonic decay of both τ leptons a pair of neutrinos for each of them are involved in the final state, the system presents then eight uknowns, which corresponds to the four-momentum of the neutrinos pairs. Four additional kinematic constraint are set by the following equations:

$$\vec{E}_T^{miss} = \vec{P}_T^{mis_1} + \vec{P}_T^{mis_2}$$
$$M_{\tau_i}^2 = m_{mis_i}^2 + m_{vis_i}^2 + 2\mathbf{P}_{vis_i} \cdot \mathbf{P}_{mis_i} \tag{2.1}$$

where the index i runs over the two τ leptons of the event and assumes the values of 1 or 2. $\vec{P}_T^{mis_i}$, m_{mis_i} and $\mathbf{P}_{mis_i}$ are respectively the transverse momentum, the invariant mass and the four momentum of the pair of neutrinos related to the τ lepton decay i with mass M_τ, the subscript *vis* indicates instead quantities related to the charged lepton from τ lepton decay. The system has still four degrees of freedom, several approximation are possible to further constraint the momentum carried by neutrinos, for example assuming them collinear to the electron or muon from τ lepton decay, however those approximation suffers of mass resolution limitations.

In this analysis, the so-called "Missing Mass Calculator" (MMC) algorithm is used to calculate the most likely di-τ system invariant mass given the event topology, the implementation of the method in this search is based on [124]. The concept of the MMC is to solve equation 2.1 assigning values to the yet undetermined variables, performing a "scan" over a four dimensional parameter space. The four

independent variables are chosen to be $m^2_{mis_i}$ and $cos\theta^*_i$, the latter defined as the angle between the charged lepton from the τ lepton decay and the boost direction of the τ lepton. The di-τ invariant mass of the event can be calculated for each given point of the parameter space that solves equations 2.1, however, the solutions are not all equally likely and the probability of a given τ decay configuration can be predicted by means of simulation (PYTHIA supplemented with TAUOLA package is used). Each point in the parameter space, corresponding to a particular di-τ invariant mass, is then weighted by its probability to occur. The estimator for the final discriminant, the mass of the di-tau system MMC_{mass} , is the maximum of the weighted invariant mass distribution calculated for the scanned points.

The missing energy plays an important role in the MMC method and its resolution has an impact on the calculation of the invariant mass. To improve E^{miss}_T resolution, a scan over a six dimensional parameter space is performed in a similar way as described above, in this case however, $\vec{E}^{miss}_T$ is also considered unknown and a scan is performed on it assigning values according to its uncertainty. The probability of each solution is calculated and the final missing transverse energy is given by the weighted mean of the scanned points.

The final procedure consist in obtaining first an estimate for E^{miss}_T by means of a six dimensional scan over the solution of equations 2.1, successively a four dimensional scan is performed fixing E^{miss}_T to the updated value and calculating the most likely invariant mass of the di-τ system. Figure 2.5 shows the final state invariant mass distribution calculated with MMC_{mass} discriminating variable, the distribution is shown after the common selection and after the full selection of both category.

2.3   Background Modeling and Validation

This section describes the strategies for background modeling and validation. Monte Carlo simulation is extensively used for model either background and signal, the simulations of any process are usually prone to systematics uncertainties due to non-perfect descriptions of pileup effects, underlying event and detector performance, therefore, data-driven background estimation method are employed for the estimate of $Z/\gamma^* \to \tau\tau$ and QCD multi-jet backgrounds, described respectively in section 2.3.3 and 2.3.2. Other background processes, such as $t\bar{t}$, single top, dibosons, $Z \to ll +$ jets (where $l = e, \mu$) and W + jets, are estimated using MC predictions. Given the particular importance of $t\bar{t}$ a dedicated study to validate this background has been made and described in section 2.3.1.

A good agreement between data and background model is found after the common selections, this is supported by figure 2.6 which shows few kinematic variables and figure 2.4 which shows analysis selection variables after common selections.

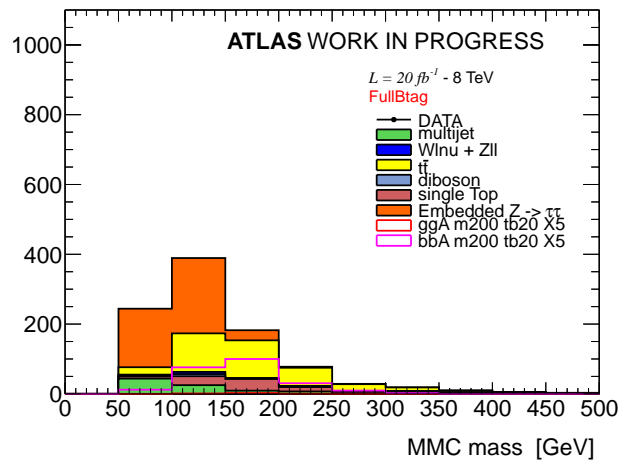### 2.3.1   Top Quark Pair Production Validation

The background from top quark pair production is estimated using a sample of simulated events with POWHEG-PYTHIA MC generator. Since this is one of the major backgrounds for this analysis a careful validation is needed, for this
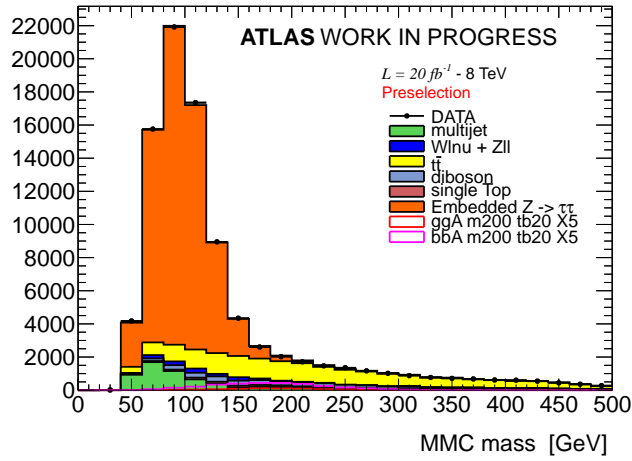
(a)
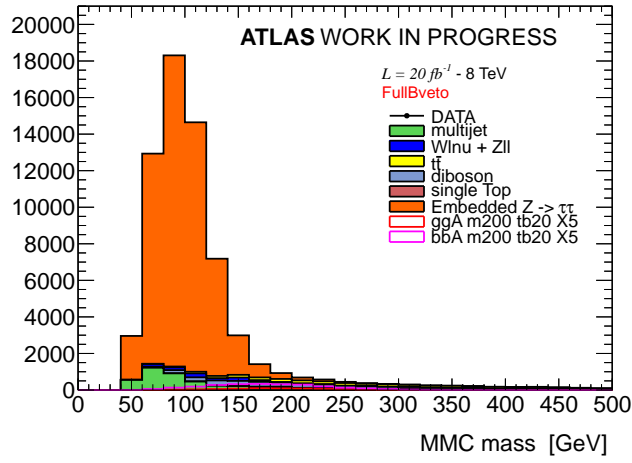
(b)

(c)

Figure 2.5: Distribution of the MMC_{mass} for different cuts stage, see text. Left column corresponds to b-tagged category, right column to b-vetoed.

sample	Lepton Charge	Lepton Isolation
A (signal sample)	OS	isolated
B	SS	isolated
C	OS	anti-isolated
D	SS	anti-isolated

Table 2.5: QCD background estimation control samples, defined by having leptons with opposite signs (OS) or same signs (SS) and by having the leptons either isolated or anti-isolated.

purpose a $t\bar{t}$ rich and signal-depleted data control sample is defined using events passing the common selections with the additional requirement of two b-tagged jets. Figures 2.7 and 2.8 show a set of kinematic and analysis selection variables in this data sample, good agreement between data and MC prediction is found: an overall data to background ratio of $0.998 \pm 0.011\text{(stat.)} \pm 0.110\text{(sys.)}$ is observed. The total systematic uncertainty on the ratio is dominated by the uncertainty on the b-tagging efficiency.

2.3.2   Multi-jet Background

The QCD multi-jet background represents an important background, especially in the b-veto category, due to its high cross-section and the relatively low cut on lepton P_T used in this analysis. This background is evaluated by a data-driven technique, the so-called ABCD method. The ABCD method consists of splitting the set of data events after the common selections in four samples: the signal sample, defined by the event selections described in Section 2.2 and three signal-depleted control data sample, which do not share events and are designed to be enriched in multi-jets events. The four samples are defined by using the relative sign of the charge of the leptons and isolation selections. To obtain data samples rich in multi-jet background, the selections on both the calorimetric and tracking isolation, described in Section 2.2.1, are inverted with respect to the nominal ones defining anti-isolated leptons. Is then possible to define four data samples: opposite sign (OS) or same sign (SS) with respectively isolated or anti-isolated leptons. Historically the letters A-D are assigned to this data samples for a quicker reference as defined in Table 2.5.

An assumption of the ABCD method is that multi-jet backgrounds populate the OS and SS events independently of lepton isolation criteria, or in other words that the ratio of OS/SS events is uncorrelated with the lepton isolation selections. In this case, the number of QCD events in the signal sample A can be estimated from the yield of multi-jet events in the control samples B, C and D, using the equation

$$N_A = N_B \times \frac{N_C}{N_D} = N_B \times R_{QCD} \tag{2.2}$$

To obtain the multi-jet yields in the data control samples, the contamination from electroweak (W+jets, Z+jets and dibosons) and top processes ($t\bar{t}$ and single top production) are subtracted in each control sample using the MC prediction for their event yield. Tables 2.6 and 2.7 show the event yield for each control sample

throughout the full cut-flows along with the predictions of non-QCD multi-jets events which are subtracted. Signal contamination has been checked in all the three control samples for different mass points. For the range of m_A and $\tan\beta$ considered in this analysis, the highest signal contamination is seen in sample B for the mass point $m_A = 300$ GeV and $\tan\beta = 50$, where a contamination of 0.2% is observed[2].

Shapes of kinematic distributions for QCD events are taken from sample B, this sample is expected to have similar kinematic property to the signal sample, however, suffers of either lower statistics and higher contamination with respect to sample C or D. This choice is made to avoid a shape bias due to isolation requirements at trigger level (only the single-electron trigger ask for isolation), figure 2.9 shows the comparison between the electron P_T distributions in sample B and D, in the latter high P_T electrons are suppressed, they do not pass trigger selections. Eventually the trigger isolation requirement could bias also the ratio OS/SS, this possibility has been checked carefully in a dedicated study and reported in Appendix ??: to a good approximation, such trigger effects cancel out in the ratio OS/SS and no additional systematic is needed.

To test the ABCD method predictions an additional control sample has been defined with the following selections:

- $E_T^{miss} < 20$ GeV

- $H_T < 70$ GeV and $\sum L_T + E_T^{miss} < 50$ GeV

- $0 < MMC_{mass} < 80$ GeV

This control sample is designed to enhance multi-jet background with respect to $Z/\gamma^* \to \tau\tau$ keeping the final state kinematics as similar as possible to the signal sample. Figure 2.10 shows the MMC_{mass} distribution for this control sample with and without b-tagging requirements, agreement between data and the background model is found within statistical and detector related systematics uncertainty.

Systematic uncertainties are assigned on the scaling factor R_{QCD} and on the shape of the discriminating variable MMC_{mass} to take into account any correlation between isolation and charge of the leptons, details on the systematic uncertainty evaluation are addressed in Section ??.

2.3.3 $Z \to \tau\tau$ + Jets Background: Embedding Technique

The background from $Z/\gamma^* \to \tau\tau$ decays is the major background to this analysis, a good understanding of it is then crucial. Unfortunately, for a light Higgs boson, it is impossible to completely separate $Z/\gamma^* \to \tau\tau$ decays from the signal and a signal free data control sample cannot be defined. However, thanks to the small Higgs coupling to muons, $Z \to \mu\mu$ decays provide a good starting point to model $Z/\gamma^* \to \tau\tau$ events in a data-driven way. An hybrid Data-MC sample, known as "Embedding" is used to model the $Z/\gamma^* \to \tau\tau$ background: $Z \to \mu\mu$ candidates

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[2] This value is mainly due to b-associated production and, as it scales with the cross section, for $\tan\beta = 20$ would be an order of magnitude smaller.
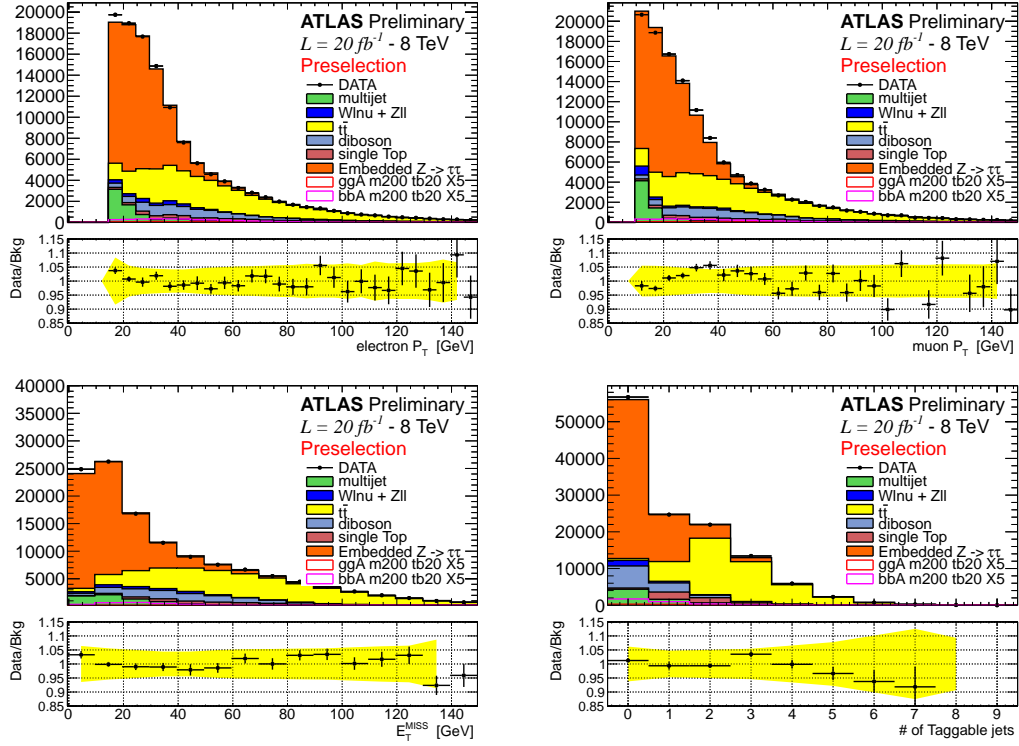
Figure 2.6: Distribution of some kinematic variables after common selections.

Selection		B	C	D	R_{QCD}
Common Selections	Data	6189	604628	312901	1.929 ± 0.004
	non-QCD	2510 ± 180	1090 ± 30	730 ± 35	
B-tag	Data	419	44619	27257	1.64 ± 0.01
	non-QCD	215 ± 10	310 ± 12	277 ± 13	
$\Delta\phi(e-\mu)$	Data	230	38810	23316	1.67 ± 0.01
	non-QCD	104 ± 6	200 ± 10	175 ± 7	
$\sum \cos\Delta\phi$	Data	149	31379	18779	1.67 ± 0.02
	non-QCD	67 ± 5	127 ± 8	114 ± 6	
$\sum H_T$	Data	83	27781	15626	1.78 ± 0.02
	non-QCD	23 ± 4	25 ± 3	22 ± 3	
$\sum L_T + E_T^{miss}$	Data	71	27735	15590	1.78 ± 0.02
	non-QCD	10 ± 3	22 ± 3	18 ± 2	
$MMC_{mass} > 0.$	Data	70	27634	15522	1.78 ± 0.02
	non-QCD	9 ± 3	20 ± 3	17 ± 2	

Table 2.6: QCD background estimation as a function of the analysis selections for the b-tagged category. The yields for the different control samples, as well as the scaling factor R_{QCD}, are reported. The error on the R_{QCD} is statistical only.
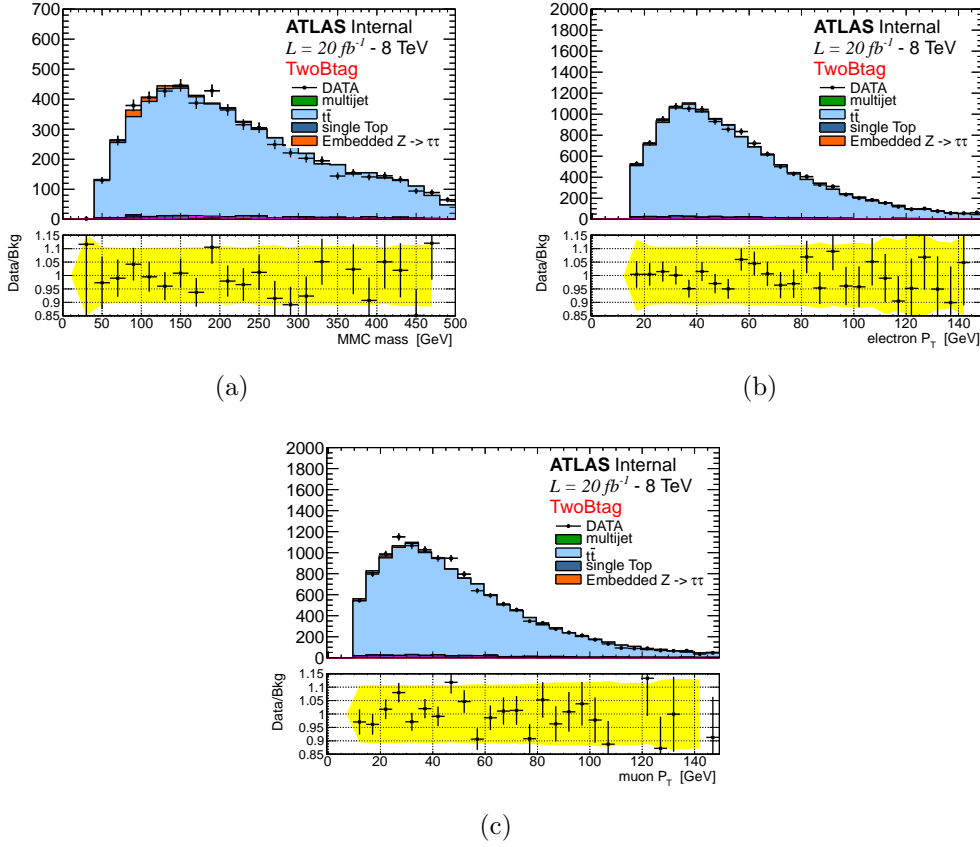
Figure 2.7: Distributions of a) the MMC mass, b) the transverse momentum of the electron $P_T(e)$ and c) the transverse momentum of the muon $P_T(\mu)$, for both data and MC in the $t\bar{t}$ control sample. The uncertainties on the points for the ratio plot show the statistical uncertainty on the data to background ratio, whereas the yellow band show the total systematic uncertainty on this ratio.

Selection		B	C	D	R_{QCD}
Common Selections	Data	6189	604628	312901	1.929 ± 0.004
	non-QCD	2510 ± 180	1090 ± 30	730 ± 35	
B-veto	Data	5673	558217	284847	1.960 ± 0.004
	non-QCD	2220 ± 180	710 ± 30	415 ± 30	
$\Delta\phi(e-\mu)i$	Data	4610	532583	271404	1.962 ± 0.005
	non-QCD	1700 ± 170	580 ± 30	345 ± 30	
$\sum \cos\Delta\phi$	Data	3417	486747	247712	1.965 ± 0.005
	non-QCD	1120 ± 100	370 ± 20	230 ± 20	
$MMC_{mass} > 0.$	Data	3177	479967	244276	1.965 ± 0.005
	non-QCD	1000 ± 100	300 ± 17	190 ± 20	

Table 2.7: QCD background estimation as a function of the analysis selections for b-veto category. The yields for the different control samples, as well as the scaling factor R_{QCD}, are reported. The error on the R_{QCD} is statistical only.

(a)   (b)

(c)   (d)
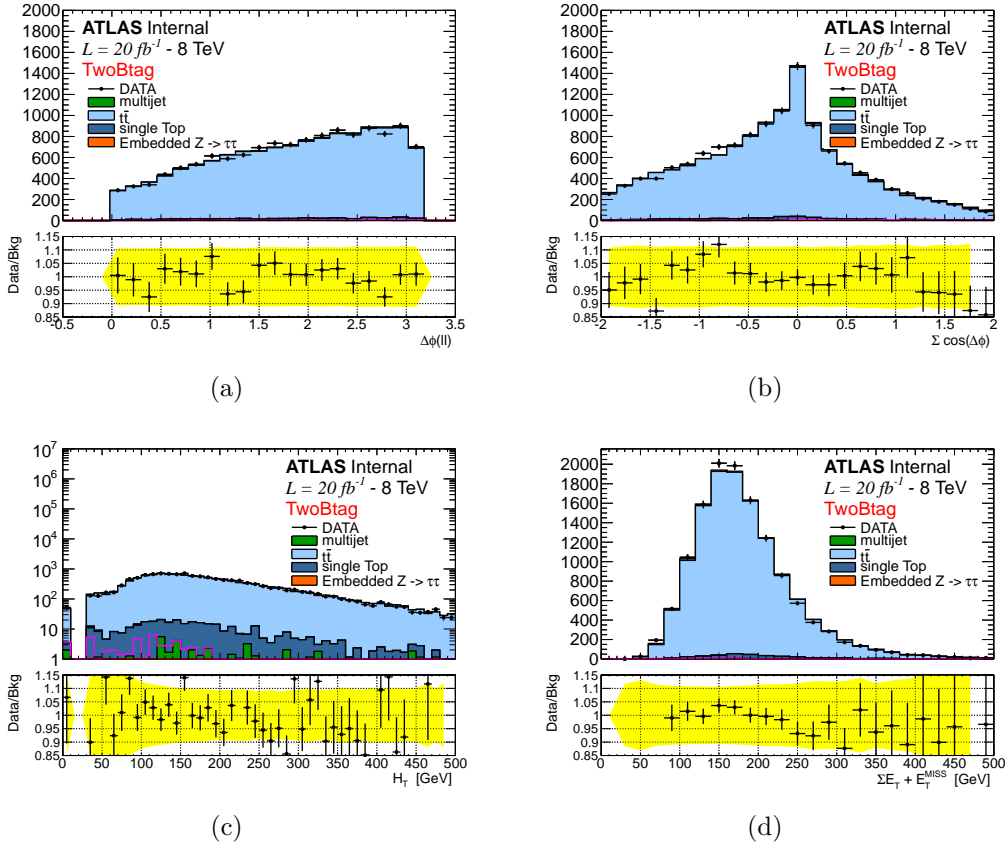
Figure 2.8: Distributions of a) $\Delta\phi(e-\mu)$, b) $\sum \cos\Delta\phi$, c) $\sum L_T + E_T^{miss}$ and d) H_T, for both data and MC in the $t\bar{t}$ control sample. The uncertainty on the points for the ratio plot show the statistical uncertainty on the data to background ratio, whereas the yellow band show the total systematic uncertainty on this ratio.

are selected in data, then, the two muons from the Z decay are substituted with the decay products from simulated taus, this means that the energy deposit and tracks in a cone around the muon are subtracted and substituted with the one from τ decay, those taus have the same kinematics as the original muons. Further details on this technique may be found in [81, 82].

Trigger is not simulated in the Embedding samples, the event yield is normalized to ALPGEN $Z/\gamma^* \to \tau\tau$ at common selection stage. Furthermore a set of corrections, as described in [83], are applied to unfold from the original $Z \to \mu\mu$ trigger and reconstruction efficiency, then trigger and reconstruction efficiency for a $e-\mu$ final state are emulated by means of event weight.

The Embedding technique has been validated in several studies, detailed in [81, 83], which show a good description of data and $Z/\gamma^* \to \tau\tau$ MC by Embedding. In the context of this analysis, figures 2.11 and 2.12 show comparisons of various kinematic variables between data, Embedding and ALPGEN $Z/\gamma^* \to \tau\tau$ simulated events at common selection. No significant deviation is seen between the MMC_{mass} distribution of the Embedding and ALPGEN samples, however other relevant vari-
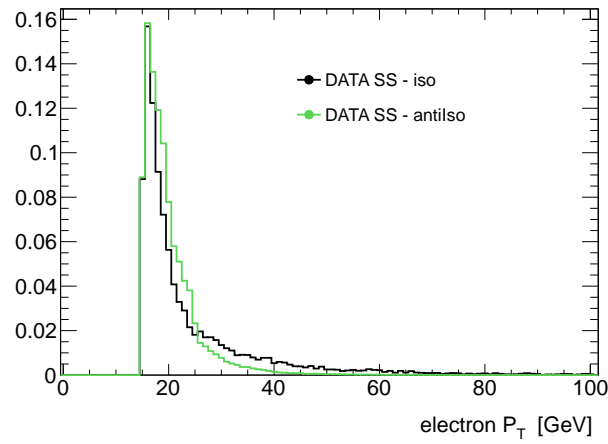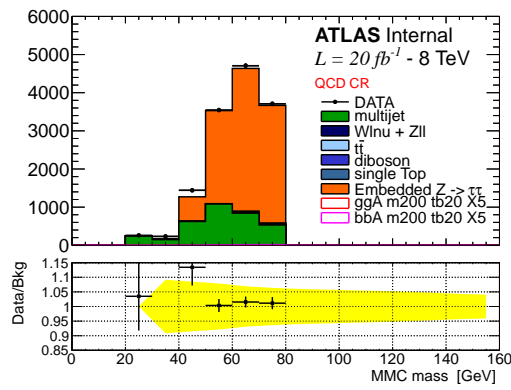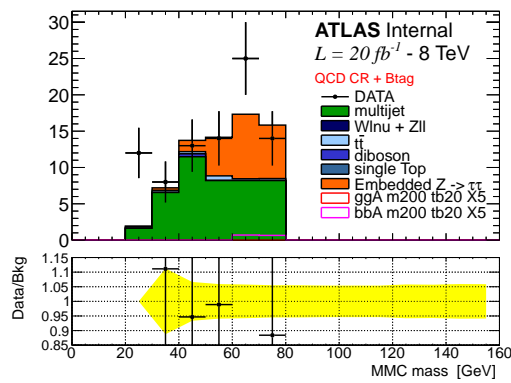
Figure 2.9: Comparison of the electron P_T distribution in sample B and sample D, showing the bias due to the trigger. The histograms are normalized to the same area.

(a)

(b)

Figure 2.10: MMC_{mass} distribution for QCD cross check samples defined in section 2.3.2 (a) and for the same control sample when in addition one b-tagged jet is required (b).
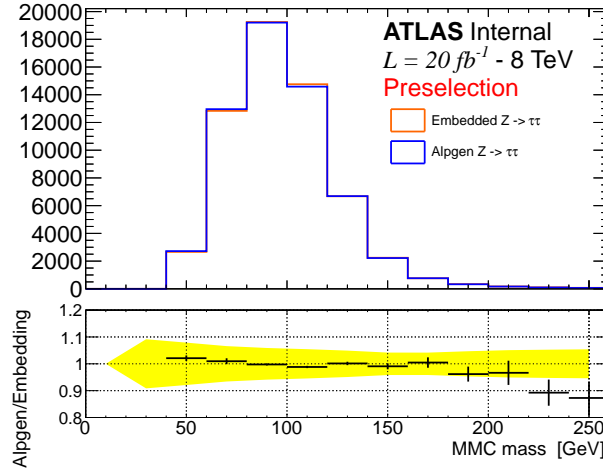
Figure 2.11: Comparison between the embedded $Z/\gamma^* \to \tau\tau$ and ALPGEN for MMC_{mass} distributions.

	Embedding yield in control sample	Transfer factor	Estimated events in signal sample	Contamination
b-tag	84 ± 9	$(2.6 \pm 0.1) \times 10^{-2}$	2.2 ± 0.2	0.5%
b-veto	84 ± 9	$(1.74 \pm 0.02) \times 10^{-1}$	15 ± 2	0.03%

Table 2.8: Evaluating Embedding $t\bar{t}$ contamination using a two b-tag CR. The transfer factor is the multiplicative factor that allows to estimate events in signal sample from the control sample.

ables for this analysis, such as the E_T^{miss} and the number of b-jets, are slightly better described by Embedding.

The Embedding sample is based on selecting $Z \to \mu\mu$ candidates in data, the selections assure a rather pure $Z \to \mu\mu$ sample, however further selections used in this analysis, for example the b-tagging requirements, could enhance the contamination fraction from other processes. Dedicated studies have been made to estimate the $t\bar{t}$ and QCD multi-jet contamination in the Embedding sample. The $t\bar{t}$ contamination is estimated by evaluating the Embedding yield in a two b-tag control sample (as described in Section 2.3.1), these events are assumed to be solely from $t\bar{t}$ and their yield in the signal sample is extrapolated using MC simulation. Table 2.8 shows a summary for the top contamination in Embedding. The multi-jet contamination can be estimated starting from the Embedding yield in (ABCD) sample C, assuming all events in this control sample as QCD multi-jet events, the contamination in the signal sample can be estimated by means of the ABCD method (see Section 2.3.2). The R_{QCD} factor, in this case, is evaluated using a $\mu - \mu$ final state with same kinematic selections as for Embedding $Z \to \mu\mu$ candidate. Table 2.9 shows the estimated contamination of QCD multi-jet in Embedding. Contamination effects are considered negligible.
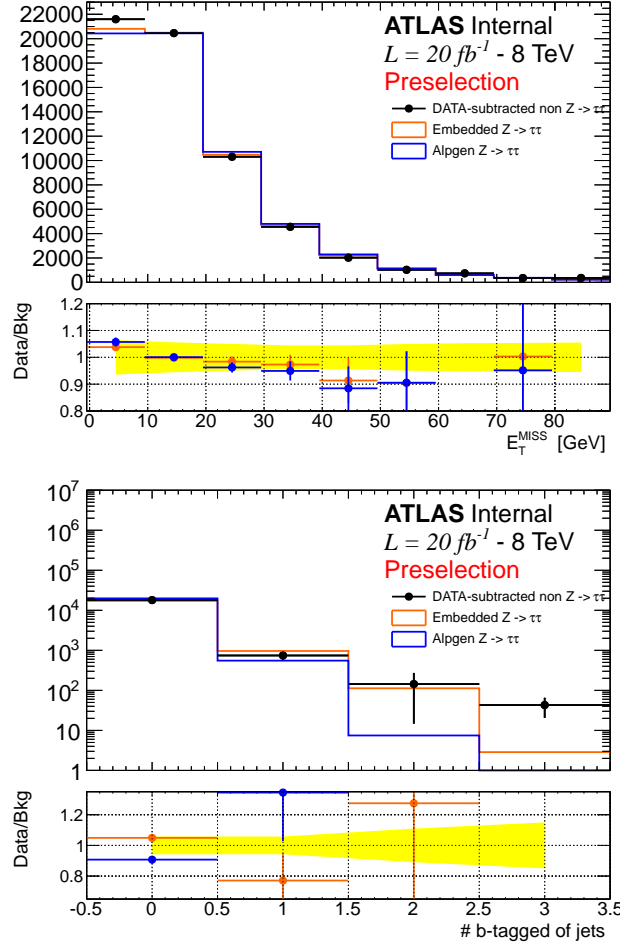
Figure 2.12: Comparison between embedded $Z/\gamma^* \to \tau\tau$ and ALPGEN for E_T^{miss} and the number of b-tagged jets distributions. Data are superimposed, with the contribution of non-$Z/\gamma^* \to \tau\tau$ are subtracted.

	Embedding yield in control sample	Transfer factor	Estimated events in signal sample	Contamination
B-tag	12 ± 3	$(7 \pm 1) \times 10^{-3}$	$(8.4 \pm 0.3) \times 10^{-2}$	0.03 %
B-veto	390 ± 20	$(2.5 \pm 0.1) \times 10^{-2}$	10.0 ± 0.5	0.02 %

Table 2.9: Evaluating Embedding contamination due to QCD multi-jet using ABCD method, the control sample here is with OS anti-isolated events (sample C). The transfer factor is the multiplicative factor that allows to estimate events in signal sample from the control sample, in this case is N_B/N_D and is evaluated using mu-mu final state with the same kinematic selection used in the definition of the Embedding sample.

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