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Chapter 1

Introduction

The Standard Model of particle physics is a theory that describes at quantum level the interaction between matter and radiation. It is a very predictive and successful theoretical framework which has been largely confirmed by experiments. The recent discovery of a new boson of mass ~ 126 GeV by the ATLAS and CMS experiments [16,17] at Large Hadron Collider in agreement with the SM prediction is another success of this theory. The most recent measurements [127–130] of its properties shows this new boson to be, within experimental uncertainties, fully compatible with the SM Higgs boson. However, 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 theories that go beyond the SM. Among all of them, Supersymmetry is a theoretically favoured scenario as the most predictive framework beyond the Standard Model. The MSSM predict the existence of five Higgs bosons three of them are neutral and two are charged. This thesis present a search for the neutral MSSM Higgs bosons decaying into a pair of τ leptons in the fully leptonic final state, the search is complementary to the search in other $\tau^+\tau^-$ final states and is performed with data recorded from the ATLAS detector. Chapter 2 of this thesis is devoted to introduce the Minimal Supersymmetric extension of the Standard Model, focusing in particular on its Higgs sector, with a description of the expected neutral MSSM Higgs bosons phenomenology.

The search presented in this thesis is based on 20.3 fb^{-1} of proton-proton collision data at a centre-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ recorded by the ATLAS experiment at the LHC during 2012. An overview of the ATLAS experiment and of the Large Hadron Collider complex is given in Chapter 3. The data recorded by the ATLAS experiment need to undergo several steps of offline reconstruction be-

fore being ready for analysis, the physics object reconstruction and quality criteria used are described in Chapter 4.

The main topic of this thesis is the search for the neutral MSSM Higgs bosons decaying into pairs of tau leptons, each subsequently decaying into an electron or muon and two neutrinos. This final state correspond to 6% of the total branching fraction of a di-tau leptons system decays, even limited by the BR this final state has a competitive sensitivity with the other channels at low mass. The search is performed for the two most significant production modes, gluon fusion and in association with b-quarks. The search is performed in two complementary event category, either with or without reconstructed b-jet and are optimized separately. Chapter 5.

In general the Higgs bosons produced in association with b-quark is characterized by the presence of relatively low-transverse momentum jets (originating from b-quarks), the reconstruction and calibration of calorimeter jets suffers strongly for such a low transverse momentum, which is one of the main reason for sensitivity loss in the category that requires a tagged jet. An alternative approach would be to

Chapter 6.

Chapter 2

The Higgs Bosons and the MSSM

This chapter introduces the theoretical concepts relevant for the experimental search presented in this thesis. A brief overview of the Standard Model of particle physics is given in Section 2.1 based on Reference [1]. Among all the extension of the Standard Model, the Minimal Supersymmetric extension (MSSM) is theoretically favoured as one of the most predictive scenarios beyond the Standard Model. The MSSM is introduced in Section 2.2 with an emphasis on the Higgs boson physics, based on References [2, 3]. Finally, a review of phenomenological aspects related to the MSSM Higgs bosons is given in Section 2.3, based on Reference [4].

2.1 The Standard Model of Particle Physics

2.1.1 Introduction

A detailed description of the Standard Model (SM) of particle physics may be found in Reference [6], only a brief overview is given below.

The SM of particle physics is a theory aimed to describe and quantitatively predict the phenomenology of fundamental particle interactions. At the quantum level the spectrum of all interactions between matter and radiation can be understood in terms of three fundamental forces: the strong, the electromagnetic and the weak forces. These interactions are described by a local relativistic quantum field theory, where a field with suitable transformation properties under the Lorentz group is associated to each particle. The theory is based on the principle of gauge invariance, i.e. invariance under symmetry transformations that operate on basic internal degrees of freedom and depend on the space-time coordinate. The gravitational force is negligible in atomic and nuclear physics, since the quantum effects of gravity are expected only at very high 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]. A vector boson is associated to each generator of the symmetry group, which acts as a mediator of the corresponding interaction. Eight gluons are associated to the $SU(3)_c$ colour generators, while four gauge bosons W^\pm , Z^0 and γ are associated to the generators of $SU(2)_L \otimes U(1)_Y$. The gluons and the photon are massless, while the remaining bosons have mass since the symmetry induced by the other three generators is spontaneously broken. In the SM the spontaneous symmetry breaking is realised by the Higgs mechanism [11–15]. The Higgs boson acts as mediator of a new class of interaction whose strength, at tree level, increases proportionally to the particle masses.

The fermionic matter fields of the SM are quarks and leptons. Quarks are subject to all SM interactions, each quark type is a colour triplet and carries electroweak charges, in particular the electric charge for up-type quarks is $+2/3$ and $-1/3$ for down-type quarks. Leptons are colourless but have electroweak charges, the leptons e , μ and τ carry an electric charge of -1 , while neutrinos ν_e , ν_μ and ν_τ are electrically neutral. Opposite sign charges are intended for respective

anti-particle. Quarks and leptons are grouped in three “generations” with equal quantum numbers but with different masses.

2.1.2 Precision Tests and Limitations of the SM

The Standard Model has been successfully tested in a vast number of experiments over a wide range of energies during the last decades. Precision tests of the electroweak theory performed at LEP, SLC and the Tevatron [20] have confirmed that the couplings of quark and leptons to the weak gauge bosons W^\pm and Z fully agree with the predictions from the gauge symmetry. Due to the experimental accuracy of a few per-mille, not only the tree level calculations, but also the impact of quantum corrections have been verified. Several other experimental results [19] including rare decays of hadrons provide additional tests of the Standard Model at low energies. The recent discovery at the LHC of a Higgs boson with a mass $m_H \sim 126$ GeV [16, 17] is also another success of the SM, the measured mass is in agreement with value expected from a global fit of electroweak observables [21], the spin and couplings properties of this new boson are also in good agreement with SM predictions for such mass.

Tension between the SM prediction and experimental data is observed for only a few observables. The most significant discrepancies, which are slightly above three standard deviations, are observed for the anomalous magnetic moment of the muon a_μ [22] and for the forward-backward asymmetry in the top quark production $A_{FB}^{t\bar{t}}$ [23].

Inspite of this success, the Standard Model is conceptually unsatisfactory due to a number of deficiencies and is widely believed to be an effective theory valid only at presently accessible energies. In addition to the fact that the SM does not include the gravitational force, it does not explain the pattern of fermion masses and in its simplest version does not include neutrino masses, the theory has at least three other conceptual problems indicating the need for new physics beyond the Standard Model (BSM):

Hierarchy Problem The radiative corrections to the Higgs boson mass introduce quadratic divergences of the order of the cut-off energy scale Λ , above which the theory is considered to be invalid and new physics is expected to appear [24]. If the cut-off scale is chosen to be $\sim M_{Planck}$, then a fine tuning between the tree-level and higher order calculations is needed with an unnaturally high precision of $\mathcal{O}(10^{-30})$ to cancel these divergences and result in a Higgs boson mass of the

order of the electroweak breaking scale, $M_{EW} \sim \mathcal{O}(100\,GeV)$. The SM provides no satisfactory answer to the question on how these cancellations can occur and why $\Lambda \gg M_{EW}$. These problems are referred to as the fine-tuning and hierarchy problem [25–27].

Dark Matter The SM does not contain a particle candidate which would explain the large contribution of non-barionic, non-luminous matter (so-called dark matter) to the density of the universe [28–30]. To be a dark matter candidate a particle should be stable, massive and should be weakly interacting with the known SM particles.

Unification Problem Another unsatisfactory aspect of the SM is that the electroweak and strong interactions cannot be unified, i.e. their couplings do not converge to the same value at high energies. Motivated by the successful 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 strengths 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 many possible extension of the SM, supersymmetry is one of the theoretically strongly favoured scenarios as it provides elegant solutions to the above problems. As discussed in Section 2.2, it gives a natural answer to the hierarchy problem, provides a suitable dark matter candidate and predicts unification of the three gauge couplings at the GUT energy scale.

2.2 The Minimal Supersymmetric Standard Model

2.2.1 Introduction to the MSSM

Supersymmetry (SUSY) [33–35] was first introduced as a natural solution to the hierarchy problem by means of a new symmetry that relates bosons to fermions. The SUSY generators \mathcal{Q} transform fermions into bosons and vice versa:

$$\mathcal{Q}|{\text{Fermion}}\rangle = |{\text{Boson}}\rangle, \quad \mathcal{Q}|{\text{Boson}}\rangle = |{\text{Fermion}}\rangle. \quad (2.1)$$

In a supersymmetric extension of the SM each of the known fundamental particles is in either a chiral or gauge *supermultiplet* and must have a superpartner with

Names	Supermultiplets	Spin 1/2	Spin 0
quark, squarks ($\times 3$ families)	Q	$(u_L \ d_L)$	$(\tilde{u}_L \ \tilde{d}_L)$
	\bar{u}	u_R^\dagger	\tilde{u}_R^*
	\bar{d}	d_R^\dagger	\tilde{d}_R^*
leptons, sleptons ($\times 3$ families)	L	$(\nu \ e_L)$	$(\tilde{\nu} \ \tilde{e}_L)$
	\bar{e}	e_R^\dagger	\tilde{e}_R^*
higgsinos, Higgs	H_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 2.1: 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. Based on Ref. [2].

spin differing by 1/2 unit. SUSY naturally solves the hierarchy problem since the quadratically divergent loop contributions to the Higgs mass from the SM particles are cancelled out by the loop contributions from the corresponding superpartners. The quarks and leptons superpartners are named by adding an “s”, standing for scalar, as prefix to the name of the corresponding SM particle. 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, which is named adding “ino” as suffix to the SM name. The symbol of superpartners is defined by adding a ($\tilde{\cdot}$) 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 inherit this feature.

The Minimal Supersymmetric extension of the Standard Model (MSSM) [36–41], is defined by requiring the minimal gauge group (i.e., the one of the SM) and the minimal particle content: three generation of fermions (without right-handed neutrinos), gauge bosons and two Higgs doublet, each with its own superpartner. The chiral and gauge supermultiplets of the MSSM are listed in Tables 2.1 and 2.2, respectively. Among the gauge eigenstates listed in these tables, the superpartners of the Higgs bosons, the *higgsinos*, mix with the *wino* and *bino* to produce the mass eigenstates: two charginos $\chi_{1,2}^\pm$ and four neutralinos $\chi_{1,2,3,4}^0$.

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
B boson, bino	B	B^0	\tilde{B}^0

Table 2.2: The gauge supermultiplets in the Minimal Supersymmetric Standard Model. Based on Ref. [2].

R-parity conservation

The MSSM requires a discrete and multiplicative symmetry called R -parity [35]. This symmetry ensures the barion and lepton number conservation and it is defined as follows:

$$R_p = (-1)^{2s+3B=L} \quad (2.2)$$

where L and B are lepton and barion numbers and s stands for the spin quantum number. The R-parity quantum number has a value of +1 for ordinary SM particles and -1 for their superpartners. This symmetry was originally introduced as a simple solution to protect against the instability of the proton. Lepton and barion number violation leads, in many cases, to an unstable proton with a lifetime shorter than the experimental lower bound. The R -parity conservation has also other important phenomenological consequences: SUSY particles are always produced in pairs and decay always into an odd number of SUSY particles. Furthermore, the lightest SUSY particle, often chosen to be one of the neutralinos, is stable and therefore provides a suitable candidate for the dark matter.

The Soft SUSY Breaking

If supersymmetry is an exact symmetry of nature, the SM particles and their corresponding superpartners should have the same mass and quantum numbers, except for the spin. However, the SUSY particle spectrum has not yet been observed, suggesting that these particles, if they exist, should be heavier than their SM superpartners. To achieve such SUSY-breaking without reintroducing the quadratic divergences to the Higgs mass value, a so called “soft-SUSY-breaking” term is introduced to the SUSY Lagrangian [42, 43]. This term explicitly breaks SUSY by introducing the mass terms for the Higgs bosons, 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 very large number of unknown parameters $\mathcal{O}(100)$ [44]. However, in absence of these phases and mixings, and if the soft terms obey a set of boundary conditions [42,43], only a few new parameters are introduced ($\mathcal{O}(10)$).

2.2.2 The Higgs Sector in the MSSM

In the MSSM two doublets of complex scalar fields of opposite hypercharge are required to break the electroweak symmetry. This requirement is necessary to separately generate the masses of 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 doublets are:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ with } Y_{H_1} = -1, \quad \text{and} \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \text{ with } Y_{H_2} = +1. \quad (2.3)$$

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 the $SU(2)_L \otimes U(1)_Y$ symmetry while preserving the electromagnetic symmetry $U(1)_Q$. The neutral components of the two Higgs field acquire vacuum expectation values:

$$\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}}, \quad \text{and} \quad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}}. \quad (2.4)$$

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 polarisations and masses. The remaining degrees of freedom correspond to five physical Higgs bosons: two neutral CP-even bosons h and H , a neutral CP-odd boson A and a pair of charged bosons H^\pm . The MSSM Higgs sector is described by six parameters: the Higgs bosons masses M_h , M_H , M_A , M_{H^\pm} , the mixing angle α in the neutral CP-even sector and the ratio between the two vacuum expectation values $\tan \beta = v_1/v_2$. At tree level, only two of these parameters are independent, commonly chosen to be $\tan \beta$ and M_A . The supersymmetric structure of the theory imposes a strong hierarchical structure of the Higgs boson mass spectrum: the h boson is the lightest and at tree level is found that $M_h < M_Z$, while $M_A < M_H$ and $M_{H^\pm}^2 = M_A^2 M_W^2$. Furthermore, the following relation holds between the mixing angles:

$$\cos^2(\beta - \alpha) = \frac{M_h^2(M_Z^2 - M_h^2)}{M_A^2(M_H^2 - M_h^2)} \quad (2.5)$$

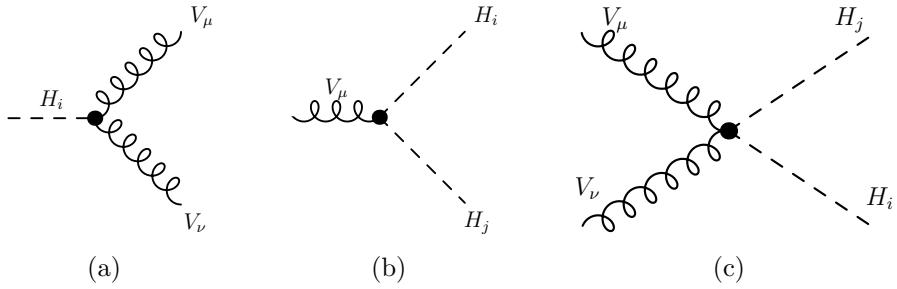


Figure 2.1: Feynman diagrams for the couplings between one Higgs boson and two gauge bosons (a), two Higgs bosons and one gauge boson (b) and two Higgs bosons and two gauge bosons (c) [3].

These relations are broken by large radiative corrections to the Higgs bosons masses [49], which among others raise the threshold of the h boson mass from M_Z to $M_h \lesssim 140$ GeV. Additionally the GUT assumptions restrict the $\tan \beta$ value to the range $1 \lesssim \tan \beta \lesssim m_t/m_b$ [50].

2.3 Phenomenology of the Neutral MSSM Higgs Bosons

2.3.1 Couplings of the MSSM Higgs Bosons to SM Particles

The phenomenology of the MSSM Higgs bosons depends on their couplings to the standard model and supersymmetric particles. A short overview of the former is given below, based on the Ref. [3]. Supersymmetric particles are assumed to be heavy enough to prevent for direct Higgs bosons decays into these particles.

The possible couplings between the MSSM Higgs bosons and vector bosons are shown in Figure 2.3.1, these are the three-linear couplings $V_\mu V_\nu H_i$ of one Higgs boson to two gauge bosons and $V_\mu H_i H_j$ of one gauge boson to two Higgs bosons, as well as the quartic couplings between two Higgs bosons and two gauge bosons $V_\mu V_\nu H_i H_j$. Among them, the most relevant coupling for MSSM Higgs phenomenology is the trilinear coupling $V_\mu V_\nu H_i$. 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, for the $V_\mu V_\nu H_i$ coupling only the following

terms remain:

$$Z_\mu Z_\nu h : ig_z M_Z \sin(\beta - \alpha) g_{\mu\nu}, \quad Z_\mu Z_\nu H : ig_z M_Z \cos(\beta - \alpha) g_{\mu\nu} \quad (2.6)$$

$$W_\mu^+ W_\nu^- h : ig_w M_W \sin(\beta - \alpha) g_{\mu\nu}, \quad W_\mu^+ W_\nu^- H : ig_w M_W \cos(\beta - \alpha) g_{\mu\nu} \quad (2.7)$$

The coupling strength of the neutral CP-even Higgs bosons h and H to a pair of vector bosons are proportional to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ respectively, where $\cos(\beta - \alpha)$ is fixed at tree level following equation (2.5). An interesting phenomenological consequence is that, with G_{VVh} and G_{Vvh} being the coupling between two generic vector bosons and one of the two neutral CP-even Higgs bosons the following equation holds:

$$G_{VVh}^2 + G_{Vvh}^2 = g_{Vvh_{SM}}^2, \quad (2.8)$$

where $g_{Vvh_{SM}}^2$ is the SM Higgs boson coupling. The equations (2.6)-(2.8) imply that the couplings of h (H) to vector bosons increase (decrease) with $\tan \beta$. For relatively large value¹ of $\tan \beta$, h has SM-like couplings to vector bosons while H decouples from them. For an overview of all other coupling properties between vector bosons and Higgs bosons, charged Higgs bosons, trilinear and quartic couplings among Higgs bosons and couplings to SUSY particles refer to [3].

The coupling of the MSSM Higgs bosons to the 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 to 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 to down-type (up-type) fermions are directly enhanced (suppressed) by $\tan \beta$.

2.3.2 MSSM Benchmark Scenarios

At tree level, the MSSM Higgs boson masses, decay branching fractions and production cross sections are all determined by two independent parameters, conventionally chosen to be M_A and $\tan \beta$. As pointed out in Section 2.2.2, the MSSM Higgs bosons masses are strongly affected by radiative corrections and the

¹For most scenarios this is valid for $\tan \beta \gtrsim 10$ and large range of m_A .

prediction of physics observables becomes dependent on additional MSSM parameters [49]. The main corrections arise from the top-stop (s)quark sector and for large $\tan \beta$ values also the bottom-sbottom (s)quark sector becomes increasingly important. Furthermore, the corrections are dependent on the SUSY-breaking scale M_{SUSY} , the trilinear Higgs-stop and Higgs-sbottom Yukawa couplings, as well as 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 for experimental searches and phenomenological studies. To cope with this difficulty, several benchmark scenarios have been proposed [4, 52] which fix the values of the SUSY parameters (entering the predictions via radiative corrections) to particular benchmark values exhibiting interesting features of the MSSM Higgs phenomenology. The parameters M_A and $\tan \beta$ are left free to vary and the results are usually presented in the $M_A - \tan \beta$ plane.

The m_h^{max} benchmark scenario [51] was frequently used in the past searches for neutral MSSM Higgs bosons performed at LEP, Tevatron and LHC [65–68]. In this benchmark scenario, the MSSM parameters are fixed such that the mass of the light CP-even Higgs boson M_h assumes its maximal value as a function of M_A and $\tan \beta$. The m_h^{max} scenario allows to set conservative lower bounds on the values of M_A , M_H^\pm and $\tan \beta$ [52]. However, given the recent discovery of a Higgs boson with mass of about 125 GeV, this scenario tends to predict a too high mass M_h for the SM-like Higgs boson candidate h , thus becoming inconsistent with the Higgs boson observation for large regions of the MSSM parameter space. This scenario is still used since it allows for the comparison of the result with past experiment.

Recently, several benchmark scenarios have been updated [4] to accommodate the experimental constraints from past searches for neutral MSSM Higgs bosons and from the observation of a SM-like Higgs boson. An interesting updated benchmark scenario is the m_h^{mod} scenario which predicts $M_h \simeq 125.5 \pm 3$ GeV for a large region of the MSSM parameter space. The configuration of the m_h^{mod} scenario is obtained by reducing the amount of mixing in the stop sector relative to the m_h^{max} scenario. This can be done for both signs of the MSSM parameter X_t , which regulates the amount of the stop mixing, 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 and m_h^{mod+} benchmark scenario has been used throughout this thesis as a reference scenario. For simplicity the m_h^{mod+} is referred in the following to as just m_h^{mod} .

Other interesting benchmark scenarios are the light-stop and the light-stau scenario. The first may lead to a modification of the gluon fusion production cross

section, while the second leads to a modification of the branching fraction for the decays of the MSSM Higgs boson h into two photons. For an overview of other relevant benchmark scenarios refer to Reference [4].

2.3.3 Production and Decay of Neutral MSSM Higgs Bosons at LHC

The MSSM predicts for large region its parameter space a Higgs boson with SM-like couplings, the additional requirement for this boson to have a mass of about 125 GeV and to be in agreement with the past searches set stringent constrain on the MSSM parameter space. Scenarios, which interpret the discovered SM-like Higgs boson as the lightest CP-even MSSM Higgs boson h , are favoured since they still present a relatively large unexplored region of parameter space. This case is assumed below and for the rest of this thesis.

Given the Higgs bosons couplings discussed in Section 2.3.1, it turns out that the MSSM Higgs bosons H and A tend to be degenerate in mass and decouple from gauge bosons. Furthermore their couplings with down (up) type fermions are enhanced (suppressed) by $\tan\beta$. Therefore for large $\tan\beta$ values, bottom-quark and τ lepton will play an important role, relative to the SM Higgs boson case, for the production and decays of the H and A Higgs bosons.

The production of the neutral CP -even MSSM Higgs bosons (h and H) at hadron colliders proceeds via the same processes as for the SM Higgs boson production [5]. The pseudoscalar A , instead, cannot be produced in association with gauge bosons or through vector boson fusion (VBF) processes at tree-level, as this coupling is forbidden due to CP -invariance. At the LHC the most relevant MSSM Higgs boson production mechanisms are gluon fusion, $gg \rightarrow A/H/h$ and the production in association with b -quarks, $pp \rightarrow b(b)A/h/H$. The latter becomes important for relatively large values of $\tan\beta$ ($\tan\beta \gtrsim 10$). Figure 2.2 shows examples of tree-level Feynman diagrams for these processes, the corresponding production cross sections are shown in Figure 2.3 assuming the m_h^{max} benchmark scenario.

The branching fraction for the decays of the neutral MSSM Higgs bosons h (under the assumption that all supersymmetric particle are heavy enough) are the same as for the SM Higgs boson, while for H and A the decays into τ lepton, studied in this thesis, is the most dominant after $b\bar{b}$ for large region of parameter space. Figure 2.4 shows the branching fractions for various decay of h , H and A assuming the m_h^{mod+} benchmark scenario as a function of the mass m_A for two

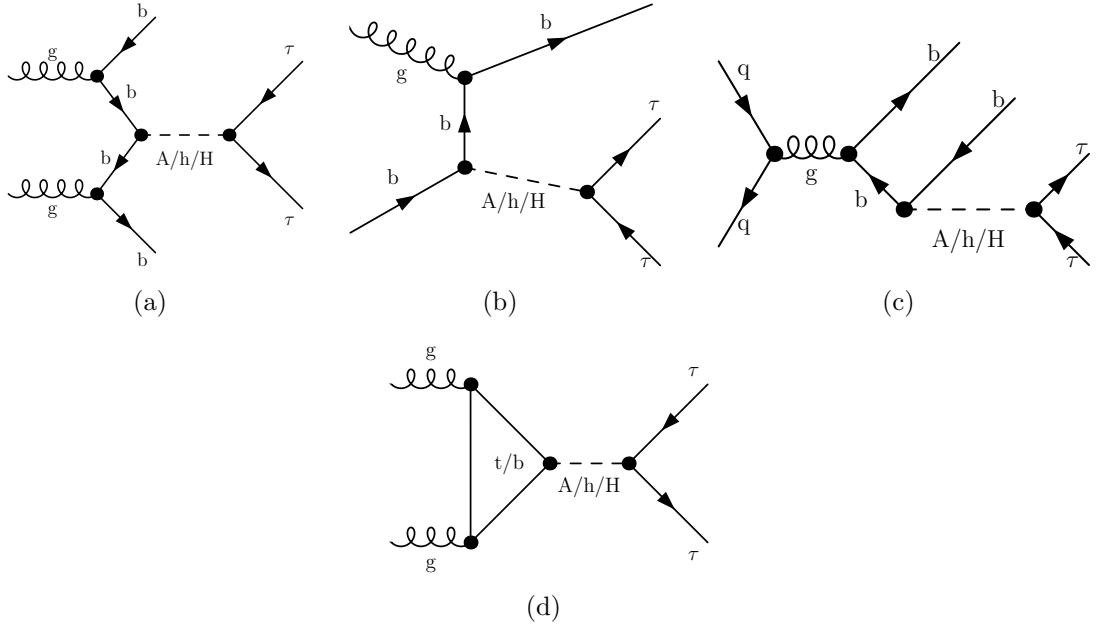


Figure 2.2: Tree-level Feynman diagram for the production of the neutral MSSM Higgs bosons in association with b -quarks (a,b,c) and via gluon fusion (d) with subsequent Higgs boson decays into a pair of τ leptons.

values of $\tan \beta$.

2.3.4 Status of the Search for Neutral MSSM Higgs Bosons

Constraint of the MSSM Higgs sector may be obtained in two ways: by the measure of the couplings of the observed SM-like Higgs boson to known SM particles or by direct searches for additional Higgs bosons in a well defined scenario.

In case the discovered SM-like Higgs boson with a mass of about 125 GeV 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 $\tan \beta$ allowing to exclude certain region of the $m_A - \tan \beta$ plane [53]. Figure 2.5 shows the excluded parameter region for a so-called “simplified MSSM” model [54, 55] obtained from the fits of the Higgs boson production and decay rates to the corresponding observed values.

The latest constraints on $m_A - \tan \beta$ plane from direct searches for neutral MSSM Higgs bosons (including also the result from the analysis presented in this

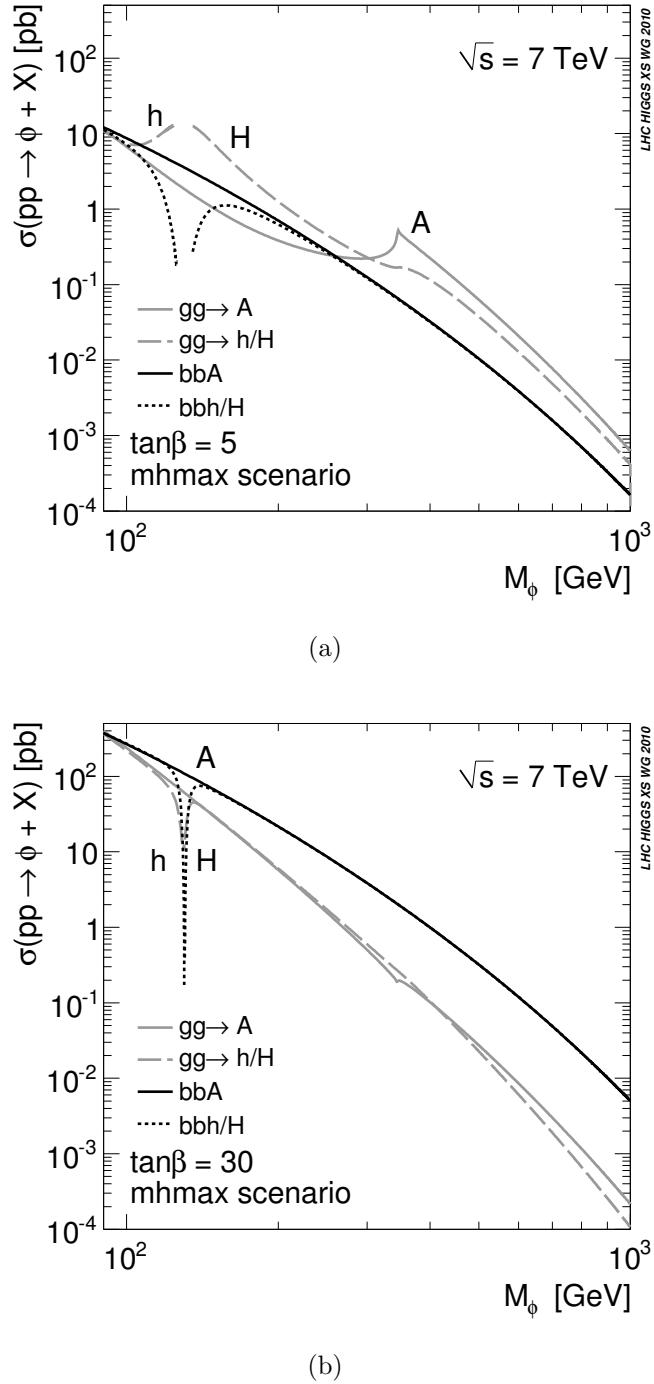


Figure 2.3: Central predictions of the total MSSM Higgs bosons production cross sections via gluon fusion and in association with bottom quarks for $\sqrt{s} = 7 \text{ TeV}$ using NNLO and NLO MSTW2008 PDF sets, assuming m_h^{max} scenario; (a) $\tan\beta = 5$, (b) $\tan\beta = 30$ [5].

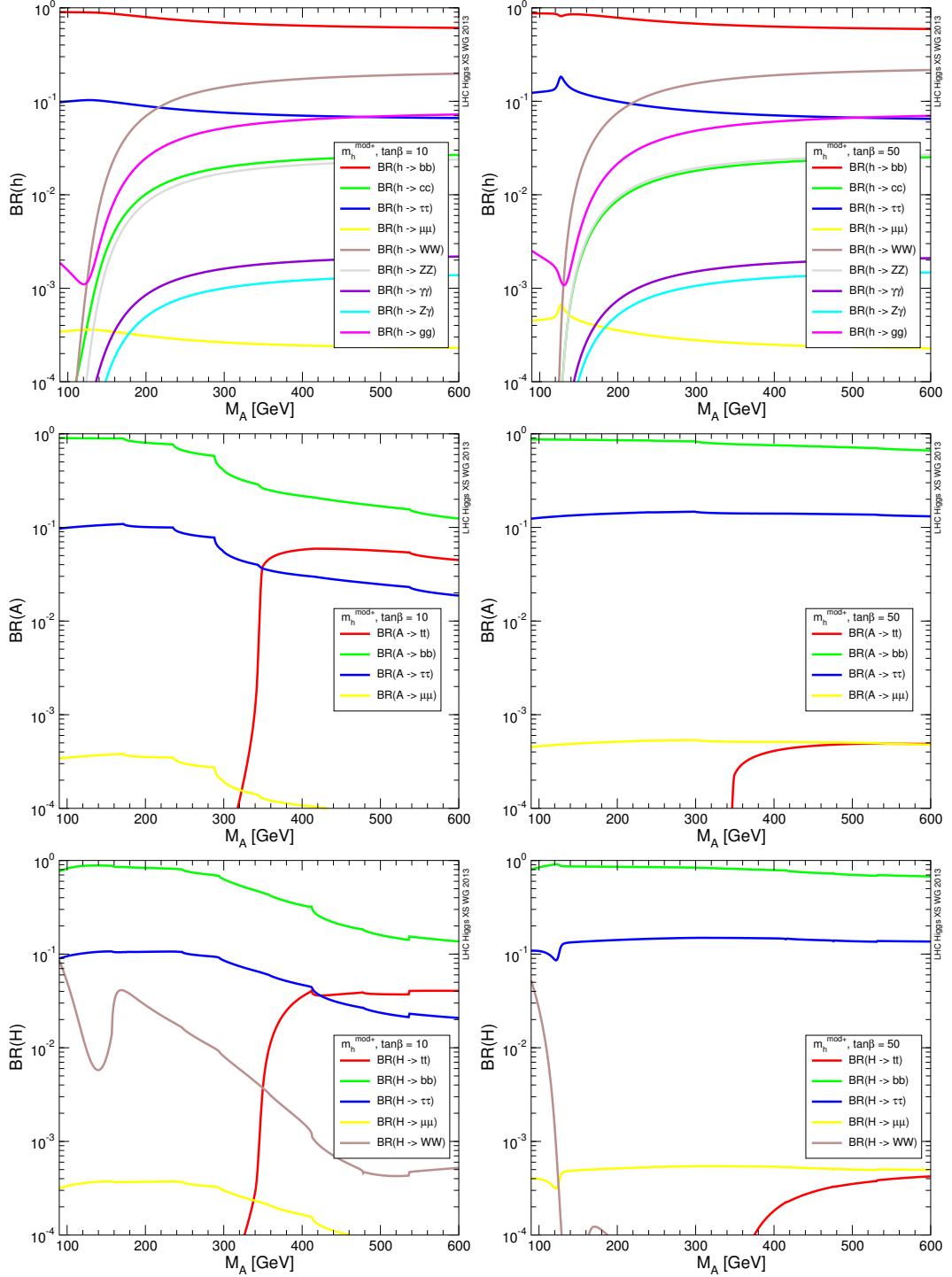


Figure 2.4: Branching fractions for various decays of the neutral MSSM Higgs bosons, $h/H/A$, shown for the $m_h^{\text{mod}+}$ scenario with $\tan\beta = 10$ and $\tan\beta = 50$ [4].

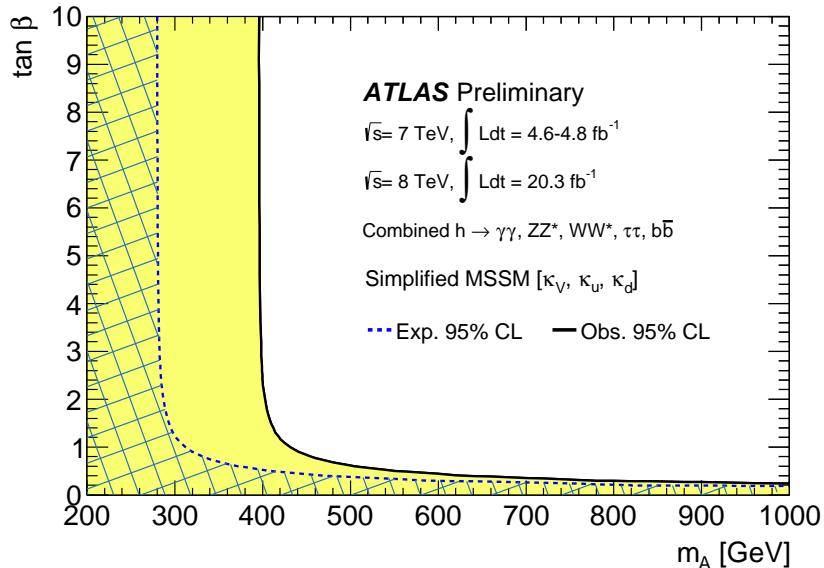


Figure 2.5: Regions of the $m_A - \tan \beta$ plane excluded in a simplified MSSM model via coupling fits to the measured of Higgs boson production and decays rates. The likelihood contours with $2 \ln \Lambda = 6.0$, corresponding approximately to an exclusion at a 95% confidence level are indicated for the observed (shaded region) and expected (hashed region) exclusion range, respectively [53].

thesis) [] are shown in Figure 2.6, the m_h^{mod} scenario is assumed.

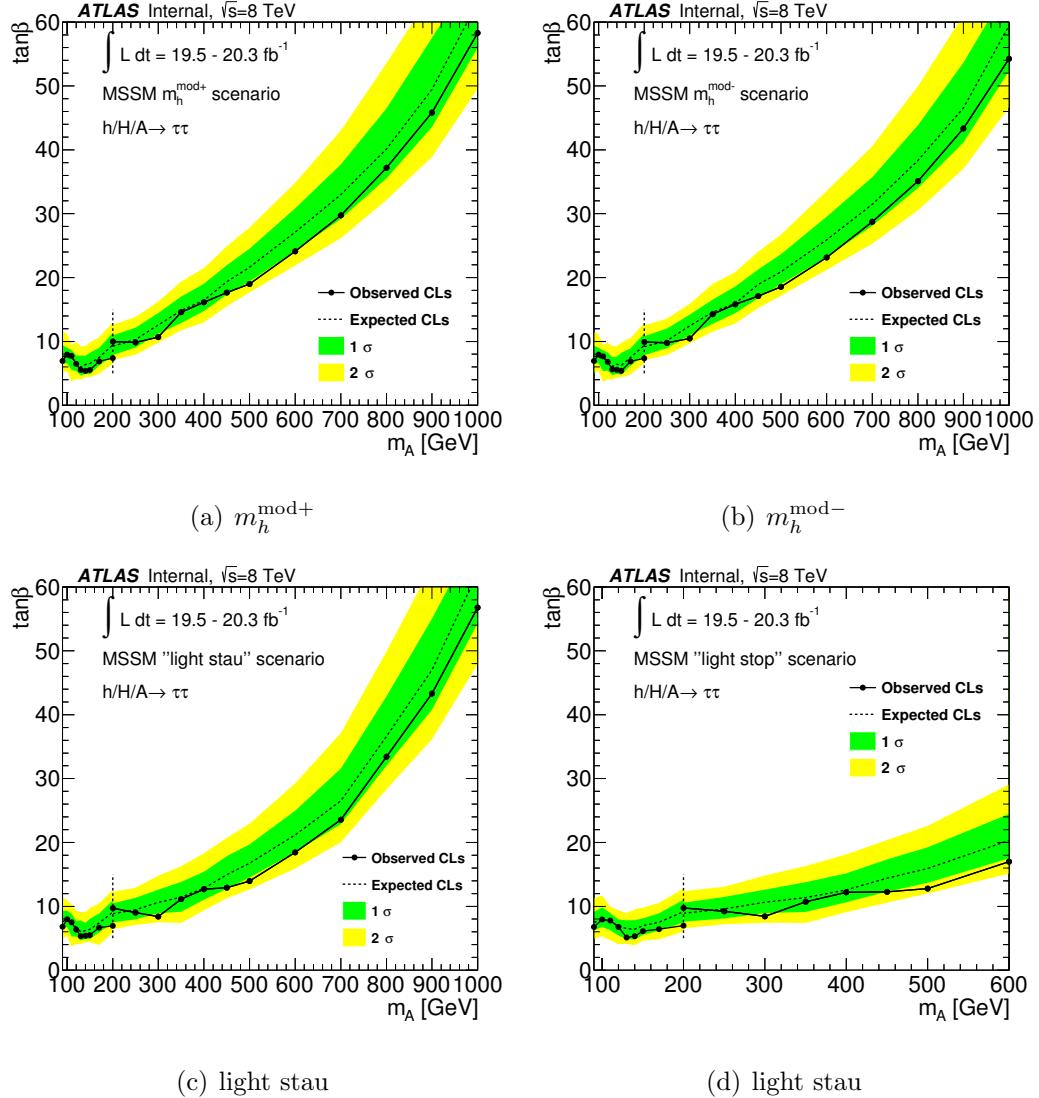


Figure 2.6: Expected (dashed bold line) and observed (solid bold line) 95% CL upper limits on $\tan\beta$ as a function of m_A . Limits are shown for the updated benchmark scenarios. Markers connected by a continuous line indicate the observed limit and dashed lines the expected. The vertical dashed line at 200 GeV indicates the transition point between low and high mass analysis categories [1].

Chapter 3

The ATLAS Detector at the LHC

The Large Hadron Collider (LHC) located at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, is the largest particle collider facility in the world, colliding protons and heavy ions at so far largest centre-of-mass energies. The ATLAS experiment is one of the several experiments at the LHC, taking data with a general-purpose detector designed to search for a wide range of new physics phenomena and to perform precision measurements of known Standard Model processes. Proton-proton collision data recorded by the ATLAS detector in 2012 has been used for the search for the neutral MSSM Higgs bosons presented in this thesis.

This chapter is organised as follows: the design and performance of the LHC are summarised in Section 3.1, based on [56], while a brief description of the ATLAS detector is given in Section 3.2, based on [57].

3.1 The Large Hadron Collider

The LHC is a superconducting hadron synchrotron collider. It is installed in the tunnel of the former Large Electron-Positron collider (LEP) with a circumference of about 27 km. LHC is designed to collide proton beams at a nominal centre-of-mass energy of 14 TeV and an unprecedented peak luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. It can also collide heavy ion (lead) beams carrying an energy of 2.8 TeV per nucleon and a peak luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$.

Figure 3.1 shows the layout of the CERN accelerator complex. The protons undergo several acceleration steps before their injection into the LHC machine. The *a linac* accelerator (*Linac 2*) accelerates the protons to an energy of 50 MeV, after which they are injected into the *booster* and further accelerated to 1.4 GeV. The proton energy is increased to 25 GeV and successively to 450 GeV by means of two synchrotron accelerators, the *Proton Synchrotron* (PS) and the *Super Proton Synchrotron* (SPS). Finally, two proton beams are injected in opposite directions into the LHC ring where they reach their final energy.

The proton beams are housed in two separate vacuum pipes and consist of up to 2835 proton bunches, each of them containing about 10^{11} protons. Radiofrequency cavities are employed to accelerate the protons, while superconducting magnets bend and focus the bunches. The nominal bunch spacing allows for bunch crossings every 25 ns and represents a challenge for any detector read-out electronics.

First proton-proton collisions took place at the LHC in 2010 at a centre-of-mass energy of 7 TeV. The LHC was successfully delivering data during years 2011 and 2012, increasing the centre-of-mass energy to 8 TeV in 2012. Peak luminosities of about $4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-2}$ and $8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-2}$ have been reached during years 2011 and 2012 respectively. The physics program of the LHC is driven by four major experiments which are ATLAS [57], CMS [59], LHCb [60] and ALICE [61]. The ATLAS experiment recorded proton-proton collision data corresponding to an integrated luminosity of 4.57 fb^{-1} during year 2011 and additional 20.3 fb^{-1} during 2012. Data recorded during these two years led among others to one of the major milestones in particle physics, the discovery of a Higgs boson with a mass of about ~ 126 GeV.

3.2 The ATLAS Detector

The ATLAS detector is a multi-purpose detector aiming to explore a wide range of physics phenomena at the Teraelectronvolt energy scales. The physics goals

CERN's Accelerator Complex

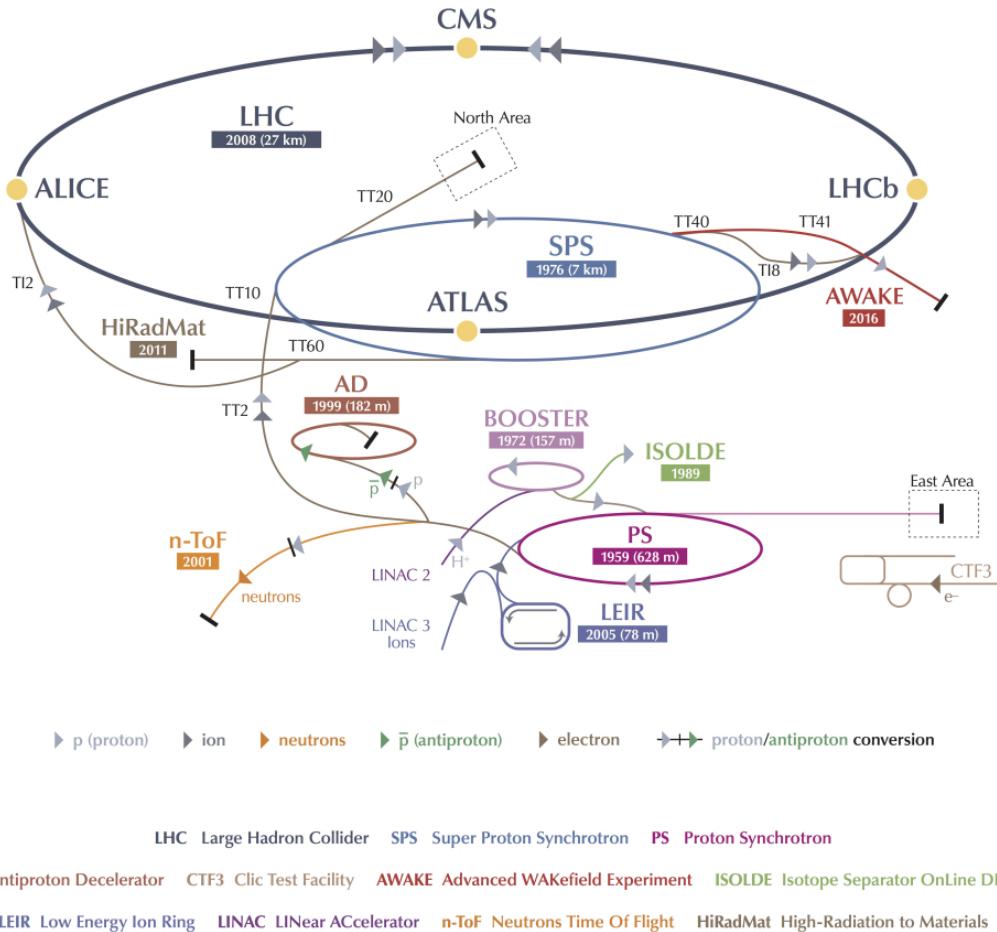


Figure 3.1: Illustration of the CERN accelerator complex [58]. The acceleration of protons starts with Linac2 followed by the acceleration in the Booster. The Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) accelerate the protons further before their final injection into the LHC machine, where they acquire their final energy.

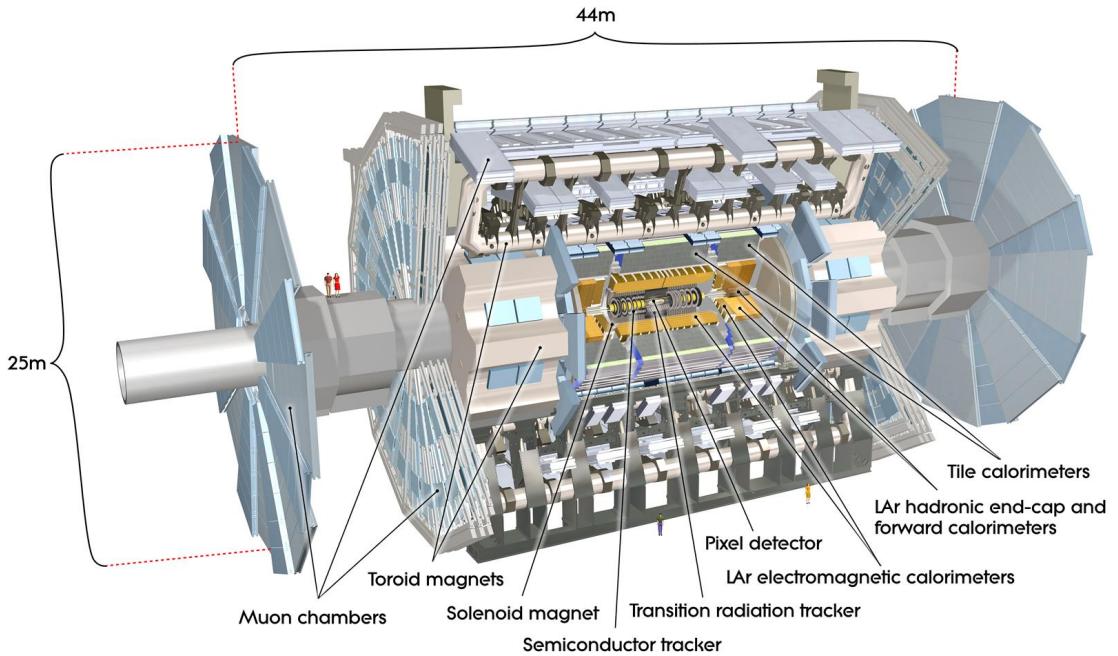


Figure 3.2: Cut-away view of the ATLAS detector with its sub-detectors [57].

drive the detector design, imposing strong requirements on particle reconstruction and identification accuracy. A schematic view of the ATLAS detector is shown in Figure 3.2, with its length of 44 m and its height of 25 m is the largest detector at the LHC, it is centred around one of the LHC interaction points about 100 under ground. ATLAS consist of four sub-detectors which are installed cylindrically around the beam pipe, symmetrically in the forward and backward direction with respect to the proton beams. The innermost sub-detector is the inner detector (ID), followed by the electromagnetic calorimeter, the hadronic calorimeter and finally a muon spectrometer (MS) in the outermost layer. Each of these sub-detector is briefly described in what follows based on Reference [57].

3.2.1 The ATLAS coordinate system

The ATLAS coordinate system has its origin at the interaction point. The z -axis is pointing along the beam direction, the y -axis upwards and the x -axis towards the centre of the LHC ring. The azimuthal angle ϕ is defined in the transverse

plane orthogonal to the beam axis, starting from the positive side of the x -axis. The polar angle θ is defined with respect to the z -axis.

A commonly used spatial coordinate in collider experiments is related to the rapidity y :

$$y = 1/2 \cdot \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (3.1)$$

where E and p_z are the particle energy and the momentum component in the z -direction, respectively. The difference in the rapidity of two particles is independent of Lorentz boosts along the beam axis. In the limit of the relative velocity β approaching to 1 (i.e. the speed of light) or for massless particles the rapidity corresponds to the pseudorapidity η ,

$$\eta = 1/2 \cdot \ln \left(\frac{\theta}{2} \right). \quad (3.2)$$

Based on the ATLAS detector layout, the detector is divided into the *barrel* region, with a cylindrical structure, extended for $|\eta| \lesssim 1.5$ (depending on the particular sub-detector) and the *endcap* region, with a disk structure, for larger η values. The angular separation between two particles is commonly quantified with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where $\Delta\eta$ and $\Delta\phi$ are the difference in pseudorapidity and azimuthal angle of these particles, respectively.

3.2.2 The Inner Detector

The inner detector performs the reconstruction of curved charged particles trajectories in a 2 T solenoidal magnetic field, providing the particles momenta as well as the position of the interaction vertices. The layout of the inner detector is illustrated in Figure 3.3. It has a total length of 5.3 m, a diameter of 2.5 m and consists of three independent detector modules with fine granularity covering the pseudorapidity region $|\eta| < 2.5$. The innermost inner detector module is the pixel detector which consists of three cylindrical layers of pixel silicon sensors in the barrel and three disks in the endcap region. The pixel layer closest to the beam pipe is referred to as the B-layer, since it provides crucial informations for the identification of b-quarks. The pixel sensors have a spatial resolution of $10 \mu\text{m}$ in the transverse and $115 \mu\text{m}$ in the longitudinal direction with respect to the beam pipe.

The Semi-Conductor Tracker (SCT) surrounds the pixel detector with four cylindrical layers of silicon microstrip sensors in the barrel and nine disks in the

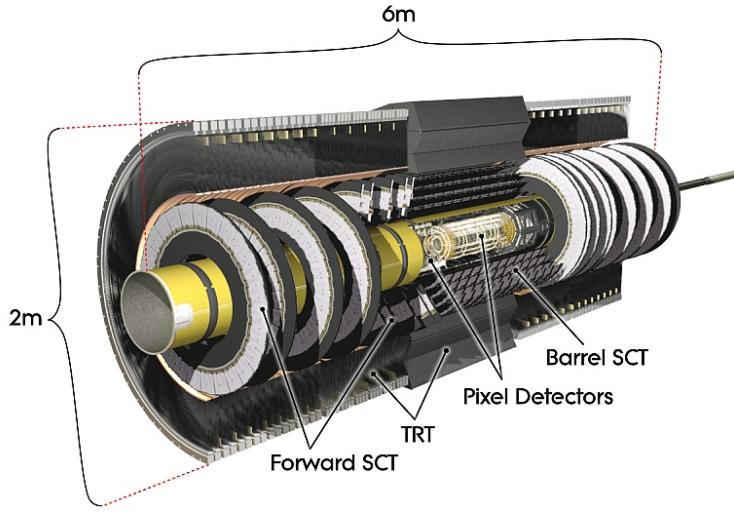


Figure 3.3: Cut-away view of the ATLAS inner detector [57].

endcap region. The spatial resolution achieved by the SCT sensors is $17\text{ }\mu\text{m}$ in the transverse and $590\text{ }\mu\text{m}$ in the longitudinal direction.

The outermost inner detector module is the Transition Radiation Tracker (TRT). It is composed of 4 mm diameter kapton straw tubes with a tungsten wire in their centre. The tubes are filled with a gas mixture (70% Xe, 27% CO₂ and 3% O₂) which allows for the detection of transition radiation photons. This detector can only measure the particle position in the transverse plane.

3.2.3 The Calorimeter System

An illustration of the ATLAS calorimeter system is shown in Figure 3.4. It consists of an electromagnetic calorimeter (EM) surrounded by a hadronic calorimeter. These calorimeters cover the pseudorapidity range $|\eta| < 4.9$. Both calorimeters are sampling calorimeters, built of alternating active material which performs the detector response and a passive absorber. The total detector material at $\eta = 0$ corresponds to an interaction length λ of 9.7.

The EM liquid-argon (LAr) calorimeter is ideally suited for the precision measurement of electron and photon energy. Liquid argon acts as active material while lead is used as an absorber. The EM calorimeter extends up to $|\eta| < 3.2$. The total

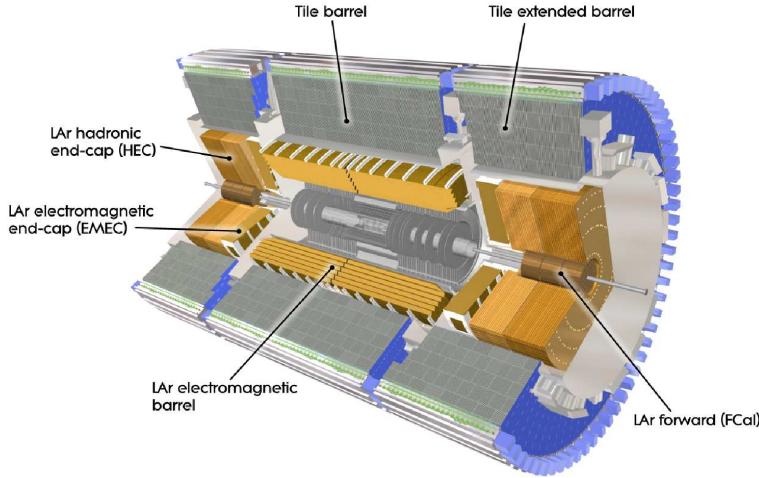


Figure 3.4: Cut-away view of the ATLAS calorimeter system [57].

thickness of the EM calorimeter is about 22 radiation lengths in the barrel and greater than 24 in the end-caps. It is divided in depth into three cylindrical layers each of them additionally segmented in $\eta - \phi$ cells with different size depending on the layer and on pseudorapidity. The ϕ and size of a cell ranges from 0.025-0.1, while its η size ranges from 0.0035-0.075. The energy resolution for electrons and photons ranges from $9\text{-}22\%/\sqrt{E}$ and from $8\text{-}14\%/\sqrt{E}$ respectively depending on pseudorapidity.

The hadronic calorimeter has a coarser granularity with respect the EM calorimeter and is suited for reconstruction of hadronic showers (jets) and measurement of missing transverse energy. It is divided in three sub-detector systems which make use of several different technologies to cope with the η -dependent radiation environment. A tile calorimeter covers the pseudorapidity range up to $|\eta| < 1.7$. Scintillating tiles are employed as active material and steel as an absorber. In the forward region, the hadronic calorimeter is instrumented with a LAr hadronic end-cap calorimeter (HEC) which extends up to $|\eta| < 3.2$ and uses argon as an active material and copper as an absorber. The most forward region with $3.1 < |\eta| < 4.9$ is instrumented with a liquid argon Forward CALorimeter (FCAL), which is divided in three modules. In the module closest to the interaction point, copper is used as absorber material, while the other two modules employ tungsten. The jet energy resolution in the barrel is of about 15% for jets of $p_T = 50$ GeV and it is of about 7% for jets of $p_T = 1$ TeV [113].

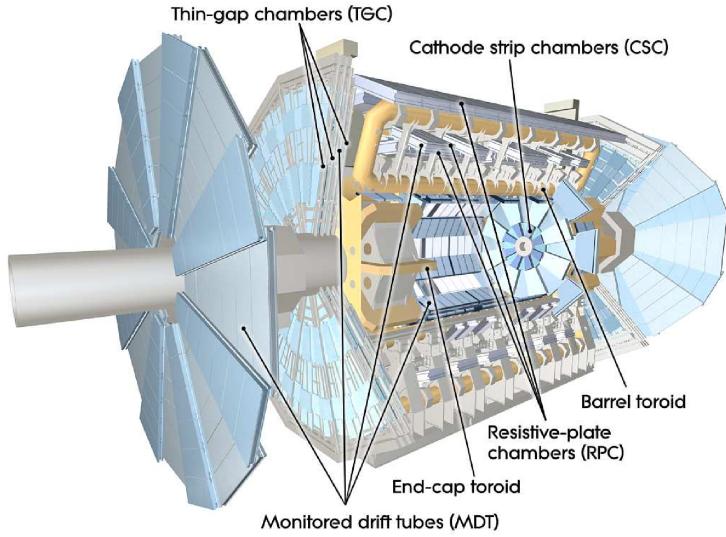


Figure 3.5: Cut-away view of the ATLAS muon spectrometer system [57].

3.2.4 The Muon Spectrometer

The muon spectrometer is instrumented with separate high-precision tracking and muon trigger chambers. The measurement of the muon momenta is performed by reconstructing the curvature of the muon trajectory in an intense toroidal magnetic field of 0.3-1.2 T, which is produced by the large superconducting air-core toroid magnets. The layout of the muon spectrometer is shown in Figure 3.5.

Precision measurement of the track coordinates in the principal bending direction of the magnetic field is provided by three layers of Monitored Drift Tube chambers (MDT), covering the pseudorapidity range $|\eta| < 2.7$. Given the high background rate at large pseudorapidities, $2 < |\eta| < 2.7$, the innermost MDT layer is replaced by the Cathode Strip Chambers (CSC). These are multi wire proportional chambers with cathodes segmented into strips. The spectrometer allows for a precise muon momentum measurement for momenta up to 1 TeV. The best momentum resolution of 3-4% is achieved for muons with transverse momenta of about 100 GeV, while resolution of about 10% can be reached for muon momenta of 1 TeV.

The trigger system covers the pseudorapidity range $|\eta| < 2.4$. Resistive Plate Chambers (RPC) used in the barrel and Thin Gap Chambers (TGC) in the end-cap region provide a relatively coarse but fast reconstruction of muon tracks needed

for the first-level muon trigger.

3.2.5 The Trigger System

For a detector like ATLAS, given the nominal LHC bunch crossing rate of 40 MHz, it is technically impossible to record and store data for each bunch crossing. A trigger system is therefore designed to reduce the initial rate to about 300 Hz, selecting only the interesting events. The triggering is performed in three stages with increasing selection power, the so called level 1 (L1), level 2 (L2), and the event filter (EF). Each trigger level refines the decisions made at the previous level and, where necessary, applies additional selection criteria.

The L1 trigger is hardware based and is designed to reach a decision within a latency of less than $2.5 \mu\text{s}$, reducing the initial rate to about 75 KHz. It relies on coarse energy deposit in the calorimeter and muon trajectory in RPC and TGC chambers. It allows for the selection of high transverse-momentum muons, electrons, photons, jets, τ leptons decaying into hadrons, as well as large missing and total transverse energy. The L1 trigger defines in each triggered event one or more regions of interest (RoI), i.e. the η and ϕ coordinates of detector regions in which a potential final state collision product is observed.

The L2 trigger selection is seeded by the RoI information provided by the L1 trigger. Unlike the L1 trigger, the L2 uses the full detector granularity in the given RoIs allowing for a more precise reconstruction of particle properties. The L2 triggers are designed to reduce the trigger rate to approximately 3.5 kHz.

The final stage of the event selection is carried out by the event filter, which reduces the event rate to roughly 300 Hz. Its selections are implemented applying reconstruction algorithms equivalent to the ones available offline. The offline reconstruction of physics object is described in Chapter 4 .

3.2.6 Luminosity Measurement

A precise measurement of the recorded instantaneous and integrated luminosity is a crucial ingredient of all physics studies at ATLAS. Several luminosity measurement techniques are therefore employed as described in [63]. The most relevant detectors for the luminosity monitoring are the inner detector, the BMC [63] and the LUCID [64] detectors. The inner detector provides the luminosity measurement from the average number of reconstructed proton-proton interactions per bunch crossing. The LUCID detector surrounds the beam pipe on both sides of

the interaction point at a distance of 17 m. It consist of Cherenkov detectors which measure the particle flux from the interaction point in a very forward re-gion. The BCM detector consists of four small diamond sensors on each side of the interaction point arranged around the beam pipe in a cross pattern. It is a fast device primarily designed to monitor the beam condition and can also pro-vide an independent luminosity estimate. The total uncertainty on the luminosity measurement obtained with these methods is about 3%.

Chapter 4

Reconstruction of Physics Objects

The raw ATLAS data, containing detectors signals of all read-out channels, need to undergo several reconstruction steps before they can be analyzed. Reconstruction software is developed within the object oriented ATLAS reconstruction software framework ATHENA [93], which allow for reconstruction and identification of various objects corresponding to physics particles traversing the detector.

This chapter briefly describes the ATLAS reconstruction strategies for physics objects relevant for the analysis presented in this thesis. For a detailed overview of the ATLAS detector reconstruction software see [94].

4.1 Reconstruction of Charged Particle Tracks

The reconstruction of charged particles tracks and interaction vertices is based on the measurements in the inner detector which allow for the reconstruction of tracks within the pseudorapidity range of $|\eta| < 2.5$. A track is characterized by its four-momentum vector and two impact parameters: d_0 , i.e., the distance of closest approach between the track and the interaction point in the transverse plane and z_0 , i.e. the z coordinate of the track calculated at the same point of closest approach.

Tracks are reconstructed by the inner detector track reconstruction software [95]. At first raw data from the pixel and SCT detectors are transformed in three-dimensional space points (so called “hits”), while the TRT detector information is translated into drift circles. Subsequently, track seeds are formed from a combination of space-points in the three pixel layers and the first SCT layer. These seeds are then extrapolated through the SCT to form track candidates from all hits on the track path. The track candidates are obtained by a fit trough all hits using a *Kalman filter* algorithm [96]. Ambiguities in the association of the hits to the track are resolved by this fitting procedure and tracks produced by a random association of hits are rejected. The selected tracks are then extrapolated to the TRT and finally refitted using the full information of all three tracking detectors. In order to improve the tracking efficiency for secondary tracks from photon conversion or decays of long-lived particles (like kaons), a complementary algorithm [95] searches for unassociated track segments in the TRT, these segments are then extrapolated towards the SCT and the pixel detector in a similar manner as in the default algorithm. All tracks with $p_T > 100$ MeV are considered for physics analysis.

4.2 Vertex Reconstruction

The vertex reconstruction algorithm and its performance are described in detail in [94,97] and only briefly summarized here. The vertex finding algorithm selects a set of well reconstructed tracks and generates a vertex seed according to the average value of the tracks z coordinate. The z coordinate of the tracks is computed relative to the expected average position of the collision point. An *adaptive vertex fitting* algorithm [98] determines the vertex position based on the vertex seed and on the tracks around it via a χ^2 fit. Based on this fit, tracks that are incompatible with the found vertex by more than seven standard deviations are used to seed the next vertex. The procedure is performed iteratively until either all tracks are

associated to a vertex or no additional vertex can be found. The performance of this procedure depends on the expected position of the average interaction point which is monitored during LHC data taking and is computed in intervals of a few minutes as described in [99].

The vertex with the largest sum of transverse momentum of all associated tracks is identified as the *primary vertex* (PV), corresponding to the interaction point of the hard scattering process in the event. All other vertices in the event are assumed to result from minimum bias interactions and are called *pile-up* vertices. In data recorded during 2012, there were on average 21 multiple interactions occurring per bunch crossing. Such a high vertex multiplicity strongly affects the ambient energy density in the event, such that an accurate pile-up description in simulation is crucial for the modelling of physics processes. In ATLAS, events are simulated assuming various pile-up conditions and weighted such to reproduce the observed average number of interactions per bunch crossing.

4.3 Electron Reconstruction and Identification

Electron are reconstructed and identified by combining EM calorimeter and inner detector measurements. The corresponding dedicated algorithm is described in [100]. The electron candidate is reconstructed as a clusters of EM calorimeter cells which is matched to a track in the inner detector. Special care during the matching is taken to account for Bremsstrahlung losses of the charged particle. The electron energy is computed as a weighted average between the cluster energy and the track momentum. Several corrections are applied to take into account energy losses in the material of the inner detector and effect of electromagnetic shower leakage. The electron direction is defined by the corresponding track parameters.

Further identification criteria are applied to electron candidates to reduce contaminating contribution of photon conversions and hadronic jets. Three different identification criteria are provided based on a multi-variate analysis program (TMVA [101]) and several selection criteria :

- Loose electron identification: variables related to the shape of the electromagnetic shower and to the amount of the hadronic leakage are used in a multi-variate analysis program.
- Medium electron identification: the total shower width and the difference between the largest and second largest energy deposit are considered in a

multi-variate analysis program in addition to the loose variables. Furthermore stricter track matching requirements are imposed.

- Tight electron identification: in addition to medium requirements, converted photons are rejected by requiring a hit in the innermost layer of the inner detector. Furthermore, the number of TRT hits associated to the electron is employed as additional variable in the multi-variate analysis program.

The performances of the electron identification are measured with several calibration data samples (using events with leptonic decays of W , Z bosons and J/ψ meson) and compared to simulation [102]. Corresponding corrections of the simulated electron identification efficiency are measured and applied as p_T and η dependent weight to each simulated electron candidate. Additional corrections are applied to the energy scale and energy resolution of simulated electrons to match the one in data according to [103]. Systematic uncertainties on the measure of the identification efficiency ranges from 1-2% depending on the transverse momentum of the electron, while uncertainties on the measure of the energy scale and resolution range approximately from 0.3-3% depending on η . Finally, the electrons used in the presented analysis are rejected if they are detected in a region of the calorimeter with readout problems or suffering from high noise.

Prompt electrons, originating from the decay of a resonance like the Z^0 boson or the Higgs boson are very likely to be *isolated*, i.e. there is little particle activity expected in their surroundings. This is in contrast to electrons originating from hadron decays, which instead will be likely to be surrounded by a jet of particles. Two isolation variables are defined to account for the activity in a cone of size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ around the electron candidate:

- Track isolation, $p_T^{cone} = \sum_{\Delta R < 0.4} p_{T,i}$, is the scalar sum of the transverse momenta $p_{T,i}$ of all tracks i in a cone $\Delta R \leq 0.4$ around the electron direction. The electron track itself is not counted here.
- Calorimeter isolation, $E_T^{cone} = \sum_{\Delta R < 0.2} E_{T,i}$, is the scalar sum of transverse energies $E_{T,i}$ of each topological cluster i in a cone $\Delta R \leq 0.2$ around the electron direction. Clusters associated to the electron itself are not counted. The value of this variable is corrected as a function of the vertex multiplicity in the event in order to account for the pile-up effects and therefore to assure a constant electron selection efficiency for each event.

4.4 Muon Reconstruction

ATLAS employs a variety of strategies for the reconstruction and identification of muons, relying primarily on the tracking in the muon spectrometer and supplemented in most cases with the tracking in the inner detector and the energy deposit in the calorimeter. A detailed description of the muon reconstruction algorithms and their performance is reported in [94]. In the following only the muon reconstruction strategy relevant for this thesis is described.

The STACO *combined* muon algorithm [104] associates tracks found in the muon spectrometer with the corresponding inner detector track and calorimeter energy deposit. At first, track segments are reconstructed in each of the three muon stations and are linked together to form a track. The muon spectrometer track is extrapolated to the inner detector taking into account the energy loss and multiple scattering in the calorimeters. The extrapolated track is matched with an inner detector track via χ^2 -matching. Finally, a statistical combination of the inner detector and muon spectrometer tracks is performed to obtain a combined muon track.

Muon identification efficiency, momentum scale and momentum resolution are evaluated in [105] where performance is compared with prediction from simulation. A set of corrections on the muon momentum scale, resolution and identification efficiency is applied to simulation to ensure a good agreement with data. Uncertainties on these corrections are of the order of a fraction of percent.

Isolation variables, are derived and employed in a similar manner as for electrons. The only difference is the use of calorimeter clusters with fixed size (so-called towers) instead of the topological cells in the definition of E_T^{cone} . Pile-up corrections similar to those employed for electrons are used for muons as well.

4.5 Jet Reconstruction and Energy Calibration

Jets are reconstructed by means of the FastJet package [106], which provides a broad range of jet finding algorithms and analysis tools. In the following jet reconstruction methods relevant for the analysis presented in this theses are briefly described, for more detail see [94].

In general, jets may be reconstructed out of any set of four vector objects. In ATLAS, the jet reconstruction relies most commonly on energy deposit measured by the calorimeters. Calorimeter cells are grouped together by a clustering algorithm forming the so called *topological clusters* [107], i.e. three-dimensional

clusters representing the energy depositions of the shower particles. The clustering procedure starts with seed calorimeter cells with a signal-to-noise ratio greater than a certain threshold. All nearby cells are combined with the seed cells if they pass a second, lower, signal-to-noise ratio threshold.

Each topological cluster is then used as input to the *anti- k_t* algorithm [108]. The algorithm defines a metric to assess distances between the clusters i and j :

$$d_{ij} = \min\left(\frac{1}{k_{t,i}^2}, \frac{1}{k_{t,j}^2}\right) \cdot \frac{\Delta R_{ij}^2}{R^2} \quad \text{and} \quad (4.1)$$

$$d_i = \frac{1}{k_{t,i}^2}, \quad (4.2)$$

where $k_{t,i}$ is the p_T of the cluster i and $\Delta R_{ij}^2 = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$ is the angular distance between the two cluster i and j . For the presented analysis the distance parameter R is chosen to be $R = 0.4$. If the distance d_{ij} between two cluster i and j is smaller than d_i , the clusters are grouped together and their four momenta are summed. Otherwise they are kept as a single entity. The clustering procedure is iterated until no further cluster can be merged. The metric is designed such that high- p_T clusters will accumulate the soft activity surrounding them, therefore leading to conical jet shapes.

Given the high pile-up environment of the LHC, it is important to distinguish jets originating from the hard scattering process and those related to pile-up interactions. For this purpose, each jet is characterized by a so-called *jet vertex fraction* (JVF). The value of the JVF is defined as the p_T -weighted fraction of inner detector tracks pointing to the primary vertex among all tracks associated to the corresponding jet:

$$\text{JVF} = \frac{\sum_{\substack{\text{PV-tracks} \\ \text{tracks}}} p_{T,i}}{\sum_{\substack{\text{tracks}}} p_{T,i}} \quad (4.3)$$

The jet vertex fraction can only be defined for jets within inner detector coverage of $|\eta| < 2.5$, while the calorimeter jet reconstruction itself is possible up to $|\eta| < 4.5$.

Energy Calibration The ATLAS calorimeters are calibrated using test beam electrons [109]. However, the response of the calorimeters to electromagnetic showers differs from the response to hadronic showers. A dedicated jet energy scale (JES) calibration is therefore performed based on simulation [110]: the jet energy is corrected to correspond, on average, to the simulated energy of the corresponding hadronizing parton. The jet direction is also corrected such to point to the

primary vertex instead to the origin of the ATLAS detector coordinate system. A set of corrections is evaluated to take into account for pile-up effects [111, 112]. Simulated jet resolution is also corrected to better describe the data [113]. Finally, several jet energy scale corrections are applied for a better agreement between data and simulation. These corrections are determined with 2011 ATLAS data using several techniques exploiting the transverse momentum balance between a jet and a reference object such as a photon, Z boson or another jet [110, 114]. Systematic uncertainties on the jet energy scale and resolution due to imperfect Monte Carlo modelling are evaluated to range from 1-6% depending on the jet p_T and pseudorapidity.

4.6 Identification of Jets from b-quarks

The typical decay length of a b-hadron in the ATLAS detector is of the order of few millimetres. Exploiting the high precision of the inner detector tracker it is possible to discriminate between the jets originating from b-quarks and those from other quarks or gluons (also referred to as light-jets). The identification technique used for this purpose is called *b-tagging* and the identified b-tagged jets are referred to as b-jets.

Several b-tagging algorithms have been developed in ATLAS. The relevant algorithms for this thesis are briefly described in what follows, for a more detailed description see [94]. The b-tagging algorithm starts by associating tracks to the jets based on their angular distance ΔR to the jet. The mentioned tracks should satisfy strict selection criteria aimed to ensure a good track quality and to reject tracks likely to come from strange hadron decays or photon conversions. The discrimination between the b-jet and other jets is based on simulated distributions of several discriminating variables. Given the relatively high mass of b-hadrons, the tracks associated to a b-jet will have a relatively wide spread of impact parameter values. This feature is used by the IP3D b-jet tagging algorithm, where a corresponding discriminating variable is defined based on impact parameter significance¹ of all tracks associated to the jet. An alternative approach, used by the SV1 algorithm, is instead to search for inclusive secondary vertex formed by the decay products of the b-hadron. The search includes also the subsequent charm hadron decays. Another algorithm, called JetFitter [116], relies instead on the direction of the

¹ The significance is defined as the value of the impact parameter divided by the error on its measurement.

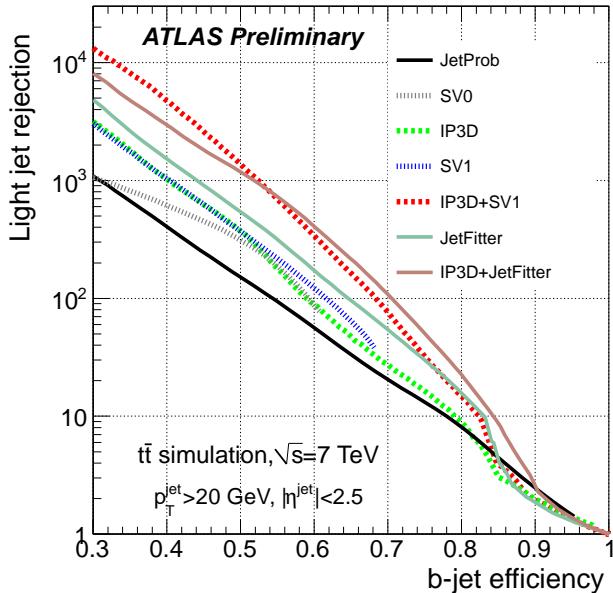


Figure 4.1: Light-jet rejection as a function of the b-jet tagging efficiency for several different tagging algorithms [117], obtained with simulated $t\bar{t}$ events. The rejection is defined as the inverse of mistagging rate of light jets.

jet to fully reconstruct the decay chain of a b-hadron, under the assumption that the decayed particles will be emitted along the jet axis. The outputs of each of these three algorithms gives a measure of the probability that the reconstructed jet originates from a b-quark. Finally, the outputs of the three described algorithms are combined based on an artificial neural network multivariate program [101] to maximise the discriminating power. The output of this neural network is referred to as *MV1* tagger and is used for the Higgs boson search presented in this thesis.

The performance of the mentioned algorithms is evaluated in data selecting $t\bar{t}$ events and compared to simulation [117]. Figure 4.1 shows the b-tagging efficiency as a function of the inverse of the light-jet mistagging rate for different b-tagging algorithm on $t\bar{t}$ simulated events. The tagging efficiency $\epsilon_b^{t\bar{t}}$ obtained from $t\bar{t}$ events is used to define several b-tagging working points. Corrections due to non perfect modelling of the b-tagging performance are evaluated by means of several methods in [118, 119] and used to determine event weights for simulated events. The uncertainties on these corrections range from 5-10% depending on the p_T and pseudorapidity of the jet.

4.7 Tau-Jet Reconstruction

The reconstruction of jets originating from hadronically decaying τ leptons (in the following τ -jets) is described in detail in [94]. A τ -jet candidate is seeded by reconstructed calorimeter jets with $p_T > 10$ GeV and $|\eta| < 2.5$. Tracks are then associated to the jet and a combination of the tracking and calorimeter information is performed. τ -jets can be distinguished from other jets by their low track multiplicity and a narrower clustering of energy deposit in the electromagnetic and hadronic calorimeters. The τ -jet identification in ATLAS is based on a Boosted Decision Trees (BDT) multivariate procedure [122]. One BDT discriminant has been developed to discriminate τ -jets from quark and gluon initiated jets and a separate one was developed to reject electrons.

4.8 Missing Transverse Energy

The missing transverse energy, E_T^{miss} , is the vectorial sum of the transverse momenta of all the physics objects and calorimeter cells in the event changed of sign. Undetected particles, such as neutrinos, lead to an unbalance of the total transverse momentum, thus, to a non zero value of E_T^{miss} .

Reconstruction and calibration of E_T^{miss} with the ATLAS detector is described in detail in [120]. The missing transverse energy measurement relies on the reconstruction of all physics objects in the event, it includes: muons and their energy deposits in the calorimeter, electrons, jets (weighted by their corresponding JVF), inner detector tracks (to take into account low- p_T particles which are not well reconstructed in the calorimeters), photons and τ leptons. The calorimeters cells are calibrated depending on the physics object with which they are associated. The transverse energy of cells not associated to any object is taken into account in the so called “CellOut” contribution. This contribution, together with the one related to jets with $10 < p_T < 20$ GeV are referred to as the *soft term* of the missing transverse energy. The soft term is found to be very sensitive to pile-up. In order to reduce the impact of pile-up, the soft term is scaled by the corresponding soft-term-vertex-fraction (STVF), which is calculated in the same way as JVF for jets.

A detailed description of the performance of the E_T^{miss} reconstruction and calibration may be found in [121].

4.9 Overlap Removal

Reconstruction of physics objects defined in the previous section may sometimes be ambiguous. For example, a τ -jet is always reconstructed also as a common jet. To avoid double counting of the physics objects originating from the same particle, an overlap removal procedure is performed. A match between physics object of different sort is seeded in a cone of $\Delta R < 0.2$. If the matching occurs, the object with the lowest ranking is removed from the event. Physics object are ranked according to the following order, starting with the highest rank: muon, electron, τ -jet and finally common jets.

4.10 Trigger

The ATLAS trigger system [123] consists of three stages. The Level-1 (L1) trigger is an hardware trigger which reduces the event rate to approximatively 100 kHz and selects the Regions of Interest (RoI) to be further investigated by the High Level Trigger (HLT). The HLT comprises the Level-2 (L2) trigger employing fast reconstruction algorithms and the Event Filter (EF) exploiting the full ATLAS event reconstruction.

In the presented search two triggers are employed: an electron EF trigger, which selects events containing an electron with $p_T > 24$ GeV and a combined muon-electron EF trigger, which requires the presence of a muon with $p_T > 8$ GeV and an electron with $p_T > 12$ GeV in the event. Detailed description of the muon and electron triggers can be found in [124, 125]. Trigger efficiency for both triggers is evaluated in data selecting Z candidate events and compared with prediction from simulation. Corrections are derived as function of the lepton pseudorapidity and transverse momentum to match the simulated trigger efficiency with the one in data [124, 125].

4.11 Truth Particles

In case of a simulated event, the ATLAS reconstruction software provides the generator-level information regarding simulated particles (also called *truth particles*). Their identity, kinematic properties, decays and interactions are stored in the event based on the conventions defined in [126]. A particle is defined stable if $c\tau > 1$ m, where τ is its mean life time. Particle emerging from interaction with

the detector are excluded from this definition. Each particle has an associated “bar-code” which is a unique identifier for that particle in that event. Jets reconstructed with the common ATLAS reconstruction algorithm from stable particles are called *truth jets*.

Chapter 5

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

In the light of the recent discovery of a Higgs boson with mass of ~ 126 GeV at the LHC [16, 17], it remains an open question whether this new particle is the only missing piece of the electroweak symmetry breaking sector of the Standard Model or whether it is one of several Higgs bosons predicted in theories that go beyond the SM. The most recent measurements [127–130] of properties of the new boson show that they are fully compatible with the ones of the SM Higgs boson. Nevertheless, such a new particle can still be accommodated within theories beyond the standard model (BSM). Among them, supersymmetric extensions of the Standard Model are theoretically favoured, in particular the minimal supersymmetric extension (MSSM) which predicts five Higgs bosons, three of them electrically neutral.

In this chapter the search with the ATLAS detector for the neutral MSSM Higgs bosons decaying into pairs of tau leptons in the fully leptonic final state is discussed. The results have been published in Ref. []¹ as a part of the ATLAS search for the neutral MSSM Higgs bosons in all final states of the tau lepton decays. The search is based on 20.3 fb^{-1} of data at a centre-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$ recorded by the ATLAS experiment during 2012. This chapter is organised as follows: a brief summary of the MSSM Higgs sector and an introduction to the analysis strategy are given in Section 5.1, while the event selection and categorization are described in Section 5.2. Section 5.3 describes the estimation of the backgrounds and in Section 5.4 methods for the evaluation of the systematic uncertainties are discussed. Finally, in Section 5.5 the results of the search are presented together with an overview of the statistical methods employed.

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

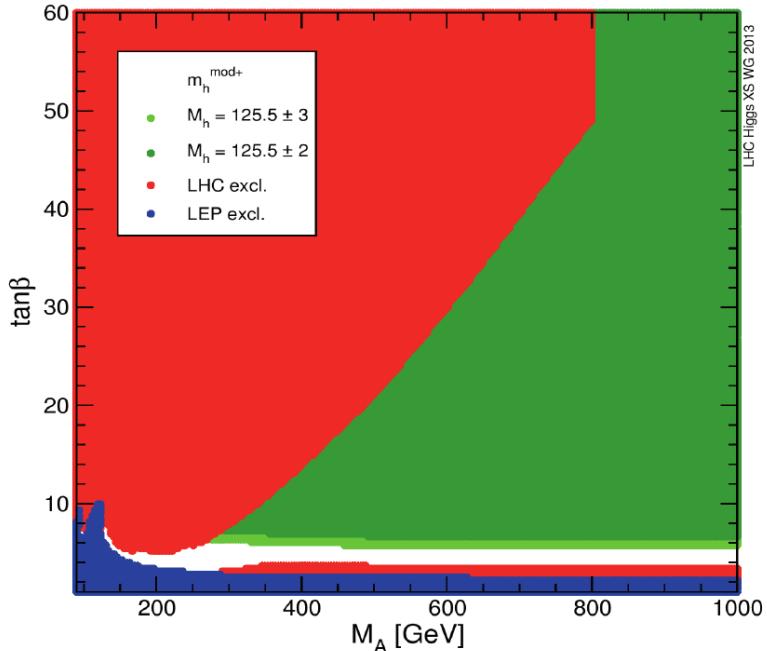


Figure 5.1: Excluded and allowed regions of the MSSM m_A – $\tan\beta$ parameter space in the m_h^{mod+} benchmark scenario [4], based on direct Higgs boson searches at LEP (blue) and LHC (red). The two green regions are compatible with the assumption that the lightest MSSM Higgs boson, h , has a mass of 125.5 GeV with an uncertainty of 2 GeV (dark green) or 3 GeV (light green).

5.1 Introduction

5.1.1 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 electroweak Higgs doublets of opposite hypercharge resulting in five observable Higgs bosons, where two of them 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 are predicted depending on 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 2). The MSSM predicts the existence of a Higgs boson with properties that resemble those of the 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 to down (up) type fermions are enhanced (suppressed) depending on the value of $\tan\beta$, such that for large $\tan\beta$ bottom-quarks and τ leptons play an important role for Higgs boson production and decay.

The two dominant neutral MSSM Higgs boson production mechanisms at the LHC are gluon fusion, $gg \rightarrow A/H/h$, and the production in association with b -quarks, $pp \rightarrow b(b)A/h/H$, the latter becoming increasingly important for large values of $\tan\beta$. These are the only production mechanisms considered in this analysis. Assuming there are no decays into supersymmetric particles (since they are too heavy) and assuming that the lightest neutral CP-even Higgs boson h is identified with the observed Higgs boson of mass ~ 126 GeV, the dominant decay mode for the neutral MSSM CP-odd A and CP-even H Higgs bosons is the decay into a b and anti- b quark pair, followed by the decay into τ leptons pairs. Since 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 [65], the Tevatron [66] and the LHC [67,68]. 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 characterised by the presence of one or two hadronically decaying τ leptons. For low m_A values the $\tau^+\tau^- \rightarrow e\mu+4\nu$ search channel provides a sensitivity to the signal comparable to the other final states, despite the fact that the $\tau\tau$ branching ratio to $e\mu+4\nu$ is only 6%. This is mainly due to the high transverse momentum threshold at the trigger level for hadronically decaying τ leptons, which is necessary to keep the jet contamination rate at an acceptable level.

As it is virtually impossible to explore the full parameter space of the MSSM, which has a large number of free parameters, several benchmark scenarios have been introduced fixing all parameters except m_A and $\tan\beta$ to typical values for the most interesting physics cases. With the recent Higgs boson discovery, benchmark scenarios of the MSSM have been updated to accommodate the new experimental constraints. As an example, Figure 5.1 shows the currently excluded and allowed regions of the MSSM $m_A - \tan\beta$ parameter space for the updated m_h^{mod+} benchmark scenario (see Section 2.3.2). In this scenario, a large region of the $m_A - \tan\beta$ parameter space is compatible with the assumption that the observed Higgs boson is in fact the neutral CP-even Higgs boson h . A relatively

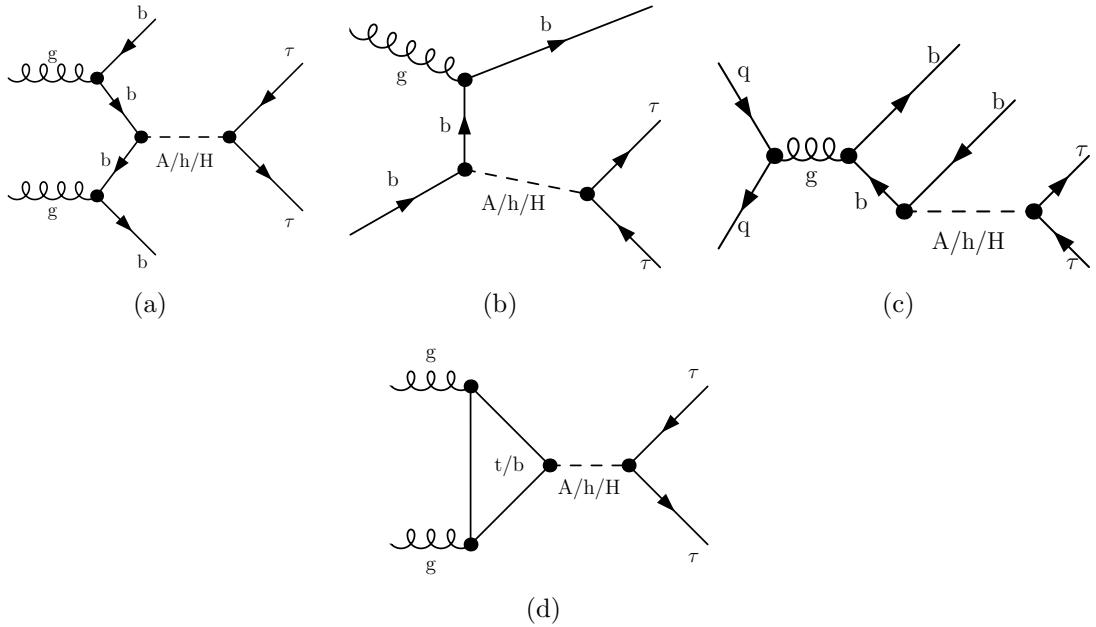


Figure 5.2: Feynman diagrams for the production of the neutral MSSM Higgs bosons in association with b -quarks (a,b,c) and via gluon fusion (d) with subsequent decay into tau lepton pairs.

large part of this parameter space is still experimentally unexplored, which is a strong motivation to pursue the search for additional neutral MSSM Higgs bosons.

5.1.2 Signal and Background Processes

Signal events in which the neutral MSSM Higgs bosons decay through $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ are characterised by the presence of one electron and one muon of opposite charge. These two leptons are isolated and have relatively high transverse momenta. In addition, four neutrinos generate high missing transverse energy in the event. Figure 5.2 shows leading order Feynman diagrams for the two signal production modes considered, gluon fusion and associated production with b -quarks. The presence (absence) of a b -jet in the final state serves as main characteristic for the categorization in the latter (former) event as described below.

The described signal topology is common to several other SM background processes which in general have higher cross sections than the sought signal. The dominant background processes are $Z/\gamma^* \rightarrow \tau^+\tau^-$ production either via the Drell-

Table 5.1: The cross sections times by the relevant branching ratios (BR) for signal and the considered background processes, with $\ell = (e, \mu, \tau)$. Signal cross sections are calculated for the m_h^{mod} scenario assuming $m_A = 150$ GeV and $\tan \beta = 20$. The masses of the other two neutral MSSM Higgs bosons are in this case $m_H = 151$ GeV and $m_h = 125$ GeV.

Process	Cross-section \times BR (pb)
Signal ($m_A = 150$ GeV, $\tan \beta = 20$, m_h^{mod} scenario)	
$gg \rightarrow A/h/H \rightarrow \tau\tau \rightarrow e\mu + 4\nu$	0.24/0.20/0.95
$pp \rightarrow b\bar{b}A/h/H \rightarrow \tau\tau \rightarrow e\mu + 4\nu$	0.53/0.05/0.49
Backgrounds	
$W \rightarrow \ell\nu + \text{jets}$	12.22×10^3
$Z/\gamma^* \rightarrow \ell\ell + \text{jets}$	5.5×10^3
$t\bar{t} \rightarrow \ell\ell + X$	137.3
Single top quark ($t-$, $s-$ and $Wt-$ channels) $\rightarrow \ell + X$	28.4, 1.8, 22.4
Dibosons (WW , WZ and ZZ) $\rightarrow \ell\ell + X$	20.6, 6.8, 1.55

Yan process or in association with jets and top quark production ($t\bar{t}$ and single top quark production). Additional significant background contributions arise from dibosons production (WW , WZ , ZZ) and QCD multi-jet events with non-prompt leptons from hadron decays. Vector boson production ($W \rightarrow \ell\nu$ or $Z \rightarrow \ell\ell$, where $\ell \equiv e, \mu$) in association with jets is also considered, but has small impact on the total background contamination. Examples of leading order Feynman diagrams for the dominant background processes are shown in Figure 5.3. The production cross sections times the branching fractions for signal and background processes are summarized in Table 5.1.

5.1.3 Analysis Strategy

In this thesis, a search for the neutral MSSM Higgs boson decays $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ is presented. The $ee + 4\nu$ and $\mu\mu + 4\nu$ final states are not considered since large background contributions are expected from $Z \rightarrow ee$ and $Z/\gamma^* \rightarrow \mu\mu$ decays, respectively, such that the sensitivity of the search in these final state is significantly reduced.

Candidate events are selected based on the topological properties of Higgs boson production and decay. The presence of exactly one electron and one muon

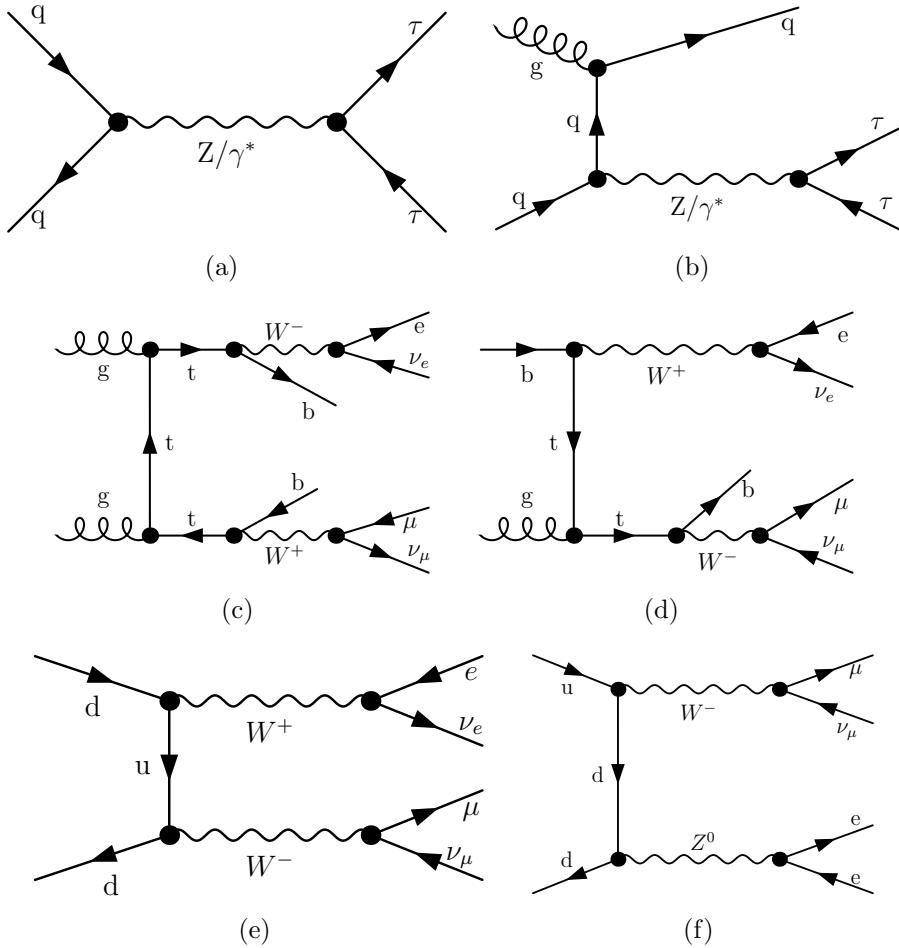


Figure 5.3: Examples of tree level Feynman diagrams for the most important background processes. The production of $Z/\gamma^* \rightarrow \tau^+\tau^-$, either via the Drell-Yan process or in association with jets, is shown in (a) and (b) respectively, top quark pair and single top quark production in (c) and (d), while WW and WZ production in (e) and (f).

is required in each event. The electron and the muon are required to be isolated and of opposite electrical charge. The events are categorized into two orthogonal categories. In the so called *b-vetoed* event category, the absence of b-tagged jets is required, thus searching mainly for the signal production via gluon fusion. The main background process in this category is $Z/\gamma^* \rightarrow \tau\tau$. In contrast, the presence of exactly one b-tagged jet is required in the so called *b-tagged* event category, in which predominantly the signal production in association with b-quark is searched for. The requirement of a b-jet in the final state suppresses the $Z/\gamma^* \rightarrow \tau\tau$ background, consequently, $t\bar{t}$ and single top quark production are the main background processes in this event category. Further selection criteria are introduced in both event categories optimised to enhance the signal with respect to the background.

The search is performed within the MSSM m_h^{mod} benchmark scenario scanning the $m_A - \tan\beta$ plane in the range $90 \leq m_A \leq 300$ GeV and $5 < \tan\beta < 60$. The signal event yields and kinematical distributions are predicted by simulation. The contribution of the dominant $Z/\gamma^* \rightarrow \tau\tau$ background process is measured in a dedicated signal-depleted control data sample in order to reduce the systematic uncertainties of the simulation. Similarly, the QCD multi-jet background contribution is also estimated from a dedicated data control sample since this background process is hard to model. The contributions of all other background processes are estimated by simulation. The modelling of the background processes is validated using different signal-depleted validation data samples where good agreement is found.

Systematic uncertainties on cross section calculations and the modelling of the detector response for simulated signal and background processes are taken into account. For background processes determined from data, the uncertainties of the measurement methods are evaluated.

The statistical interpretation of the data is based on the comparison of the observed $\tau\tau$ invariant mass distributions with the predictions of the background-only and signal-plus-background hypotheses. Exclusion limits on the signal production are set by means of a binned profiled likelihood ratio test statistic within the MSSM m_h^{mod} scenario as constraints in the $m_A - \tan\beta$ plane. Furthermore, the data are interpreted in a less model-dependent way in terms of upper limits on the cross section for the production of a generic Higgs boson ϕ with mass m_ϕ via the processes $pp \rightarrow b\bar{b}\phi$ and $gg \rightarrow \phi$.

5.1.4 Data and Simulated Event Samples

Data Sample

The presented results are based on proton-proton collision data recorded by the ATLAS experiment during 2012 at a centre-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 trigger and combined electron-muon triggers. Only events recorded with all relevant components of the ATLAS detector fully operational are considered. Additional data quality requirements are applied according to [115], rejecting events with jet activity in known noisy calorimeter regions.

Signal Samples

Signal production via the gluon fusion process $gg \rightarrow A/H/h$ was simulated with POWHEG [78] and the associated $b\bar{b}A/H/h$ production with SHERPA [79]. The pseudo-scalar Higgs boson samples were generated in the mass range from 90 GeV to 300 GeV assuming $\tan\beta = 20$. Re-weighting of the production cross sections is applied to simulate other $\tan\beta$ values. All three neutral Higgs bosons A, h, H are assumed to decay with the same kinematical properties. The m_h^{mod} MSSM benchmark scenario is assumed for the prediction of the mass and cross sections of the three neutral Higgs bosons for given m_A and $\tan\beta$ values.

Background Samples

The production of W and Z/γ^* bosons in association with jets was simulated with the ALPGEN [71] generator. The $t\bar{t}$ process was generated using the POWHEG program. Single top quark production via the s-channel and via the Wt process was generated using MC@NLO [73], while single top quark production via t-channel was generated with the AcerMC [74]. Diboson processes (WW , WZ , ZZ) were generated with HERWIG [75]. For all ALPGEN and MC@NLO event samples described above, the parton shower and hadronization were simulated with the HERWIG and the underlying event activity with the JIMMY [76] programme. Different sets of parton density functions (PDFs) are used depending on the generator: CTEQ6L1 [80] is used with the ALPGEN and AcerMC while CT10 [81] is used with SHERPA, POWHEG and MC@NLO.

TAUOLA [83] and PHOTOS [84] are used to model the tau lepton decay and additional photon radiation from final state charged leptons in the leading-log

approximation, respectively.

The ATLAS detector response is simulated for all generated samples using the GEANT4 [85, 86] package. The reconstruction of physics objects, described in chapter 4, is performed with the same software as used for the data. The effects of simultaneous recording of additional proton collisions from the same or neighbouring bunch crossings (pile-up) are taken into account in the detector simulation.

5.2 Event Selection and Categorization

5.2.1 The Common Selection Criteria

According to the kinematical properties of signal events, each event in data and simulation have to satisfy the selection criteria described in the following. Since these are shared by both the b-tagged and the b-vetoed event category, they are referred to as common selection criteria:

- (i) The trigger selection requires the presence of a single electron with $p_T > 24$ GeV or, alternatively, an electron with $p_T > 12$ GeV together with a muon with $p_T > 8$ GeV.
- (ii) At least one reconstructed vertex with more than three associated tracks in order to reject background from cosmic muons.
- (iii) Exactly one reconstructed “Tight” electron with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ and $p_T > 15$ 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 have to be isolated with $E_T^{cone}/p_T < 0.08$ and $P_T^{cone}/p_T < 0.06$.
- (vi) The muon have to be isolated with $E_T^{cone}/p_T < 0.04$ and $P_T^{cone}/p_T < 0.06$.
- (vii) Muon and electron have to be of opposite charge.
- (viii) Removal of overlap between reconstructed electron, muon, τ -jets and jets is performed.

- (ix) The event is rejected if at least one hadronic τ lepton decay is found with τ -jet transverse momentum $p_T > 15$ GeV. τ -jets candidate are required to be associated to one or three charged tracks, for the identification a “Medium” BDT working point is chosen, additionally, a BDT-based electron veto is applied.
- (x) To reduce QCD multi-jet background contamination, the invariant mass of electron and muon has to be greater than 30 GeV.

Details on the definition of physics objects and the applied quality criteria can be found in chapter 4.

Events accepted by the common selection criteria are divided into *b-tagged* and *b-vetoed* categories by requiring the presence or the absence, respectively, of exactly one b-tagged jet in the event. A jet is tagged ad a b-jet if has $p_T > 20$ GeV, $|\eta| < 2.5$, $\text{JVF} > 0.5$ and if it passes the *MV1* b-tagging criteria corresponding to 70% of b-quark efficiency $\epsilon_b^{t\bar{t}}$ in $t\bar{t}$ events. Further selection criteria are applied to each category and optimized separately as described in the following.

5.2.2 b-Vetoed Event Category

A veto on the presence of b-tagged jets in the final state allows for the selection of signal events produced predominantly via gluon fusion. In this event category, the $Z/\gamma^* \rightarrow \tau\tau$ process is an irreducible background due to the same topology of the Higgs and Z boson decay. Other background processes can be discriminated from the signal due to their kinematical properties. The τ leptons from the Higgs boson decay are highly boosted and so are their decay products, resulting in significantly different lepton kinematics in the Higgs decays than in diboson or $t\bar{t}$ background processes. Firstly, the electron and muon from Higgs boson decay are predominantly emitted back-to-back as illustrated in Figure 5.4(a) which shows the angular distance $\Delta\phi_{e,\mu} = |\phi_e - \phi_\mu|$ between the two leptons in the transverse plane for the signal and background processes. Secondly, the neutrinos from Higgs boson decay are predominantly collinear with the charged leptons. Thus, the angular correlation between the direction of the missing transverse energy and the two charged leptons in the transverse plane,

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

tends to zero as shown in Figure 5.4(b). These two features are used to discriminate between signal and the W boson, top quark and dibosons background

Table 5.2: Summary of the event selection criteria in the b-tagged and b-vetoed event categories applied after the common event selection has been performed.

Category	Selection
b-vetoed	No b-tagged jets $\Delta\phi_{e,\mu} > 1.6$ $\sum \cos \Delta\phi_{E_T,\ell} > -0.4$
b-tagged	Exactly one b-tagged jet $\Delta\phi_{e,\mu} > 2$ $\sum \cos \Delta\phi_{E_T,\ell} > -0.2$ $H_T < 100 \text{ GeV}$ $P_{T\mu} + P_{Te} + E_T^{miss} < 100 \text{ GeV}$

processes. No further selection criteria are applied in the b-vetoed category, since no significant improvement in signal sensitivity could be achieved. The described selection criteria are listed in Table 5.2, while in Table 5.3 the predicted numbers of signal and background events after each selection stage are shown.

5.2.3 b-Tagged Event Category

The requirement of exactly one b-tagged jet in the b-tagged event category predominantly selects signal events produced where the Higgs bosons are produced in association with b-quarks. Background processes with b-jets, as the $t\bar{t}$ and single top quark production, are enhanced compared to the $Z/\gamma^* \rightarrow \tau\tau$ background. Also in this category requirements on $\Delta\phi_{e,\mu}$ and $\sum \cos \Delta\phi$ are imposed to reduce the top quark and diboson background contributions as described for the b-vetoed event category. Further selection criteria specific for the b-tagged category are employed as described below.

Signal events in this event category can be discriminated from top quark given their relatively low jet activity. The $t\bar{t}$ events are likely to have two or more highly energetic reconstructed jets, unlike the signal b-jets which have relatively low energy. Low jet activity is ensured by requesting the sum of the jet transverse momenta H_T to be small. The H_T distribution is shown in Figure 5.4(c). The jets used for the calculation of H_T have to fulfill $p_T > 30 \text{ GeV}$, $|\eta| < 4.5$ and $\text{JVF} > 0.5$ (if $|\eta| < 2.5$).

Another feature that discriminates top quark pair production from the Higgs

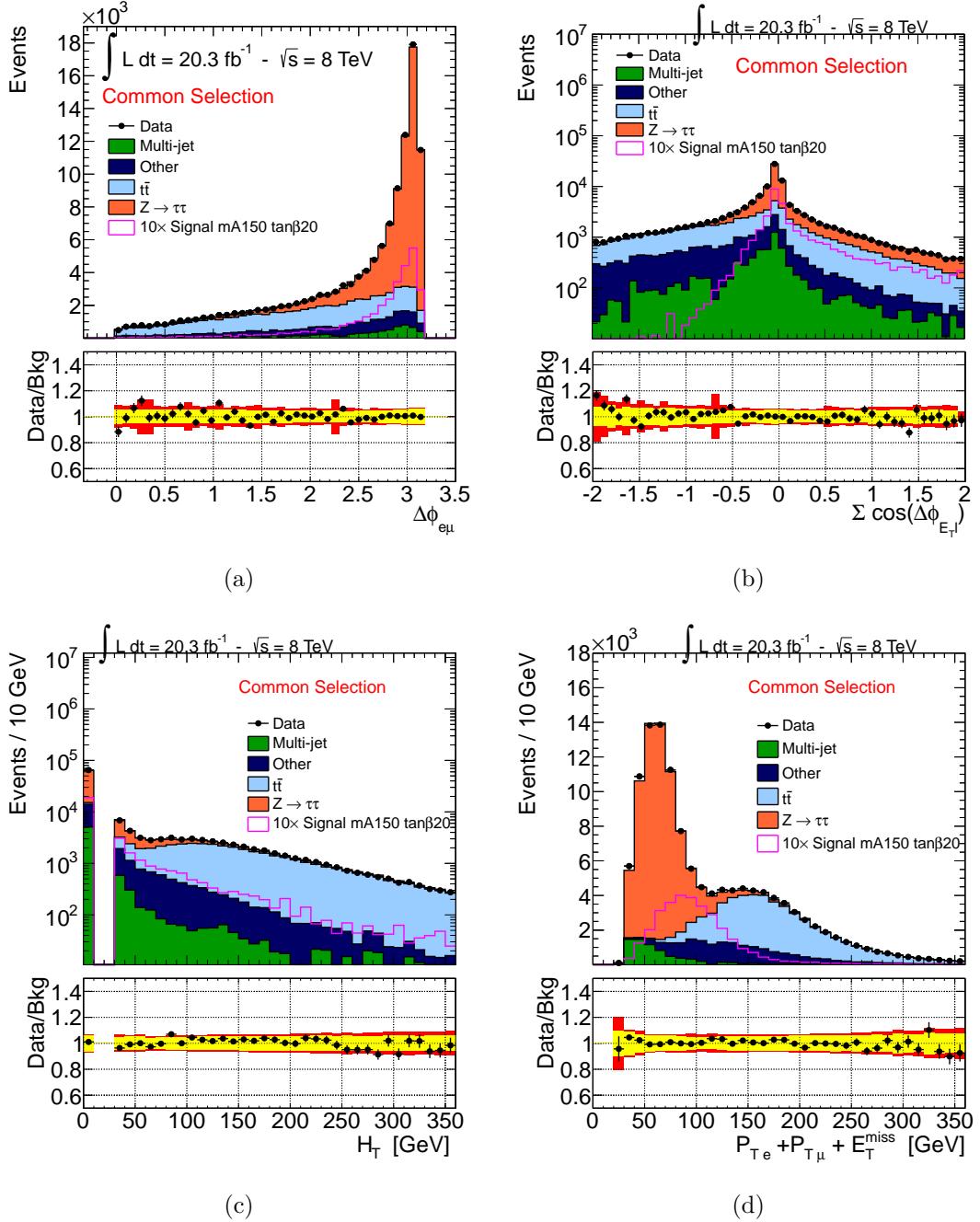


Figure 5.4: Distributions of discriminating variables electron-muon angular separation $\Delta\phi_{e,\mu}$ (a), the angular correlation between charged lepton and E_T^{miss} $\sum \cos \Delta\phi_{E_T,\ell}$ (b), the total sum of jet p_T (c), the sum of charged lepton p_T and E_T^{miss} (d), after the common selection has been applied. The notation “Other” stands for the electroweak processes $W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$, diboson and single top quark production. The prediction for the background contributions is determined as described in Section 5.3. The superimposed signal is obtained assuming the m_h^{mod} scenario for $m_A = 150$ GeV and $\tan\beta = 20$ and it is scaled by a factor ten. The error bars on the ratio of observed and predicted events represent the statistical uncertainty on data, whereas the yellow and red band indicates the systematic and statistical uncertainty on the background prediction (see Section 5.4), respectively.

boson signal is the higher invariant mass of the decay products of the former as the highest Higgs mass considered in this search is 300 GeV. The sum of the electron and muon transverse momenta and of E_T^{miss} is used as discriminating variable and is shown in Figure 5.4(d).

The optimized selection criteria for the b-tagged event category are shown in Table 5.2. In Table 5.4 the predicted numbers of signal and background events after each selection stage are given in the b-tagged event category.

5.2.4 Mass Reconstruction with the MMC Technique

Acurate invariant mass reconstruction of a di- τ resonance is a challenging task due to the undetected neutrinos. In this analysis there are a total of four neutrinos in the final state, two from each of the τ lepton decays. The invariant mass depends on eight unknown which are the components of the total neutrino four-momenta in each of the τ lepton decays. These unknowns are constrained by the two measured component of the missing transverse energy \vec{E}_T^{miss} and by the τ lepton mass M_τ via the following four equations:

$$\begin{aligned}\vec{E}_T^{miss} &= \vec{P}_T^{mis_1} + \vec{P}_T^{mis_2}, \\ M_{\tau_i}^2 &= m_{mis_i}^2 + m_{vis_i}^2 + 2\mathbf{P}_{vis_i} \cdot \mathbf{P}_{mis_i},\end{aligned}\tag{5.1}$$

where $i=1,2$ distinguish the two τ leptons. $\vec{P}_T^{mis_i}$, m_{mis_i} and \mathbf{P}_{mis_i} are the transverse momentum vector, the invariant mass and the four momentum of the neutrino pair originating from the decay of the i -th τ lepton. \mathbf{P}_{vis_i} and m_{vis_i} are the known four momenta and mass of the charged lepton from the i -th τ lepton decay. The remaining four degrees of freedom can be further constrained, assuming for example that the neutrinos are collinear with the electron or muon from the same τ lepton decay. This so-called collinear approximation, however, leads to rather limited mass resolution.

In this analysis, the so-called "Missing Mass Calculator" (MMC) algorithm is used to determine the most likely invariant mass of the di- τ system for a given event topology. The implementation of the MMC method in this search is based on [131]. The MMC algorithm solves the equations 5.1 for a set of grid points in a four-dimensional parameter space. The four independent variables are chosen to be $m_{mis_i}^2$ and $\cos\theta_i^*$. Where θ_i^* is the angle between the τ lepton and the charged lepton originating from its decay. The di- τ invariant mass in each event is calculated for each grid point of the parameter space. Each solution is weighted by the probability for that parameter configuration determined by Monte Carlo

	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
$Z \rightarrow \ell\ell$	569 ± 48	564 ± 48	516 ± 47	434 ± 44
$W \rightarrow \ell\nu$	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
$Z/\gamma^* \rightarrow \tau\tau$	61503 ± 68	60440 ± 67	58078 ± 65	55303 ± 64

Table 5.3: Number of observed and predicted signal and background events, after each selection stage in the b-vetoed event category.

Table 5.4: Numbers of observed and predicted signal and background events after each selection stage in the b-tagged event category.

	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	
$Z \rightarrow \ell\ell$	5.2 ± 1.8	2.3 ± 1.1	2.3 ± 1.1	1.7 ± 1.0	0.9 ± 0.8
$W \rightarrow \ell\nu$	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
$Z/\gamma^* \rightarrow \tau\tau$	952 ± 9	625 ± 7	540 ± 7	482 ± 6	421 ± 6

simulation using the PYTHIA generator supplemented by the TAUOLA package. The invariant mass $m_{\tau\tau}^{MMC}$ of the di- τ system is then estimated as the maximum of the weighted invariant mass distribution from all grid points.

The accuracy of the invariant mass obtained with the $m_{\tau\tau}^{MMC}$ method depends strongly on the resolution of the missing transverse energy measurement. To improve the E_T^{miss} resolution, a scan of a six-dimensional parameter space is performed in a similar manner as described above. For this purpose, the absolute value of \vec{E}_T^{miss} is also considered unknown and a scan is performed over all possible values constrained by the measured E_T^{miss} and its corresponding uncertainty.

Figure 5.5 shows the $m_{\tau\tau}^{MMC}$ invariant mass distribution after the common selection and after the event categorization.

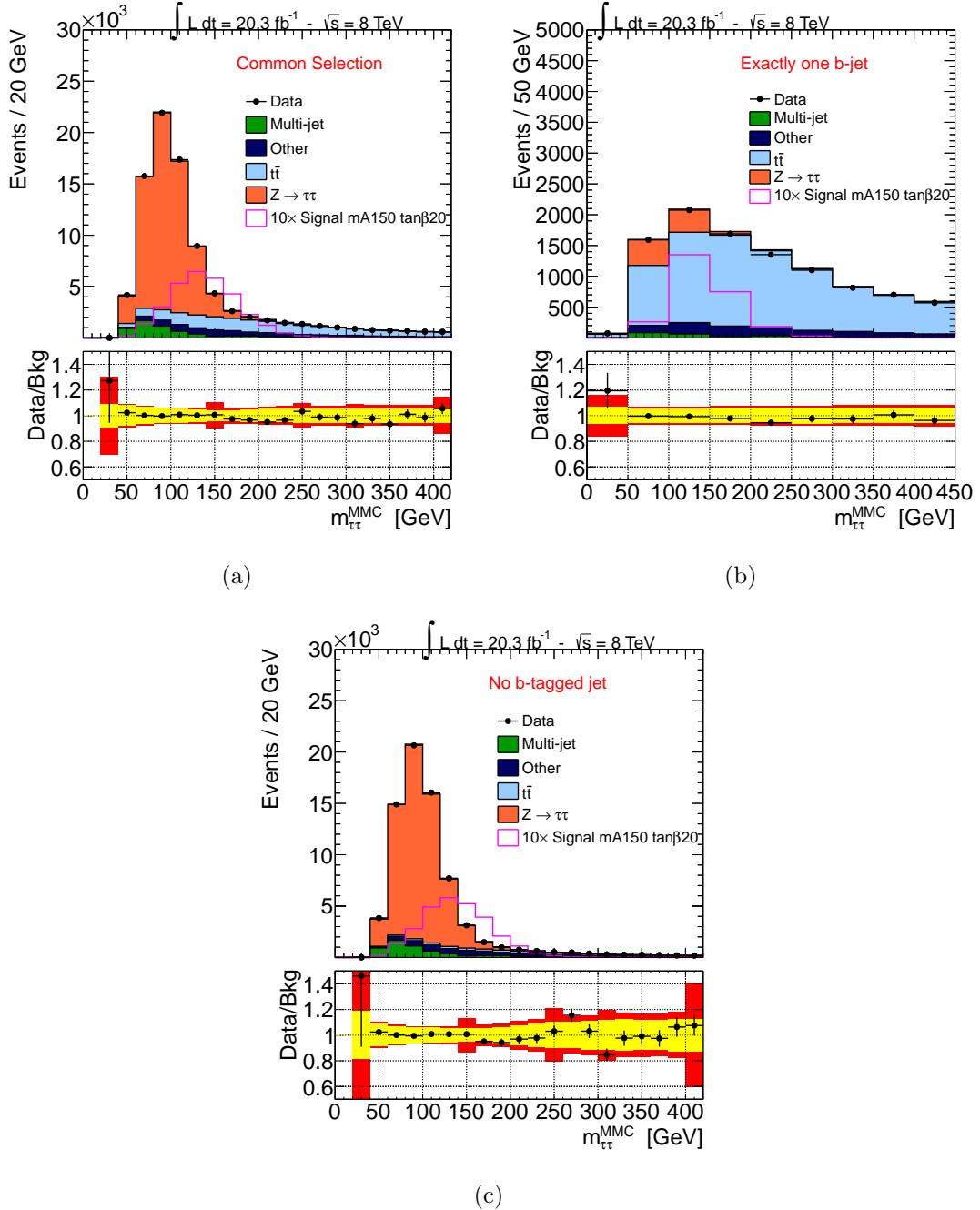


Figure 5.5: Observed and expected distribution of the invariant di- τ mass estimate $m_{\tau\tau}^{MMC}$ at different stage of the analysis: (a) after the common selection, (b) after requiring exactly one b-tagged jet and (c) for the b-vetoed sample. The predictions of the background model is compared to the data (as in Figure 5.4).

5.3 Background Prediction and Validation

In this section the strategies for the prediction of the background contributions and validation of these predictions are described. Monte Carlo simulation is extensively used to model the kinematical properties of the signal and background processes. However, since the simulation is prone to systematic uncertainties due to a non-perfect description of pileup effects, the underlying event and the detector performance, the QCD multi-jet and $Z/\gamma^* \rightarrow \tau\tau$ background contributions are estimated using dedicated signal-free control data samples as described in sections 5.3.2 and 5.3.3. The contributions of the other background processes, such as $t\bar{t}$, single top quark, diboson, $Z \rightarrow ll + \text{jets}$ (where $l = e, \mu$) and $W + \text{jets}$, are estimated from simulation. Because of the relatively large contribution of $t\bar{t}$ background, a study to validate this background prediction has been performed as described in section 5.3.1.

Good agreement between data and background prediction is found after the common selection as can be seen in Figures 5.4 and 5.6.

5.3.1 Validation of the $t\bar{t}$ Background Simulation

The background contribution from top quark pair production is estimated using the POWHEG-PYTHIA Monte Carlo generator. Since this is one of the major background processes for this analysis, a careful validation of the predicted contribution is needed. For this purpose a signal-depleted data sample is enriched with $t\bar{t}$ events by requiring the presence of exactly two b-tagged jets after the common selection criteria. Figures 5.7 and 5.8 show the distributions of kinematical variables and of the discriminating variables for this data sample. Good agreement between data and Monte Carlo prediction is found with a ratio of observed to predicted numbers of $t\bar{t}$ events of $0.998 \pm 0.011(\text{stat.}) \pm 0.110(\text{sys.})$. The total systematic uncertainty in the ratio is dominated by the uncertainty in the b-tagging efficiency.

5.3.2 Measurement of Multi-jet Background

QCD multi-jet production represents an important background, especially in the b-vetoed event category, due to its high cross-section and the relatively low lepton p_T threshold used in this analysis. The contribution of this background is evaluated by the so-called ABCD data-driven technique. In the ABCD method, the data events after the common selection are split into four sub-samples: the signal sample

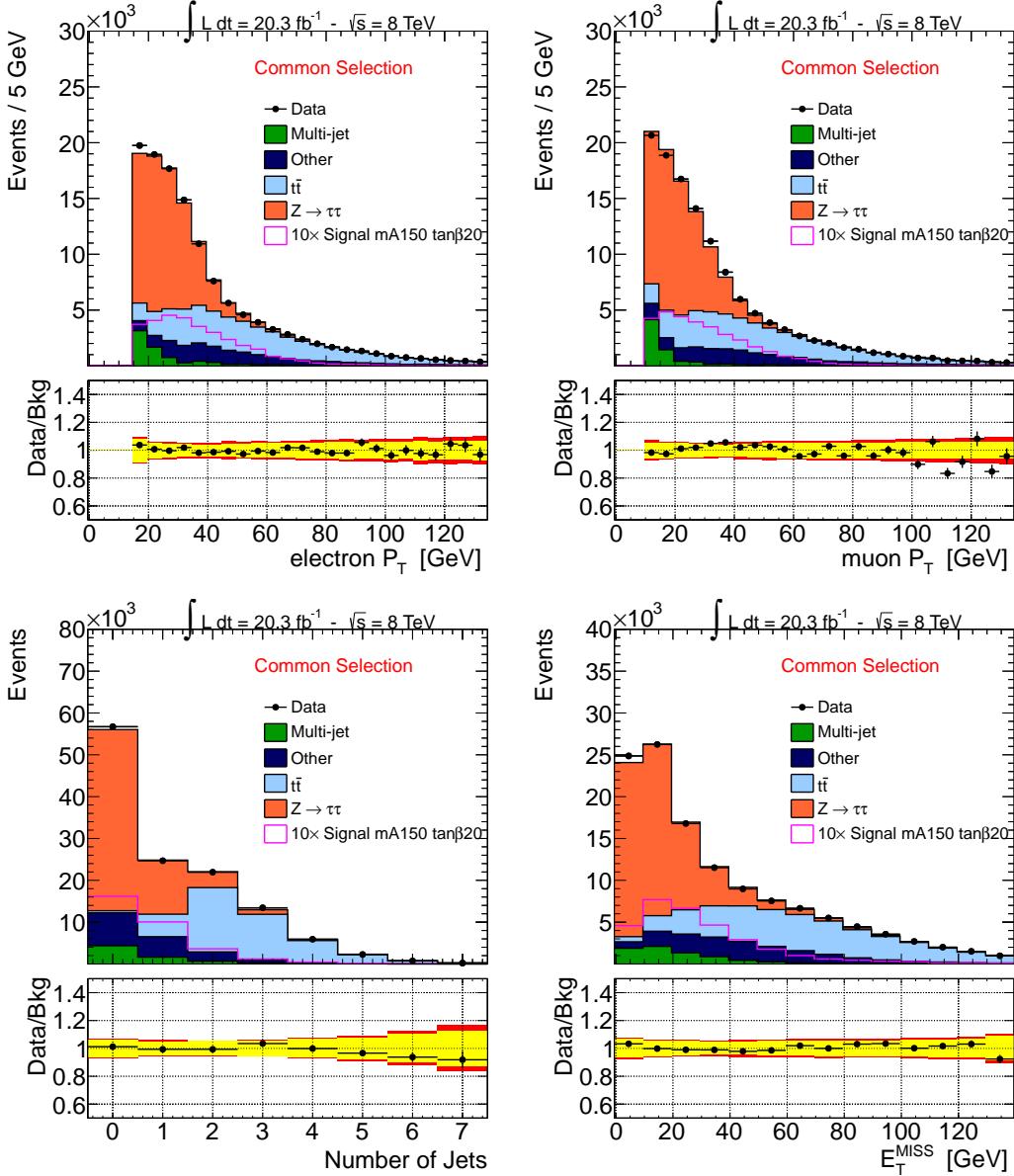


Figure 5.6: Observed and expected distributions of kinematical variables after the common selection. The predictions of the background model are compared to data (as in Figure 5.4).

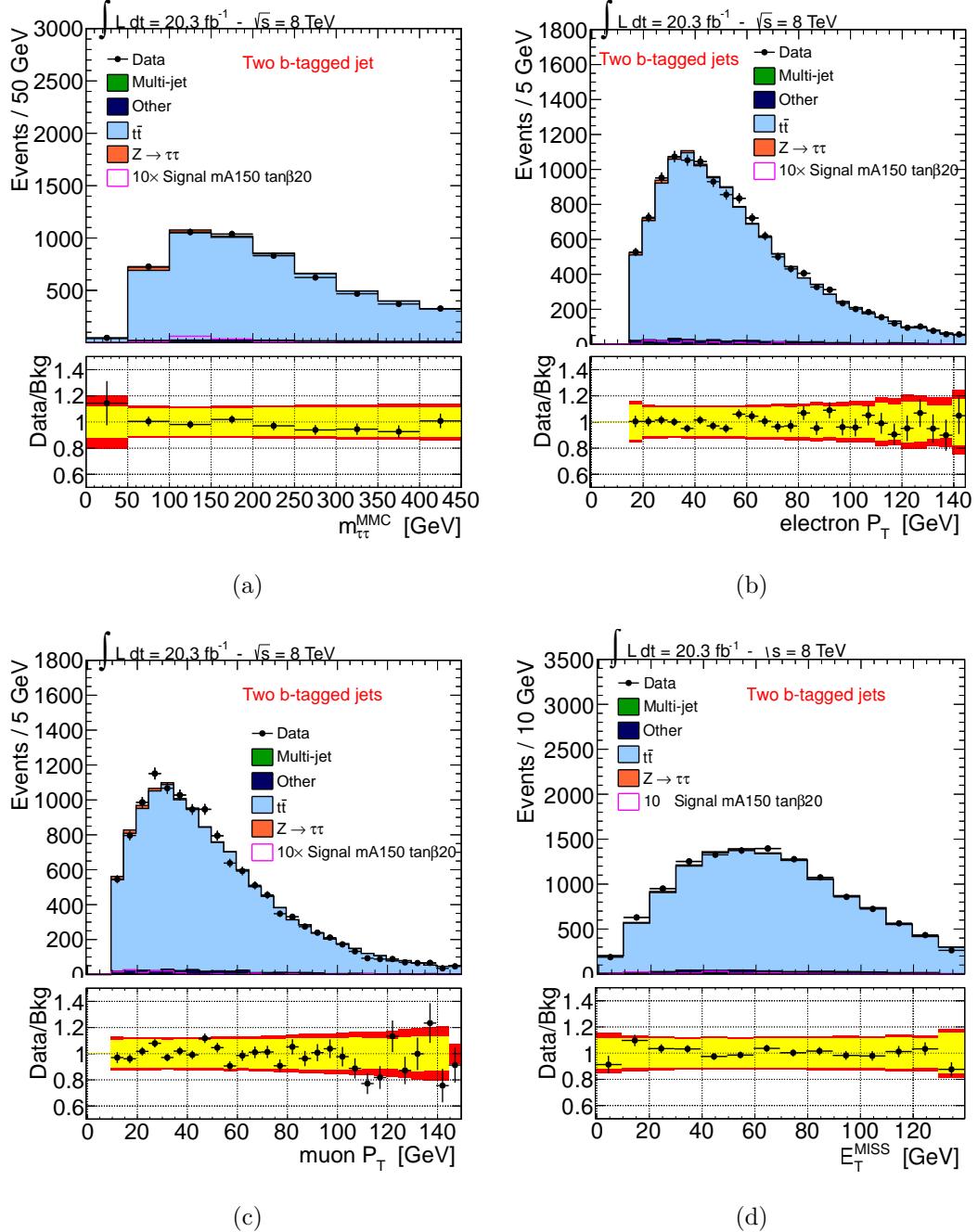


Figure 5.7: Observed and expected distributions in the $t\bar{t}$ validation sample of (a) the di- τ invariant mass estimated with $m_{\tau\tau}^{MMC}$, (b) the electron and (c) the muon transverse momentum, (d) the missing transverse energy E_T^{miss} . The predictions of the background model are compared to data (as in Figure 5.4).

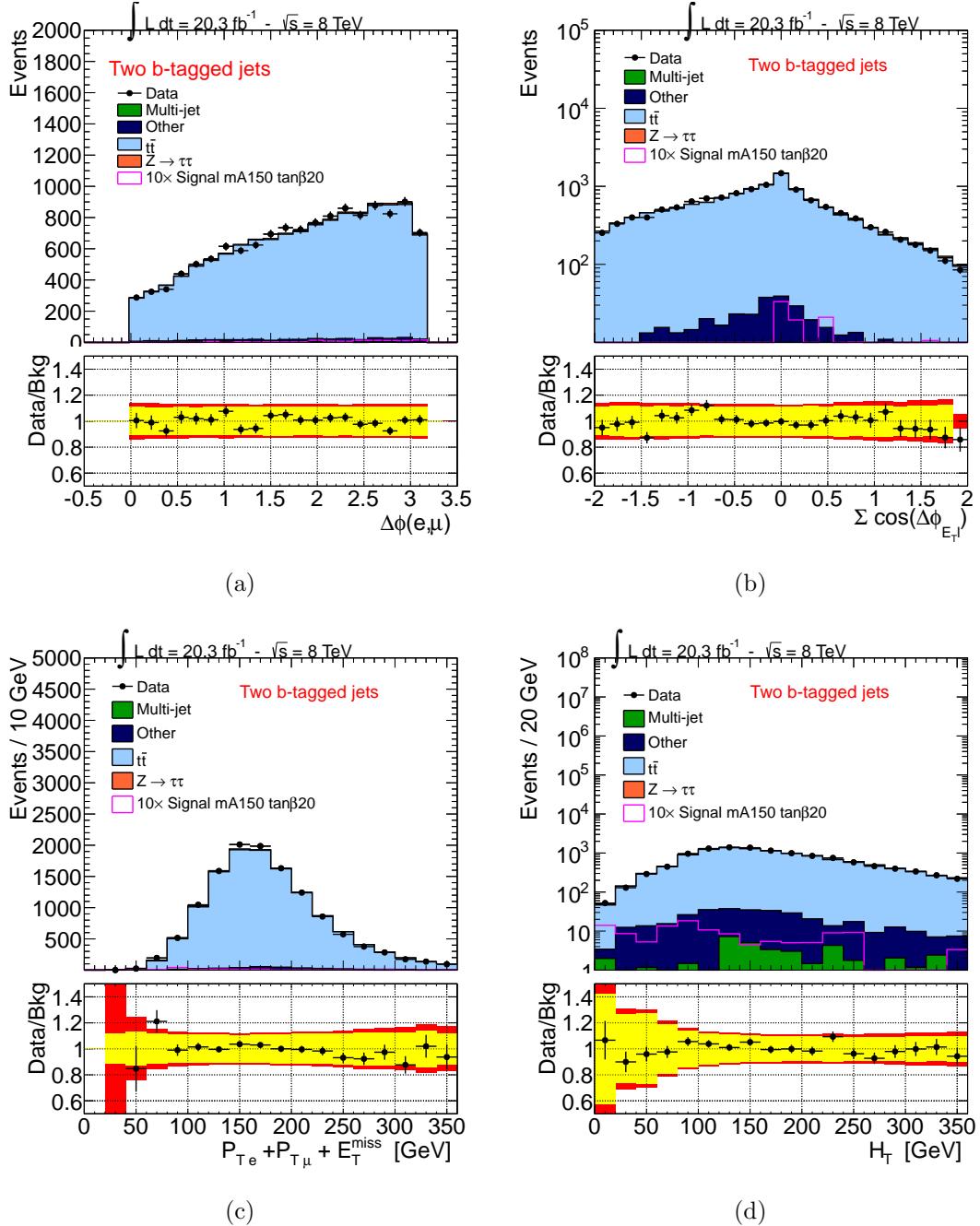


Figure 5.8: Observed and expected distributions of the discriminating variables (a) $\Delta\phi(e - \mu)$, (b) $\sum \cos \Delta\phi$, (c) $p_{T\mu} + p_{Te} + E_T^{miss}$ and (d) H_T in the $t\bar{t}$ validation sample. The predictions of the background model are compared to data (as in Figure 5.4).

Table 5.5: Control data samples for the measurement of the QCD multi-jet background. The samples are defined by requirements on the relative sign of the two lepton charges (OS,SS) and on the lepton isolation (isolated or non-isolated). See text.

Data sample	Relative lepton charge	Lepton isolation
A (signal sample)	OS	isolated
B	SS	isolated
C	OS	non-isolated
D	SS	non-isolated

(A) defined by the event selection criteria described in Section 5.2 and three signal-depleted control data samples (B,C,D) which are mutually exclusive and enriched in multi-jet events. The three control data samples are defined by inverting the requirements on the relative sign of the electron and muon charge and on the isolation criteria. Both the calorimetric and tracking isolation criteria described in Section 5.2.1 are inverted for each electron and muon with respect to the nominal values, thus defining the so-called anti-isolated leptons. The data are divided into four samples of events with leptons of opposite sign charge (OS) or same sign charge (SS) with respectively isolated or anti-isolated leptons, as summarized in Table 5.5.

The ABCD method assumes that there is no correlation between the requirements of relative charge sign and of lepton isolation in QCD multi-jet events. In this case, the number N_A of QCD multi-jet events in the signal sample A can be estimated from the yields N_B , N_C and N_D of multi-jet events in the control samples B , C and D using the equation

$$N_A = N_B \times \frac{N_C}{N_D} = N_B \times R_{QCD}. \quad (5.2)$$

To obtain the QCD multi-jet event yields in the control data samples, the contributions of contaminating electroweak ($W+jets$, $Z+jets$ and dibosons) and top quark ($t\bar{t}$, single top quark production) processes are subtracted based on the prediction from simulation. Tables 5.6 and 5.7 show the observed event yields in the control samples at different stages of the event selection along with the non-QCD background predictions which are subtracted. Contamination by signal events has been evaluated in all three control samples for different m_A and $\tan\beta$ values in the range considered in this analysis. The highest signal contamination of 0.2% is

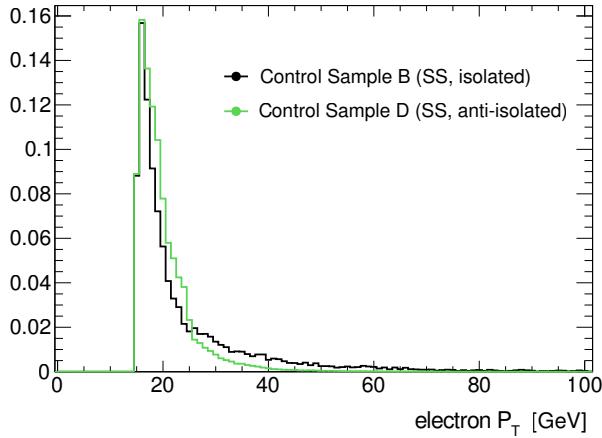


Figure 5.9: Comparison of the electron p_T distributions in control samples B and D, showing the bias due to the trigger. The histograms are normalized to the same area.

observed² in sample B for $m_A = 300$ GeV and $\tan \beta = 50$.

The shapes of the kinematical distributions in QCD multi-jet events are modeled by the data sample B which is expected to have similar kinematical properties as the signal sample. A drawback of this choice is a rather low number of events and a higher contamination with non-QCD process compared to samples C and D. Sample B is chosen to avoid bias in the shapes due to the isolation requirements at the trigger level, since the single-electron trigger already imposes isolation requirements. Figure 5.9 shows the comparison of the electron p_T distributions in samples B and D. In the latter, high- p_T electrons are suppressed as they do not pass the trigger selection. The trigger isolation requirement could in principle also bias the ratio R_{QCD} . This possibility has been investigated in a dedicated study discussed in Appendix A. To good approximation, the trigger effects cancel in the ratio R_{QCD} and no additional systematic uncertainty arises.

To test the predictions of the ABCD method, an additional validation sample has been defined with the following criteria applied after the common selection:

- $E_T^{miss} < 20$ GeV,
- $H_T < 70$ GeV and $p_{T\mu} + p_{Te} + E_T^{miss} < 50$ GeV,

² This signal contamination originates mainly from the production in association with b-quarks and, as it scales with the cross section, it is an order of magnitude smaller for $\tan \beta = 20$.

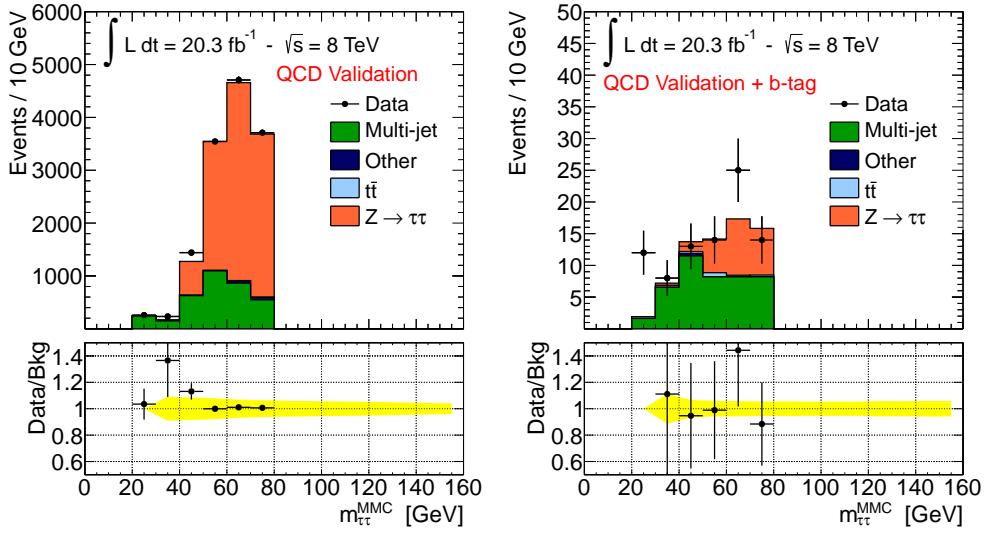


Figure 5.10: $m_{\tau\tau}^{MMC}$ distributions for the QCD validation samples defined in Section 5.3.2 without (left) and with (right) additional requirement of exactly one b-tagged jet in the final state. The error bars and the yellow band indicate the statistical and systematic uncertainties, respectively.

Table 5.6: Numbers of observed events and the non-QCD contributions at different stages of the event selection for the b-vetoed category. The error on R_{QCD} ratio is statistical only.

Event Selection		B	C	D	R_{QCD}
Common Selection	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	
$\Delta\phi_{e,\mu}$	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	
$m_{\tau\tau}^{MMC} > 0.$	Data	3177	479967	244276	1.965 ± 0.005
	non-QCD	1000 ± 100	300 ± 17	190 ± 20	

- $0 < m_{\tau\tau}^{MMC} < 80$ GeV .

These requirement are designed to enhance the multi-jet background contribution with respect to $Z/\gamma^* \rightarrow \tau\tau$ keeping the final state kinematics as similar as possible to the signal sample. Figure 5.10 shows the $m_{\tau\tau}^{MMC}$ distribution for this validation sample with and without the b-tagging requirements. Agreement between data and the background predictions 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 $m_{\tau\tau}^{MMC}$ to take into account any correlation between the isolation and the relative charge of the leptons as detailed in Section 5.4.

5.3.3 $Z \rightarrow \tau\tau + \text{Jets}$ Background Measurement

The $Z/\gamma^* \rightarrow \tau\tau$ production is the main source of background in this analysis and needs to be well understood. Unfortunately, for a light Higgs boson, it is impossible to fully discriminate between $Z/\gamma^* \rightarrow \tau\tau$ decays and the signal because of the similarity of the final state, a dedicated signal-free data control sample, thus, cannot be defined. However, thanks to the small Higgs boson coupling to muons, $Z/\gamma^* \rightarrow \mu\mu$ events from data provide a good starting point to model $Z/\gamma^* \rightarrow \tau\tau$ events. A hybrid approach relying on data and simulation known as "embedding"

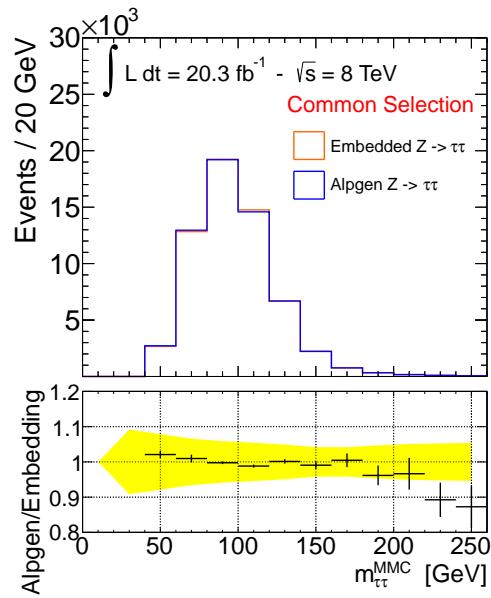


Figure 5.11: Comparison of the $m_{\tau\tau}^{MMC}$ distributions obtained from the ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ simulation and from the embedding technique after the requirements of the common selection has been applied. The yellow band indicates the total systematic uncertainty relative to the ALPGEN simulation sample.

Table 5.7: Numbers of observed events and the non-QCD contributions at different stages of the event selection for the b-tagged category. The error on R_{QCD} ratio is statistical only.

Event Selection		B	C	D	R_{QCD}
Common Selection	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	
$p_{T\mu} + p_{Te} + E_T^{miss}$	Data	71	27735	15590	1.78 ± 0.02
	non-QCD	10 ± 3	22 ± 3	18 ± 2	
$m_{\tau\tau}^{MMC} > 0.$	Data	70	27634	15522	1.78 ± 0.02
	non-QCD	9 ± 3	20 ± 3	17 ± 2	

is used for this purpose. $Z/\gamma^* \rightarrow \mu\mu$ event candidates are selected in data. Each of the two muons from the Z decay is then substituted by the decay products from a simulated decay of a τ lepton, which has the same kinematical properties as the muon. The energy deposits in the calorimeters and the reconstructed tracks within a cone around the muon are subtracted in the data and substituted by the simulated τ lepton decay. Further details on the embedding technique can be found in [87, 88].

As the trigger requirement are not simulated in the embedded samples, only the shapes of kinematical variables distribution are modelled by the embedding, while the $Z \rightarrow \tau\tau$ event yield is normalized to the ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ background prediction after the common selection. Furthermore, a set of corrections described in [89] are applied as event weight to recover the original $Z/\gamma^* \rightarrow \mu\mu$ distribution of kinematical variable from the data biased by a muon trigger. Subsequently, the trigger and reconstruction efficiency of the $e\mu + 4\nu$ final state are emulated by means of event weights.

The embedding technique has been validated in several studies detailed in [87, 89] demonstrating reliable description of the data. Figure 5.11 shows the excellent

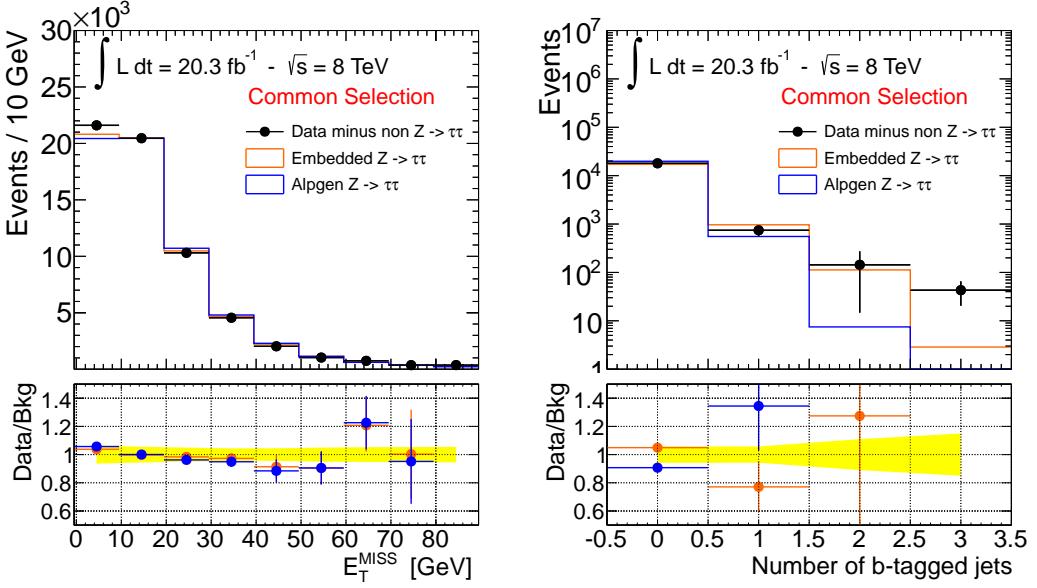


Figure 5.12: Comparison of the E_T^{miss} (left) and b-tagged jet multiplicity (right) distributions in embedded and in ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ events after the common selection. Data are superimposed after subtracting the contributions of non- $Z/\gamma^* \rightarrow \tau\tau$ processes. The yellow band indicates the total systematic uncertainty of the ALPGEN simulation.

agreement between the $m_{\tau\tau}^{MMC}$ distributions of embedded and simulated $Z/\gamma^* \rightarrow \tau\tau$ events. On the other hand, other important variables, such as the E_T^{miss} and the number of b-jets in the final state, are better described by the embedded rather than the simulated $Z/\gamma^* \rightarrow \tau\tau$ sample as shown in Figure 5.12. This is expected and is due to the imperfect modelling of these variables in the simulation.

The embedding method uses selected $Z/\gamma^* \rightarrow \mu\mu$ data events. The $Z/\gamma^* \rightarrow \mu\mu$ selection criteria assure a pure $Z/\gamma^* \rightarrow \mu\mu$ sample, however, further event selection criteria used in this analysis, for example the b-tagging requirements, can enhance the contamination of this sample. Dedicated studies have been made to estimate the $t\bar{t}$ and QCD multi-jet contamination in the embedded sample. The $t\bar{t}$ contamination is estimated by evaluating the yield of embedded $Z \rightarrow \tau\tau$ events with the additional requirement of two b-tagged jets as described in Section 5.3.1. These events are assumed to originate solely from $t\bar{t}$ production and the corresponding yield in the signal sample is determined by extrapolation using the simulation. Table 5.8 summarises the estimated top quark contamination in

the embedded $Z \rightarrow \tau\tau$ sample separately for the two event categories. The multi-jet contamination is estimated in a similar way starting from the yield of embedded events in sample C of the ABCD method. It is assumed that all events in this validation sample are QCD multi-jet events. The QCD multi-jet contamination of the embedded events in the signal region A is estimated as

$$N_A^{QCD-emb} = N_C^{QCD-emb} \times \frac{N_B^{\mu\mu}}{N_D^{\mu\mu}} = N_B \times R_{QCD}^{\mu\mu}. \quad (5.3)$$

The transfer factor $R_{QCD}^{\mu\mu}$ is evaluated using a di-muon final state with the same kinematical selection criteria as for the $Z/\gamma^* \rightarrow \mu\mu$ candidates used for the embedding procedure. Table 5.9 shows the estimated contamination of embedded sample with QCD multi-jet events which is considered negligible.

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

Table 5.8: Evaluation of the $t\bar{t}$ contamination in the embedded $Z \rightarrow \tau\tau$ sample requiring a two b-tagged jets. The transfer factor from the validation sample to the signal sample is obtained from simulation.

	Embedded event yield in QCD control sample C	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 5.9: Evaluation of the QCD multi-jet contamination in the embedded $Z \rightarrow \tau\tau$ sample requiring OS non-isolated leptons (sample C). The transfer factor $R_{QCD}^{\mu\mu}$ extrapolates the event yield measured in control sample C to the signal sample (see text).

5.4 Systematic Uncertainties

This section describes a number of sources of systematic uncertainties that are relevant for the presented analysis. To account for differences in the observed and

simulated detector response a set of corrections is applied at the level of object reconstruction and at event level as described in chapter 4. The uncertainties due to such corrections are referred to as detector-related systematic uncertainties and are addressed in section 5.4.1. For all processes whose contributions are predicted from simulation, also theory-related systematic uncertainties need to be accounted for. These include uncertainties on the cross-section and on the acceptance of events after the given analysis selection criteria and are described in section 5.4.2 . Further systematic uncertainties related to the background measurements with dedicated control data are described in Sections 5.4.3 and 5.4.4 .

Each source of systematic uncertainty can contribute separately to the uncertainty on the final event yield and on the shape of the $m_{\tau\tau}^{MMC}$ distribution which is used as final discriminating variable in the statistical interpretation of data. Systematic uncertainties that affect the shape of the mass distribution are documented in appendix C.3. Uncertainty on the $m_{\tau\tau}^{MMC}$ shape distribution are found to be negligible for all except the embedded sample, for which significant deviation from the nominal distribution are found in the b-vetoed category only. Systematic uncertainties that do not affect the shape of the mass distribution and have an impact on the event yield of less than 0.5% for each process are neglected.

5.4.1 Detector-related Systematics Uncertainties

Systematic uncertainties related to object reconstruction and event-by-event corrections are based on the calibration measurements of the relevant parameter. Each of those parameters correspond to a nuisance parameter in the probability model used for the statistical interpretation as described in Section 5.5. Each parameter is varied independently by one standard deviation according to its measured uncertainty. The corresponding impact on the yield of simulated events is evaluated for each signal and background sample. In the following, detector-related uncertainty are described in more details. Tables 5.11 and 5.10 briefly summarize the impact of these uncertainties on the predicted sample yields.

Luminosity The integrated luminosity of the 8 TeV data recorded with the ATLAS detector during 2012 is measured to be 20.3 fb^{-1} [63] with an uncertainty of 2.8%.

Pileup Simulated events are re-weighted to reproduce the average number of interactions per bunch crossing $\langle \mu \rangle$ as seen in data. Those event weights have

an uncertainty which is propagated to each simulated sample.

Trigger Efficiency is corrected in simulation to match (on the average) the one observed in data. Those correction weights are evaluated as a function of p_T and η of the corresponding leptons and have associated uncertainties. Systematic uncertainties on both the single electron and electron-muon trigger efficiency are taken into account independently and range approximately from 1-2%.

In the embedded $Z \rightarrow \tau\tau$ sample, the trigger is emulated by applying weights according to the event topology. Those weights are related to the ones described above and have similar uncertainties. Trigger efficiency uncertainty for the embedded sample are considered uncorrelated with those of other samples.

Electrons Two sources of uncertainty on reconstructed electron objects are considered: the first related to electron identification and reconstruction efficiencies ("Electron ID") which range approximately from 1-2% depending on the transverse momentum of the electron, the second related to electron energy scale and resolution corrections, both ranging from 0.3-3% depending on η . The energy scale uncertainties are described by a set of six different nuisance parameters [103]. However, only a few of them give a non-negligible contribution to the analysis. Two of them are found to affect the shape of the $m_{\tau\tau}^{MMC}$ distribution and are considered independently: uncertainty arising from the electron momentum measurement with $Z \rightarrow ee$ data ("Electron Zee") and the one related to low momentum electrons ("Electron LOWPT"). All other uncertainties related to energy scale and resolution are summed in quadrature ("Electron E").

Muons The uncertainty on muon identification efficiency depends on the charge and momentum of the muon. Typically these uncertainties are of the order of a fraction of percent, and are referred as "Muon ID". The uncertainties on the muon energy scale and resolution are considered independently for the inner detector and muon spectrometer measurements and are then added in quadrature to estimate the final uncertainty ("Muon E").

Taus-Jets The jets from the hadronically decaying τ leptons are only considered in the analysis by applying a veto on their presence in an event. Uncertainties on both τ -jet energy scale and identification efficiency have been investigated and are found to be negligible for this analysis.

Jets The systematic uncertainties on the Jet Energy Scale (JES) are described by multiple sets of nuisance parameters [114] related to different effects and jet energy components, for example the sensitivity to pileup effects or to the flavour composition of the jet. The overall uncertainty on the JES ranges between 3% and 7%, depending on the p_T and η of the jet. The overall impact of the JES uncertainty on the analysis yields is shown in Tables 5.11 and 5.10 by summing all component in quadrature, while in the statistical interpretation of data those uncertainties are considered uncorrelated. Systematic uncertainty due to the jet resolution ("Jet Resolution") are obtained by smearing the jet energy according to the measured uncertainty which ranges from 10-20% depending on the direction of the jet.

b-Tagging Corrections are applied to simulation to match the b-tagging efficiency observed in data. Uncertainties on the knowledge of the b-tagging efficiencies for the 70% $\epsilon_b^{t\bar{t}}$ working point of the MV1 b-tagger are considered [118, 119]. These uncertainties range from 5-10% depending on the p_T of the jet. The effect of those uncertainties is evaluated independently for the b-quark, c-quark and light or gluon initiated jets and referred to respectively as "B Eff", "C Eff" and "L Eff". The tagging and mis-tagging efficiency uncertainties are considered to be fully anti-correlated.

Missing Transverse Energy The effect of the energy scale uncertainties for all physics objects is propagated to the E_T^{miss} calculation. In addition, uncertainty on the energy scale and resolution due to the remaining unassociated calorimeter energy deposits, the "soft-terms", is considered and estimated to be of the order of 10% [120]. E_T^{miss} uncertainties are independently propagated through the analysis and are added in quadrature, this final term is referred to as the "MET" uncertainty.

5.4.2 Theoretical Uncertainties

Uncertainties on the cross-sections that have been used to normalize the contribution of simulated samples to the integrated luminosity of analyzed data are reported in Table 5.12. These uncertainties include contributions due to parton distribution functions (PDFs), the choice of the value of the strong coupling constant, the renormalisation and factorisation scales. Furthermore, the uncertainties

Source	b-vetoed event category, Uncertainties on event yields (%)				
	Signal bbH	Signal ggH	$Z/\gamma^* \rightarrow \tau\tau$	Top	Other
Electron ID	2.4	2.3	2.9 (s)	1.4	1.6
Electron E.	0.4	0.5	0.4	0.5	0.9
Electron LOWPT	0.3	0.5	0.4 (s)	0.0	1.2
Electron Zee	0.4	0.4	0.4 (s)	0.1	0.3
Muon ID	0.3	0.3	0.3	0.3	0.3
Muon E.	0.1	0.1	0.1	0.5	0.5
Trigger Single Ele.	0.6	0.6	0.5	0.9	0.9
Trigger Dilep.	1.0	1.0	1.3	0.2	0.3
Embedding MFS	-	-	0.1 (s)	-	-
Embedding Iso.	-	-	0.0 (s)	-	-
JES	0.6	0.7	-	1.0	1.2
JER	0.5	0.3	-	0.6	0.3
B Eff	1.8	0.0	-	12.0	0.8
C Eff	0.0	0.1	-	0.1	0.0
L Eff	0.0	0.1	-	0.2	0.1
Pileup	0.5	0.8	0.4	0.3	0.3
MET	0.2	0.8	0.1	0.2	0.5
Luminosity	2.8	2.8	2.8	2.8	2.8

Table 5.10: Impact of the experimental systematic uncertainties on the event yields in different simulated samples in the b-vetoed event category. Here "Other" refers to the sum of all remaining background samples: $W \rightarrow \ell\nu$, dibosons, $Z \rightarrow \ell\ell$ and single top quark processes. The signal produced in association with b-quarks and via gluon fusion is considered separately assuming $m_A = 150$ GeV and $\tan \beta = 20$. Uncertainty that impacts the $m_{\tau\tau}^{MMC}$ mass distribution are noted with the symbol (s).

Source	b-tagged event category, Uncertainties on event yields (%)				
	Signal bbH	Signal ggH	$Z/\gamma^* \rightarrow \tau\tau$	Top	Other
Electron ID	2.3	2.6	2.8	1.8	2.0
Electron E	0.7	1.2	0.5	0.5	0.9
Electron LOWPT	0.4	0.0	0.4	0.1	0.4
Electron Zee	0.3	0.6	0.4	0.6	0.5
Muon ID	0.3	0.3	0.3	0.3	0.3
Muon E	0.5	0.8	0.1	0.1	0.2
Trigger Single Ele.	0.7	0.5	0.5	0.8	0.8
Trigger Dilepton	1.0	1.2	1.4	0.6	0.6
Embedding MFS	-	-	0.0	-	-
Embedding Iso.	-	-	1.3	-	-
JES	2.7	7.3	-	10.0	7.0
JER	1.4	6.3	-	2.9	3.0
B Eff	10.2	3.1	-	2.6	5.0
C Eff	0.2	4.3	-	0.0	1.2
L Eff	0.4	8.0	-	0.1	1.2
Pileup	0.4	0.7	0.4	0.4	0.9
MET	0.7	0.5	0.2	1.0	1.2
Luminosity	2.8	2.8	2.8	2.8	2.8

Table 5.11: Impact of the experimental systematic uncertainties on the event yields in different simulated samples in the b-taged event category. Here "Other" refers to the sum of all remaining background samples: $W \rightarrow \ell\nu$, dibosons, $Z \rightarrow \ell\ell$ and single top quark processes. The signal produced in association with b-quarks and via gluon fusion is considered separately assuming $m_A = 150$ GeV and $\tan \beta = 20$.

Generator	Process	Uncertainty
ALPGEN	$Z \rightarrow \tau\tau/ee/\mu\mu$	$\pm 5\%$
POWHEG	$t\bar{t}$	$\pm 5.5\%$
ALPGEN	$W \rightarrow \tau\nu/e\nu/\mu\nu$	$\pm 5\%$
AcerMC	single top	$\pm 13\%$
HERWIG	dibosons	$\pm 6\%$
SHERPA	$bbA/h/H$ ($m_A \geq 120$ GeV)	$-(< 20)\%, +(< 9) \%$
SHERPA	$bbA/h/H$ ($m_A = 110$ GeV)	$-(< 25)\%, +(< 9) \%$
SHERPA	$bbA/h/H$ ($m_A = 100$ GeV)	$-(< 28)\%, +(< 9) \%$
SHERPA	$bbA/h/H$ ($m_A = 90$ GeV)	$-(< 30)\%, +(< 9) \%$
POWHEG	$ggA/h/H$ ($m_A \leq 300$ GeV)	$< 15\%$

Table 5.12: Cross-section uncertainties for background and signal processes, $\tan\beta = 20$ is assumed for all signal samples.

on the signal cross-section depend on the $\tan\beta$ value, the nature of the Higgs boson ($A/h/H$) and its mass.

The impact of systematic uncertainties due to various Monte Carlo tuning parameters for the description of the underlying event and lepton kinematic properties is considered. Since the distribution of the invariant mass of all visible τ lepton decay products is found to be not affected by these systematic, uncertainties only the variation in the acceptance is considered as a systematic uncertainty. The acceptance uncertainties for the simulated ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ sample, which is used for the normalization of the embedded sample, are estimated at the common selection stage to be 4% [138]. Since additional selection criteria are applied directly to the embedded sample, no further acceptance uncertainties are considered. Acceptance uncertainties on the yield of $t\bar{t}$ simulated events are estimated to be 2% [139]. The acceptance uncertainties on dibosons and single top quark production are estimated to be 2% [138].

Uncertainties on the signal acceptance have been estimated with signal samples produced varying generator parameters. The impact on the selection of leptons, τ -jet and jets is evaluated at the particle level, prior to simulation of the detector response. This truth-level study is implemented within the Rivet framework [141], where the b-tagging is performed by identifying the b-quarks and applying weights according to the measured ATLAS b-tagging efficiencies [118]. The variation of the acceptance with respect to the nominal Monte Carlo tune has been considered as a source of systematic uncertainty. For signal a total acceptance uncertainty

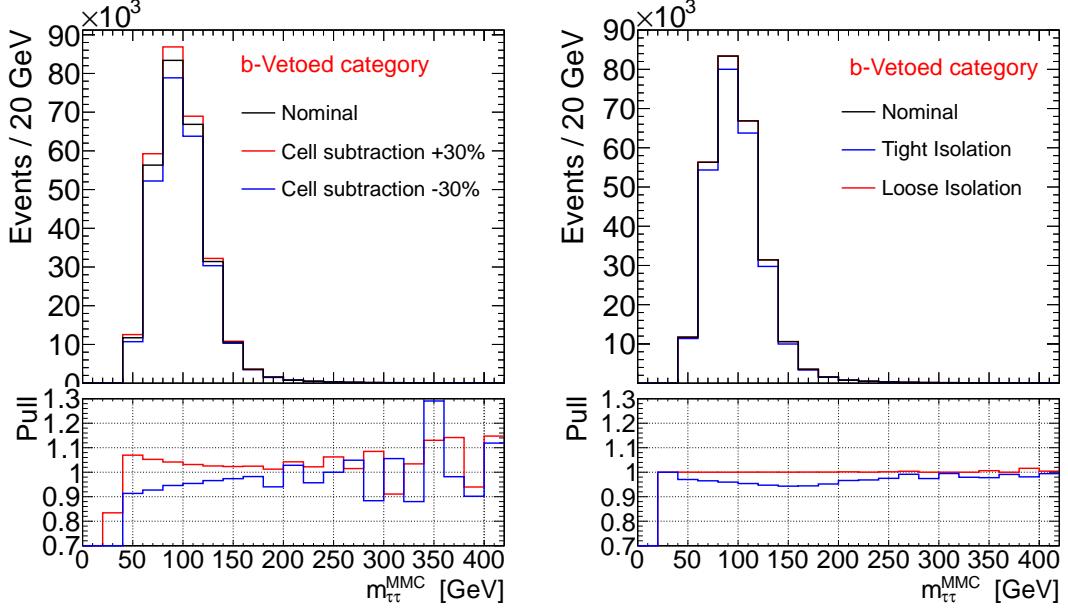


Figure 5.13: Impact of EMB_MFS (left) and EMB_ISO (right) systematic uncertainties on the $m_{\tau\tau}^{MMC}$ mass distribution for the embedded sample. Significant impact is observed only in the b-vetoed event category.

varies from 4% to 30% depending on M_A , production process and on the analysis category.

5.4.3 Systematic Uncertainties of the $Z/\gamma^* \rightarrow \tau\tau$ Embedded Sample

An important element of the embedding method is the subtraction of the calorimeter cells associated with the muons in the original $Z/\gamma^* \rightarrow \mu\mu$ event and their substitution with those from the simulated τ lepton decays. To make a conservative estimate of the systematic uncertainty on this procedure, the energy of the subtracted cells is scaled up or down by 30%. The analysis is repeated with those modified samples and the relative uncertainty is referred as "EMB_MFS". This uncertainty affects mainly the shape of the $m_{\tau\tau}^{MMC}$ mass distribution, shown in Figure 5.13.

In the sample of $Z/\gamma^* \rightarrow \mu\mu$ candidates used for the embedding, only a loose requirement on the muon track isolation is applied. A different muon isolation re-

Selection	R_{QCD}	R_{QCD}^{AB}	R_{QCD}^{iso}
common selection	1.929 ± 0.004	2.12 ± 0.17	2.22 ± 0.16
No b-tagged jets	1.965 ± 0.005	2.10 ± 0.16	2.22 ± 0.16
Exactly one b-tagged jet	1.78 ± 0.02	1.9 ± 0.9	2.0 ± 0.8

Table 5.13: Comparison between R_{QCD} , R_{QCD}^{AB} and R_{QCD}^{iso} after the common selection stage and after requiring or vetoing the presence of b-tagged jets. Only the statistical uncertainty is reported here. The value of R_{QCD}^{iso} is reported for the lepton isolation threshold which is twice the nominal value, while for R_{QCD}^{AB} and R_{QCD} the nominal values are reported.

quirement may affect the selected sample by modifying the topology of the event, changing the contamination with other processes or the activity in the calorimeter. To estimate the importance of these effects in the embedded sample, the muon isolation criteria used in the original $Z/\gamma^* \rightarrow \mu\mu$ sample are tightened, while an even looser selection would have a rather small impact due to isolation requirements at the trigger level. The resulting uncertainty, referred to as "EMB_ISO", affects both the event yield and the shape of the $m_{\tau\tau}^{MMC}$ mass distribution in the embedded sample, as shown in Figure 5.13.

Finally, because the normalization of the embedded sample is determined from the simulated ALPGEN sample, the uncertainties related to the cross section and to luminosity are assigned. In addition all detector-related systematic uncertainties relevant to the decay products of the simulated τ lepton decay are propagated to the embedded sample.

5.4.4 QCD Multi-Jet Systematic Uncertainties

The QCD multi-jet background is estimated via the ABCD method, as described in Section 5.3.2. This technique relies strongly on the assumption that the lepton isolation variables are uncorrelated to the relative charge of the two leptons. Systematic uncertainties are assigned to take into account possible deviations from this assumption. First the correlation between the ratio R_{QCD} and the lepton isolation criteria is considered, then the result is compared with an auxiliary measurement.

Figure 5.14 shows the R_{QCD} factor, i.e. the ratio between the QCD yields in data samples C and D, as a function of a sliding lepton isolation threshold relative to the nominal analysis selection (red points). As described previously,

the expected contamination of non-QCD background processes is subtracted from the data in samples C and D. To estimate the uncertainty on the value of R_{QCD} an additional transfer factor is defined: $R_{QCD}^{iso} = N_{\hat{A}}/N_{\hat{B}}$, where \hat{A} and \hat{B} are semi-isolated OS and SS samples defined by requiring the lepton isolation to be larger than the nominal one, but smaller than a given sliding threshold value (defined by the X -axis of the plot). Also here the non-QCD contributions are subtracted from the data yields. The semi-isolated samples \hat{A} and \hat{B} are chosen given the high contamination with non-QCD background processes and with possible signal in data samples A and B. Figure 5.14 shows R_{QCD}^{iso} as a function of the relative lepton isolation threshold (black points). The difference between R_{QCD} and R_{QCD}^{iso} in the vicinity of the nominal isolation threshold is then assigned as a systematic uncertainty on R_{QCD} . For the lepton isolation threshold which is twice the nominal value, a systematic uncertainty of 15% is found. The result shown in Figure 5.14 are obtained after common selection. Similar results after the full analysis selection in the two event categories are shown in Appendix B.

As a test of the result described above an additional measurement is performed. The R_{QCD}^{AB} is calculated as the ratio between the estimated QCD multi-jet contributions in samples A and B instead of C and D. The non-QCD contributions are subtracted from data. Due to the large contribution of this non-QCD background, along with small numbers of observed events and possible signal contamination, this measurement is only used for cross check. Table 5.13 shows a comparison between R_{QCD} , R_{QCD}^{iso} and R_{QCD}^{AB} after the common selection stage and after requiring or vetoing the presence of b-tagged jets, at these selection stages the signal contamination is negligible. Good agreement is seen between the results of these methods.

The shape of the $m_{\tau\tau}^{MMC}$ mass distribution differs between the OS and SS in anti-isolated samples (C and D) as shown in Figure 5.15. The size of this effect is within the above R_{QCD} uncertainty for the relevant mass range of the QCD multi-jet background (QCD multi-jet background contribution is negligible for $m_{\tau\tau}^{MMC} > 150$ GeV) and hence no correction factor is applied to the mass shape of sample B. It is assumed, however, that there could be the same shape difference in the isolated samples and thus a shape uncertainty is assigned to the mass distribution in sample B to account for this deviation. Further shape uncertainties due to non-QCD background subtraction are found to be negligible. The uncertainty due to the use of an isolation requirement at the trigger level is discussed in Appendix A and is found to be negligible.

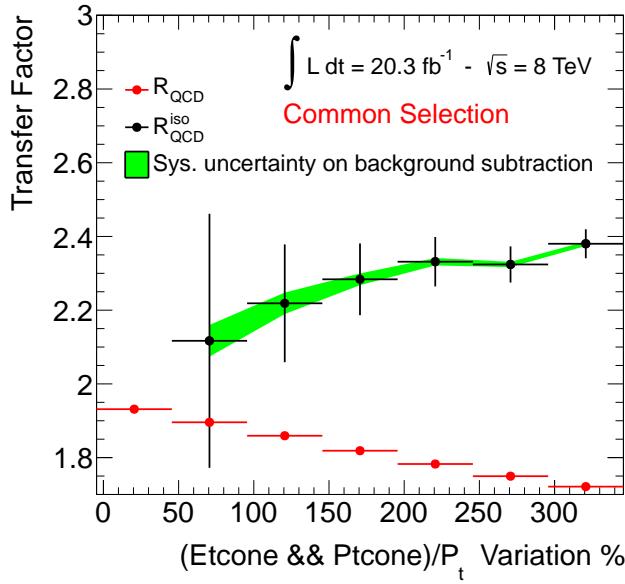


Figure 5.14: Transfer factors R_{QCD} and R_{QCD}^{iso} (see text) as a function of the sliding lepton isolation thresholds. The thresholds are varied in percentages relative to the nominal lepton isolation threshold (value of zero on the plot). The common selection are applied.

5.5 Results

5.5.1 Statistical Procedure

The statistical interpretation of data in the presented search is based on profiled likelihood ratio test statistic used for the Higgs boson searches [142]. The statistical procedures described in the following are implemented in the software packages described in [143–145].

The Likelihood Function

The statistical interpretation of data is performed by means of testing the compatibility of the *background only* and the *signal-plus-background* hypotheses with the observed data. The main ingredient of the hypothesis *test statistic*, defined later on in this section, is a binned likelihood function for the data set, \mathcal{D} :

$$\mathcal{L}(\mathcal{D} \mid \mu, \boldsymbol{\theta}) = \text{Pois}(\mathcal{D} \mid \mu \cdot s(\boldsymbol{\theta}) + b(\boldsymbol{\theta})) \cdot \prod_{j,i} \mathcal{G}(\theta_j^{sys} \mid 0, 1) \cdot \Gamma(\theta_i^{stat} \mid \beta_i) \quad (5.4)$$

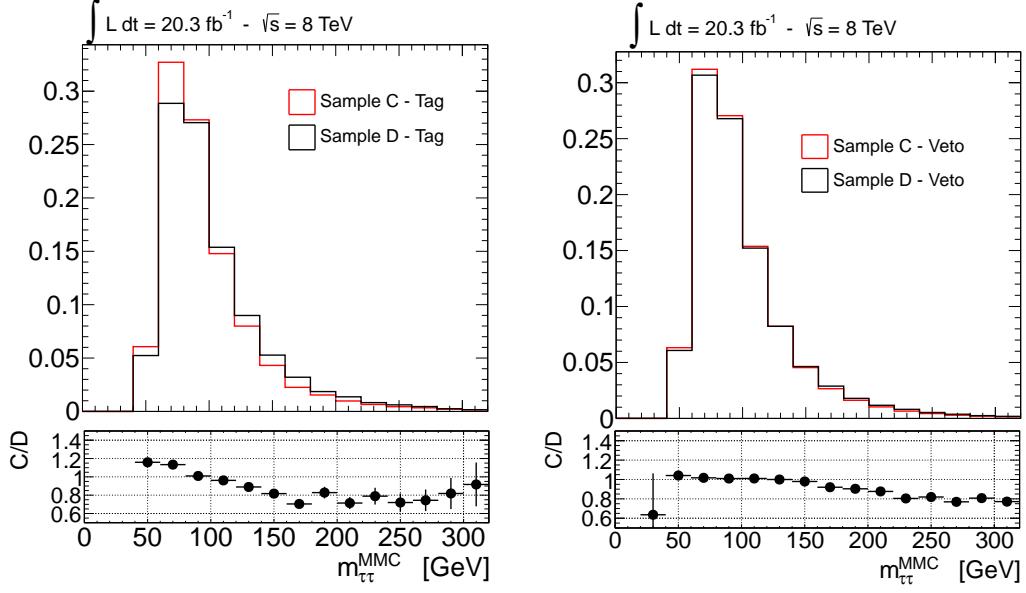


Figure 5.15: Differences in the shape of the invariant $m_{\tau\tau}^{MMC}$ mass distribution in data samples C and D shown separately for the b-tagged and b-vetoed event categories. The data samples C and D are normalised to the same number of events.

describing how likely is a certain hypothesis given the observation of the data set \mathcal{D} . The signal strength modifier μ allows for reproducing a continuous set of signal hypotheses with different cross-section. The value of $\mu = 0$ corresponds to the background-only hypothesis. The vector $\boldsymbol{\theta}$ represents the set of *nuisance* parameters related to the systematic (θ_j^{sys}) and to the statistical (θ_i^{stat}) uncertainties of the background and signal predictions. The functions $s(\boldsymbol{\theta})$ and $b(\boldsymbol{\theta})$ represent the expected signal and background distribution respectively, these are binned histograms of the invariant $m_{\tau\tau}^{MMC}$ mass distribution. The function $\mathcal{G}(\theta_j^{sys} | 0, 1)$ is the Gaussian³ probability density function (p.d.f.) for the nuisance parameter θ_j^{sys} , which is assumed to be distributed with mean = 0 and $\sigma = 1$. The impact of the corresponding systematic uncertainty on the signal and backgrounds yields and on the shape of the $m_{\tau\tau}^{MMC}$ invariant mass distribution is evaluated separately as described in Section 5.4. The function $\Gamma(\theta_i^{stat} | \beta_i)$ is an extended gamma function

³Evaluation of systematic uncertainties is obtained from auxiliary measurements. From Bayes theorem, assuming a flat prior and a Gaussian distribution for the measured parameter a Gaussian posterior is obtained.

⁴ describing the p.d.f. for the nuisance parameter θ_i^{stat} related to the statistical uncertainty β_i , for the bin i of the considered histogram. Each value of the nuisance parameter set $\boldsymbol{\theta}$ is associated with a variation of the predicted signal and background event yields with respect to the nominal prediction. The Poisson distribution in equation (5.4) is a binned p.d.f. and stands for a product of Poisson probabilities to observe n_i events in the bin i of the $m_{\tau\tau}^{MMC}$ mass distribution histogram:

$$\text{Pois}(\mathcal{D} \mid \mu \cdot s(\boldsymbol{\theta}) + b(\boldsymbol{\theta})) = \prod_i \frac{(\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))^{n_i}}{n_i!} e^{-\mu s_i(\boldsymbol{\theta}) - b_i(\boldsymbol{\theta})}$$

The $m_{\tau\tau}^{MMC}$ mass distributions in the b-tagged and b-vetoed category are analysed separately. The actual implementation in the likelihood function of the ABCD method follows that suggested in [136] and it is described in more detail in Appendix C.

Statistical Combination of Results From Two Event Categories

Complementary event categories in one search channel, like the b-tagged and b-vetoed event categories, can be combined in order to increase the sensitivity to the signal. If there are no events entering both categories, as is the case for the presented analysis, the statistical combination is the product of the likelihood functions for the individual categories. For the combination, the convention described in [142] is used to take into account the correlation between different sources of uncertainties. Uncertainties are considered either as fully correlated, which means that the same nuisance parameter is describing the given systematic effect in both categories, or fully uncorrelated, in which case different nuisance parameter are employed in the two categories. Partially correlated uncertainties are either split into component which are fully uncorrelated or they are defined as to either fully correlated or uncorrelated, depending on which assumption is the most conservative.

The Test Statistic and the Exclusion Limits

To compute the compatibility of the data with a given hypothesis a test statistic is defined based on the *profiled likelihood ratio* [146]:

$$\tilde{q}_\mu = -2\ln \frac{\mathcal{L}(\mathcal{D} \mid \mu, \hat{\boldsymbol{\theta}}_\mu)}{\mathcal{L}(\mathcal{D} \mid \hat{\mu}, \hat{\boldsymbol{\theta}})} \quad \text{with the constraint } 0 \leq \hat{\mu} \leq \mu. \quad (5.5)$$

⁴The posterior of a Poisson distribution assuming a flat prior is a gamma function

where \mathcal{L} is the likelihood function defined in equation (5.4), $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ are the global maximum likelihood estimators for μ and $\boldsymbol{\theta}$ given the data, whereas $\hat{\boldsymbol{\theta}}_\mu$ is the maximum likelihood estimator of $\boldsymbol{\theta}$ given the data but with a signal strength fixed to the value of μ . \tilde{q}_μ is increasing with increasing disagreement between data and the given μ hypothesis. Based on this, the procedure for setting upper exclusion limits on the signal cross-section is defined as follows:

1. The probability density function of \tilde{q}_μ is determined under the background-only (H_0) and the signal-plus-background (H_μ) hypotheses for any given value of μ . Since the determination of these distributions by means of pseudo-data demands large computing resources, asymptotic approximation formulas described in [146] are employed.
2. Once the p.d.f. for the background-only and signal-plus-background hypothesis are obtained, it is possible to define for a given dataset two probability values (p-values) for any given value of μ . These are the probabilities to obtain data less compatible with the considered hypothesis than the actual observation:

$$p_{s+b} = P(\tilde{q}_\mu > \tilde{q}_\mu^{\text{observed}} \mid H_\mu)$$

$$p_b = P(\tilde{q}_\mu > \tilde{q}_\mu^{\text{observed}} \mid H_0)$$

The ratio of this two probabilities defines the quantity $CL_s = p_{s+b}/p_b$ [147, 148].

3. If for a given μ the CL_s value of $CL_s \leq \alpha$ is obtained, the signal-plus-background hypothesis (with the corresponding μ value) is considered to be excluded at a $(1 - \alpha)$ CL_s confidence level. The 95% confidence level upper limit on μ , denoted as $\mu^{95\%}$, is defined as the smallest value of μ for which the CL_s is no longer greater than 0.05.

By construction, rejecting all values of $\mu > \mu^{95\%}$, the signal-plus-background hypothesis will be rejected when it is true at most 5% of the time. The CL_s prescription is a conservative approach protecting the signal exclusion upper limit from downward fluctuation of the data. The expected median exclusion upper-limit and its error are evaluated with the procedure described above under the background-only hypothesis. The obtained results have been cross-checked using generated pseudo-data instead of the asymptotic approximation for the determination of the \tilde{q}_μ probability density functions.

5.5.2 Exclusion Limits on the Signal Production

The statistical procedure described in section 5.5.1 is the general one used for the SM Higgs boson where only the Higgs boson mass determines the signal properties. For the MSSM further complication arises: there are three neutral Higgs bosons contributing to the total signal yield, in a particular scenario the masses and cross section are defined by two parameter $\tan\beta$ and m_A . Thus, the previously described procedure has to be repeated for each point in the $\tan\beta - m_A$ plane. For the m_h^{mod} scenario exclusion limits at 95% CLs confidence level are derived on the cross section for the neutral MSSM Higgs bosons ($A/h/H$) production via gluon fusion and in association with b-quarks, the considered Higgs bosons decay is $A/H/h \rightarrow \tau\tau \rightarrow \mu e + 4\nu$. A scan has been performed over for 15 $\tan\beta$ values ranging⁵ from $\tan\beta = 5$ to $\tan\beta = 60$. A point in the $\tan\beta - m_A$ plane is excluded if $\mu^{95} \leq 1$ for that point. A linear interpolation is used to determine the excluded $\tan\beta$ for a given m_A . The procedure is repeated for a set of 12 CP-odd Higgs boson masses values m_A ranging from 90 GeV to 300 GeV⁶. The expected and observed event yields are compared in bins of the $m_{\tau\tau}^{MMC}$ mass distribution. The bin sizes are chosen such that the number of events per bin is high enough to justify the use of the asymptotic approximation. Table 5.14 compares the expected and the observed event yields in the two event categories at the final stage of the event selection. Additionally, Figure 5.16 shows the corresponding $m_{\tau\tau}^{MMC}$ mass distributions.

The resulting exclusion limit on the MSSM $m_A - \tan\beta$ parameter space are interpreted within the m_h^{mod} benchmark scenario and shown in Figure 5.17. The expected and observed exclusion limits at 95% CL_s confidence-level are shown as dashed and solid black lines respectively. The green and yellow bands correspond to the 1σ and 2σ error bands on the expected exclusion limit. The analysis is sensitive to the MSSM Higgs boson production for $\tan\beta \geq 13$ and the mass range $90 < m_A < 200$ GeV. The observed limit is

The outcome of the search is also interpreted in a model-independent way, by setting the limits on the production cross-section of a scalar boson produced in the $pp \rightarrow gg \rightarrow \phi$ or $pp \rightarrow bb\phi$ mode and decaying in a di-tau pair. The corresponding expected and observed 95% CL_s confidence-level limits are shown in Figure 5.18. The limits in the production in association with b-quarks and via gluon fusion

⁵ The set of $\tan\beta$ values used is 5, 8, 10, 13, 16, 20, 23, 26, 30, 35, 40, 45, 50, 55, 60

⁶ The set of m_A values used is: 90, 100, 110, 120, 125, 130, 140, 150, 170, 200, 250 and 300 GeV

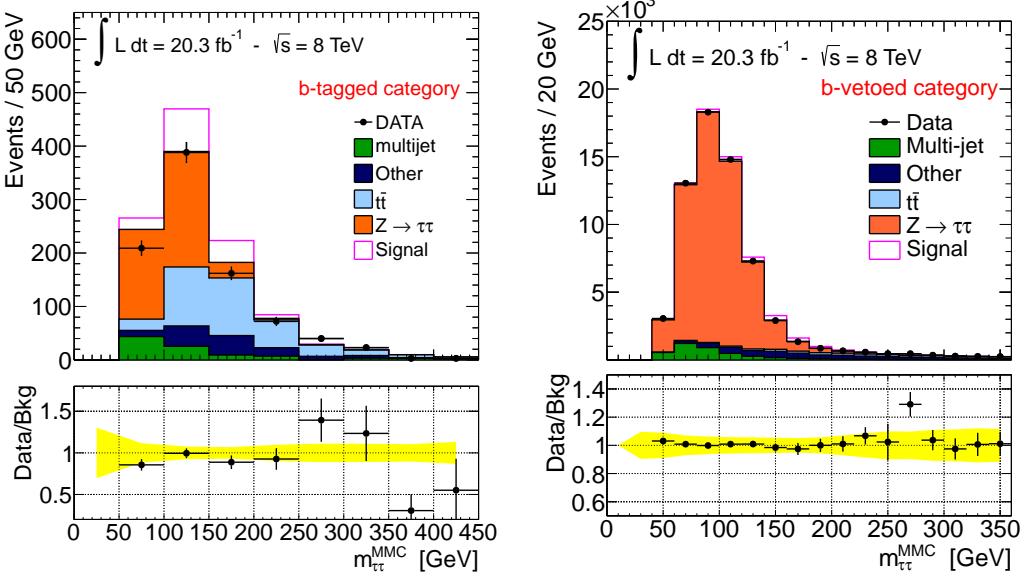


Figure 5.16: Observed and expected distribution of the $m_{\tau\tau}^{MMC}$ mass for (left) the b-tagged event category and (right) the b-vetoed event category after the full event selections. The prediction of the background model is compared to data. The contribution of the $Z/\gamma^* \rightarrow \tau\tau$ and QCD multi-jet background processes is measured in dedicated signal-depleted control data samples, the prediction for all the other background processes is obtained from simulation. The notation ‘‘Other’’ stands for the electroweak processes $W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$, diboson and single top quark production. The prediction for the signal is evaluated considering the production of the three neutral MSSM Higgs bosons in association with b-quarks and via the gluon fusion processes in the m_H^{mod} scenario for values of $m_A = 150$ GeV and $\tan\beta = 20$. The yellow band represents the total systematic uncertainty for the background model prediction.

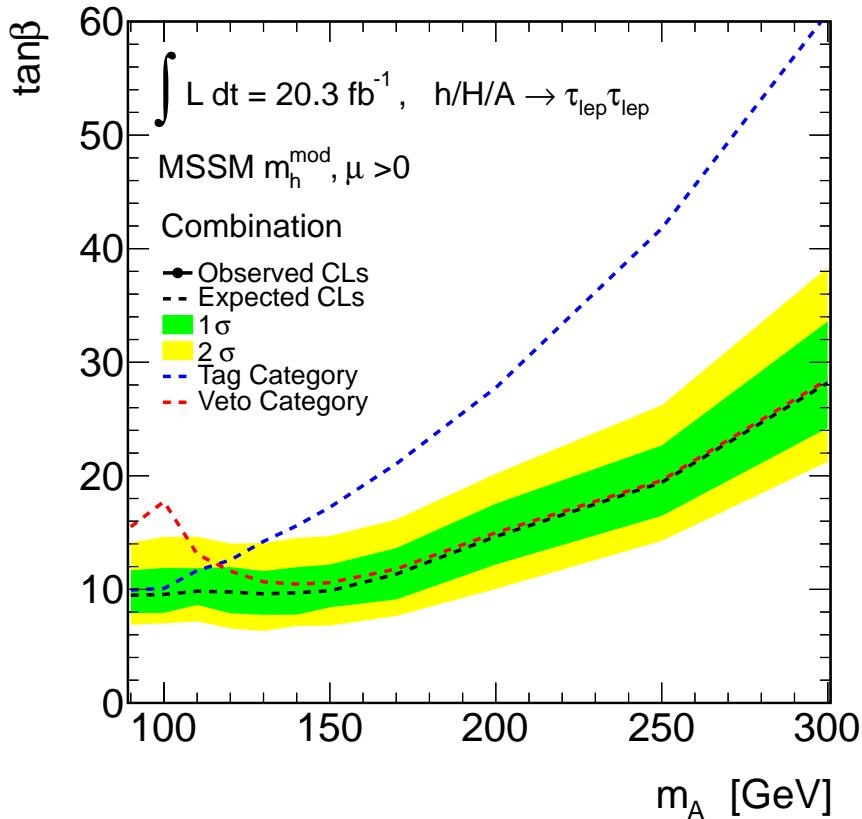


Figure 5.17: Expected and observed exclusion limits at the 95% CL_s confidence-level for MSSM Higgs bosons production interpreted in the $m_A - \tan\beta$ parameter space of the m_h^{mod} scenario. Combined result of the b-tagged and b-vetoed category is shown.

Sample	b-tag category			b-veto category		
	N(event)	Stat.	Syst.	N(event)	Stat.	Syst.
$Z/\gamma^* \rightarrow \tau\tau$	418	± 6	$^{+27}_{-27}$	54680	± 60	$^{+3500}_{-3500}$
$t\bar{t}$	330	± 10	$^{+37}_{-35}$	2159	± 25	$^{+280}_{-300}$
Multijet	101	± 15	$^{+15}_{-15}$	3930	± 330	$^{+590}_{-590}$
Other	114	± 9	$^{+12}_{-12}$	4450	± 110	$^{+250}_{-250}$
Total	963	± 21	$^{+50}_{-50}$	65220	± 360	$^{+3600}_{-3600}$
Signal	144	± 7	$^{+24}_{-33}$	2028	± 27	$^{+150}_{-100}$
Data	-	-	-	-	-	-

Table 5.14: Expected and observed number event yields in the b-tagged and b-vetoed event category after the full event selections. The various background and signal expected event yields are normalized to the integrated luminosity of the data sample (20.3 fb^{-1}). The notation ‘‘Other’’ stands for the electroweak processes $W \rightarrow \ell\nu$, $Z \rightarrow \ell\ell$, diboson and single top quark production. $Z/\gamma^* \rightarrow \tau\tau$ has been estimated using the embedding technique. The uncertainties quoted include the statistical uncertainty (first number) and the systematic uncertainties (second number). For the prediction of the MSSM Higgs bosons signal yield, $m_A = 150 \text{ GeV}$ and $\tan \beta = 20$ is assumed in the m_h^{mod} scenario.

are shown separately. More information on the limit setting procedure and its validation can be found in Appendix C.

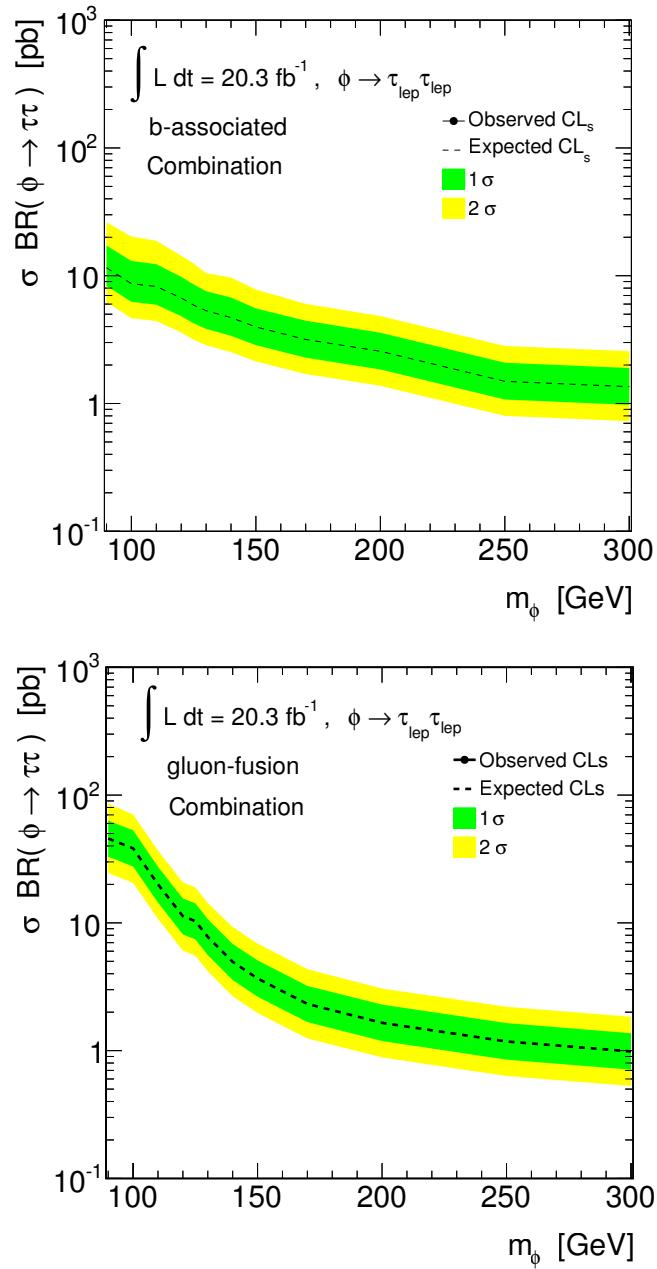


Figure 5.18: Limits on the production of a scalar particle decaying to a di-tau pair and produced in association with b quarks (top) or via gluon-gluon fusion (bottom).

Chapter 6

Prospects for Improved Higgs Search with b-tagging of Track-Jet

The search for the neutral MSSM Higgs bosons described in the previous chapter suffers strongly from poor b-tagging performance due to the relatively low energy of the b-jet produced in association with the signal. Improvements on the b-tagging performance would result in a major improvement of the search sensitivity. This chapter investigates an alternative b-jet identification procedure in which the b-tagging algorithm is applied on track-based jets instead on the commonly used calorimeter jets. While the calorimeter jets are reconstructed from the energy clusters in the calorimeter, the track-based jets consist of inner detector tracks. The performance of the b-tagging on track-based jets is investigated for the first time. The prospects for improvements of the neutral MSSM Higgs bosons search due to the employment of track-based jets for b-tagging are reported. In Section 6.1 the challenges of the MSSM Higgs boson search due to b-tagging are presented along with a description of track-based jet reconstruction. Section 6.2 describes the performance of the b-tagging algorithms with track-based jets in comparison to the nominal b-tagging with calorimeter jets. Preliminary evaluation of the corresponding impact on the analysis is also described here. Finally, in Section 6.3 a description of the related track-based jets systematic uncertainty is given.

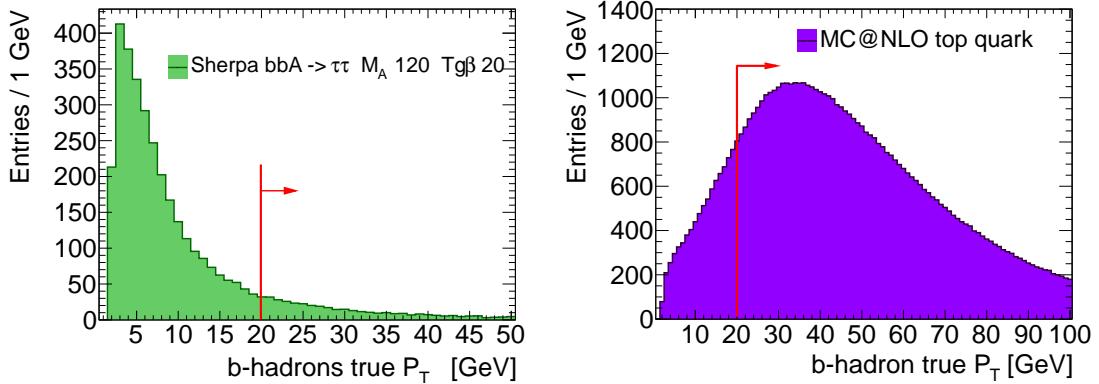


Figure 6.1: Simulated p_T distribution of b-hadron for the neutral MSSM Higgs boson produced in association with b-quarks (left) and for $t\bar{t}$ events (right). The red line in the figure shows the acceptance region in which the energy of the calorimeter jets can be calibrated.

6.1 Track-based Jets

In the search for the neutral MSSM Higgs bosons, as described in chapter 5, the selected events are categorized in two categories based on the presence or the absence of a b-tagged jet in the event. The b-tagged event category is optimized for the selection of Higgs bosons produced in association with b-quarks. Figure 6.1 shows a comparison between the p_T spectra of simulated b-hadron (hadrons containing a b-quark) in $pp \rightarrow b(b) A/h/H$ process and in $t\bar{t}$ events. The signal contains b-hadrons with relatively low transverse momenta, imposing a major challenge for the analysis of the b-tagged event category. Due to the high amount of pileup and ambient energy density in the events, the energy of the calorimeter jets with $p_T < 20$ GeV is not calibrated (see chapter 4), the jet reconstruction performance and related systematic uncertainties are not evaluated for these jets. The reconstruction of calorimeter jets in the $pp \rightarrow b(b) A/h/H$ signal production process is therefore not optimal and represent the major source of the sensitivity losses in the b-tagged event category. An additional challenge of the presented search is the worsening of the b-tagging performance for jets with low transverse momenta. The efficiency obtained with the MV1 tagger decreases rapidly with jet p_T , reaching a minimum of 50% at 20 GeV for the tagging point with $\epsilon_b^{t\bar{t}} = 70\%$ [118, 119].

The performance of the jet reconstruction for low transverse momenta may be improved by introducing *track-based* jets (in the following track-jets) in replace-

ment to the commonly used calorimeter jets. Track-jets are reconstructed with the anti- kt algorithm by clustering inner detector tracks. Conversely to calorimeter clusters, tracks have associated impact parameter informations and track-jets can be reconstructed with tracks originating from the same interaction point, making their reconstruction very robust against the impact of pile-up.

Track-jets are built by the *TrackZTool* reconstruction software which runs the anti- kt clustering algorithm on a subset of user-defined tracks. For the purposes of this thesis track-jets are reconstructed from tracks satisfying the following quality selection criteria:

- The track should be associated to the primary vertex (PV), $|z_{\text{track}} - z_{\text{PV}}| < 2 \text{ mm}$, where z_{track} and z_{PV} are the absolute z coordinate of the track and of the primary vertex, respectively.
- The track is required to point to the PV in the plane containing the beam axis by $|z_{\text{PV}} \cdot \sin(\theta)| < 1.5 \text{ mm}$, where θ is the angle between the track and the beam axis.
- The distance of minimum approach of the track to the primary vertex in the plane orthogonal to the beam axis is required to be $d_{\text{PV}} < 1.5 \text{ mm}$.
- At least one pixel hit and at least 6 SCT hits (including SCT holes) should be detected for each track.
- A b-layer hit should be present if the b-layer module passed by the track was active.
- The pseudorapidity of the track is required to be $|\eta| < 2.5$, corresponding to the coverage of the inner detector.
- The track transverse momentum should be $p_T > 300 \text{ MeV}$ to ensure a low track fake rate.

A track-jet is seeded by a cluster of at least two tracks which satisfy the above selection criteria, the sum of the transverse momenta of all associated tracks is required to be $\sum_i p_{T,i} > 2 \text{ GeV}$. It has been shown that the above selection criteria, together with a maximum cone size for clustering of $\Delta R = 0.6$, give the best compromise between the power of rejecting fake tracks and the b-hadron reconstruction efficiency. Several simulation samples have been produced to study the performance of the track-jets reconstruction and of the b-tagging procedure

Process	MC Generator	Purpose
Minimum bias	Pythia	Systematics study
$b\bar{b}$	Alpgen	Performance for low p_T b-tagging
$Z/\gamma^* \rightarrow \tau\tau$	Pythia	Impact on the MSSM Higgs search
$t\bar{t}$	MC@NLO	Impact on the MSSM Higgs search
MSSM $bb/A/h/H$	Sherpa	Impact on the MSSM Higgs search

Table 6.1: Monte Carlo simulation samples.

applied to these jets. Table 6.1 gives a list of the produced samples along with the type of studies performed with them.

B-tagging has never been tested before on track-jets, in section 6.2 the first study of b-tagging over track-jets performances is reported.

6.2 Performance of the Track-based Jets Reconstruction and b-tagging

6.2.1 Track-based Jets Reconstruction

Many analyses could profit from an enhanced b-jet reconstruction efficiency at low values of p_T . The studies presented in this section are aimed at comparing the performance of the b-jet reconstruction efficiency and the common b-tagging algorithm for the calorimeter and track-based jets, focusing in particular on jets with low transverse momenta.

Even though the track-jets are more robust against pile-up effects, which is the main reason for not using calorimeter jets at low transverse momenta, they contain only the charged fraction of the jet, while the neutral jet component is lost. According to isospin invariance the expected charged fraction in a jet amounts to roughly 2/3 of the total energy. The track-jet momentum is therefore shifted accordingly and there is a larger uncertainty on its measured direction. Figure 6.2 shows the distribution of transverse momentum residual $p_{T\text{true}} - p_{T\text{jet}}$ relative to the truth value $p_{T\text{true}}$ from *truth-jet* (see chapter 4) separately for calorimeter and track-jets. Here truth-jets are matched with reconstructed jets within a cone of size $\Delta R = 0.4$ ¹. As expected the track-jets energy is shifted from zero. This effect can be critical for most of the b-tagging algorithms since the likelihood func-

¹jet splitting effects are resolved by matching with the nearest jet

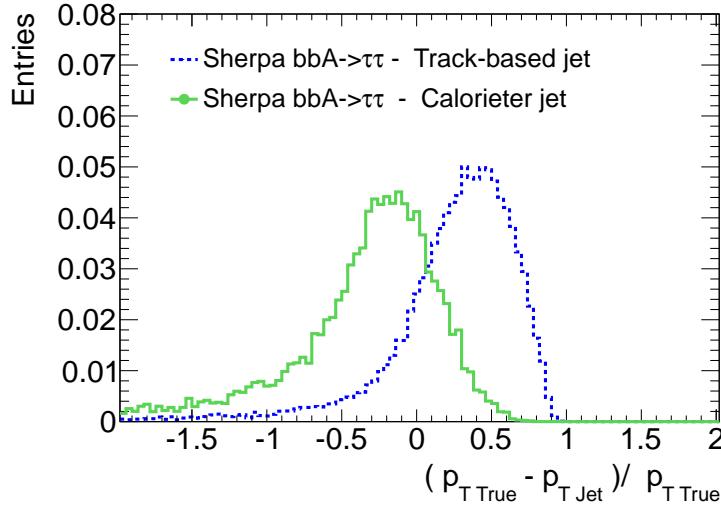


Figure 6.2: Distribution of transverse momentum residuals relative to the true value $P_{T\,true}$, shown separately for the calorimeter and track-jets.

tions used for decision making are derived separately for different region of jets p_T and pseudorapidity. A dedicated track-jets calibration of b-tagging algorithm is auspucable for future application of b-tagging on these jets.

To compare the performance of calorimeter and track-jet reconstruction, an anti- k_t algorithm with cone size of $\Delta R = 0.4$ is chosen. If the angular distance between the reconstructed jets and a simulated b-hadron in the event is $\Delta R < 0.3$, this jet is said to *match* with a b-hadron. b-hadron *Reconstruction efficiency* is then defined as the ratio between the number of matched b-hadrons and the total number of b-hadrons within inner detector acceptance. Figure 6.3 shows the b-hadron reconstruction efficiency for the calorimeter and track-jets. The latter exhibit a higher reconstruction efficiency at low transverse momenta due to their robustness against pile-up effects.

6.2.2 B-tagging with Track-Based Jets

Performance of the b-tagging algorithms is usually described in terms of the b-tagging efficiency and rejection power against misidentified jets. The *b-tagging efficiency* is the fraction of jets matched to a true b-hadron which pass a given tagging selection criteria, i.e. which are *b-tagged*. The *rejection power* is the inverse of the misidentification rate, i.e. the inverse of the fraction of jets which are not matched with a b-hadron or c-hadron, but are b-tagged. Figure 6.4 shows the

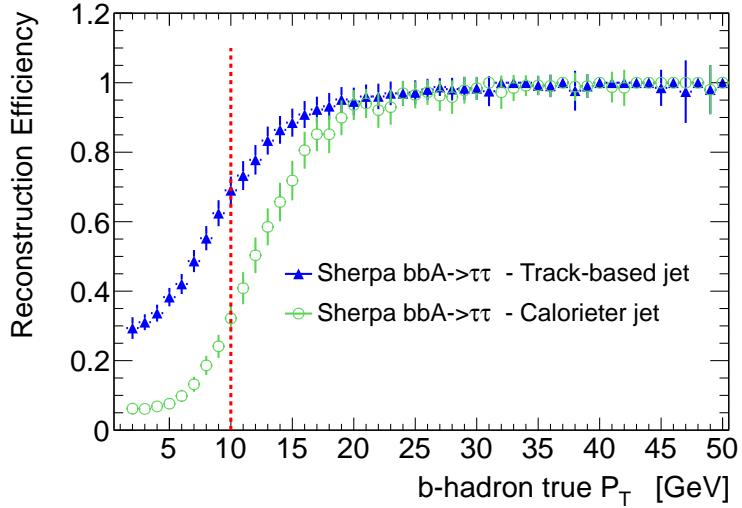


Figure 6.3: b-hadron reconstruction efficiency for track-jet and calorimeter jets as a function of the true b-hadron p_T . Note that calorimeter and track-based jet are required to have at reconstruction level $p_T > 7$ and 2 GeV, respectively. A fair comparison in this plot is only possible for $p_T > 10$ GeV.

rejection power as a function of the b-tagging efficiency for various b-tagging algorithms applied on track-jets and calorimeter jets separately. Figure 6.5 shows the rejection power as a function of jet p_T for the b-tagging working point which gives 50% b-tagging efficiency, calorimeter and track-based jet are shown separately. Mistagging rate is rapidly increasing for low transverse momentum jets due to increasing particle multiple scattering and secondary interactions in the material, revealing the necessity of a dedicated b-tagging algorithm for low p_T jets.

The described rejection power and b-tagging efficiency cannot serve for a fair comparison of the track-based and calorimeter jets. The latter can be reconstructed even if there are no associated tracks to them, in which case any b-tagging algorithm will most likely fail. The distribution of the rejection power is therefore altered by such jets. It is instead convenient to introduce the: *effective rejection power*, which is the inverse of the number of mistagged jets per event. Figure 6.6 shows the effective rejection power as a function of the b-hadron reconstruction efficiency, for calorimeter and track-based jets. For a given b-hadron reconstruction efficiency, a higher effective rejection of mistagged jets can be achieved by track-jets. For a fair comparison with calojets the track-jets in Figure 6.6 are selected in the transverse momentum range between 4 and 33 GeV, while the transverse momen-

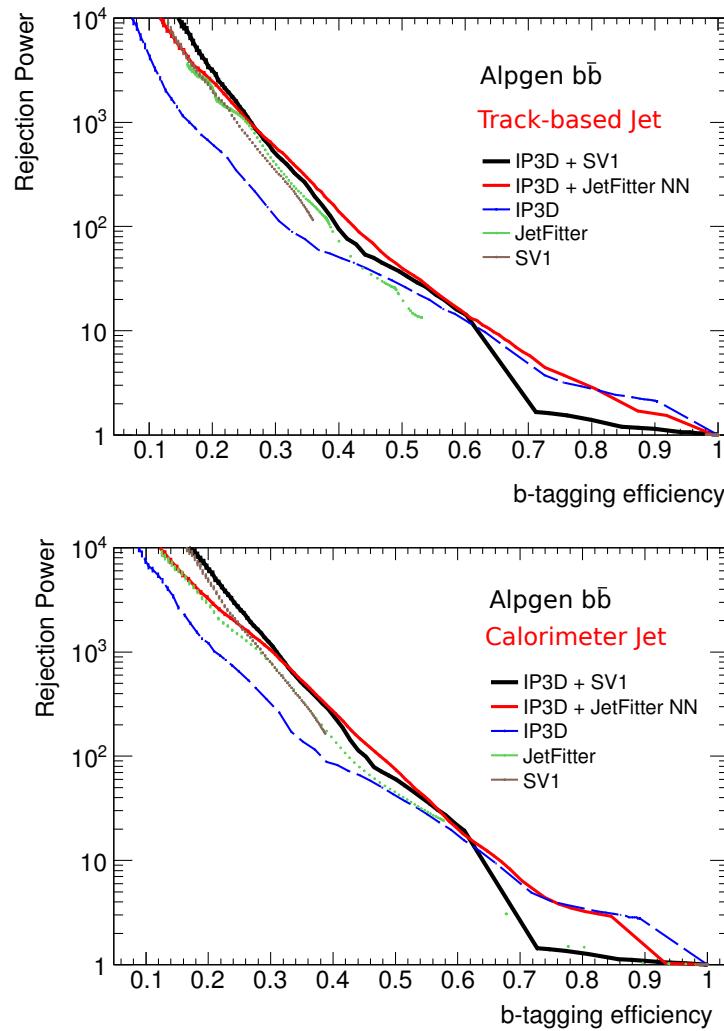


Figure 6.4: Rejection power as a function of the b-tagging efficiency for different b-tagging algorithm applied on track-jets (top) and on calorimeter jet (bottom) for simulated $b\bar{b}$ events.

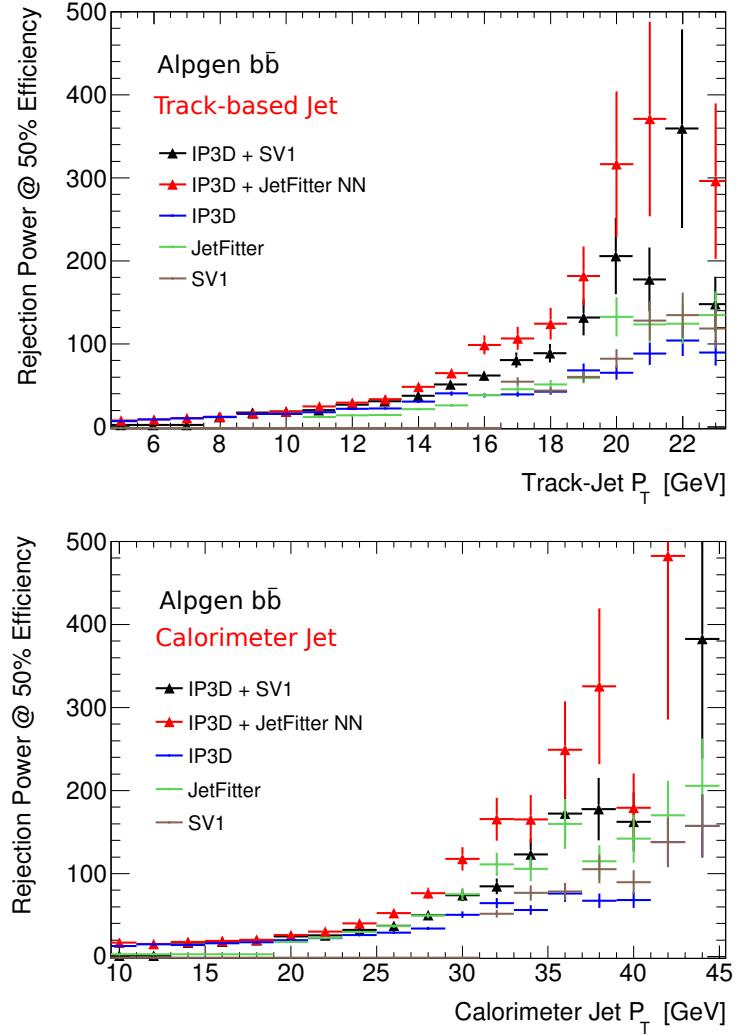


Figure 6.5: Rejection power as a function of the jet transverse momentum for the b-agging working point whita 50% b-tagging efficiency at that p_T value, track-jet (top) and calorimeter jet (bottom) are shown separately. Results are obtained using simulated $b\bar{b}$ events and shown for several b-tagging algorithms.

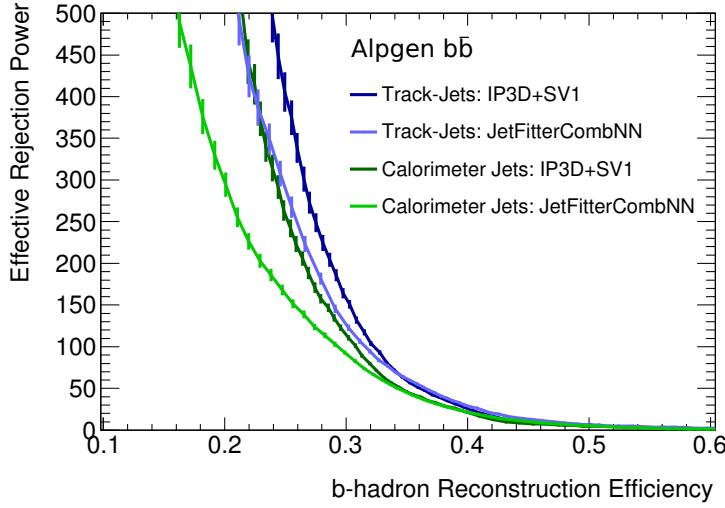


Figure 6.6: Effective rejection as a function of b-hadron reconstruction efficiency, track-jet and calo jets are compared for two different ATLAS tagging algorithms. Track-jets are selected in the transverse momentum range between 4 and 33 GeV, while calojets between 8 and 50 GeV.

tum of calorimeter jets ranges from 8 to 50 GeV. The introduced p_T -thresholds corresponds in average to the same p_T range, Figure 6.2 is only valid for low p_T jets and the fraction of undetected momentum from neutral jet component approaches 1/3 for higher p_T track-jets. In conclusion, for jets with low transverse momentum the track-jets provide a higher b-hadron reconstruction efficiency than calorimeter jets and are more suitable for low p_T b-tagging.

6.2.3 Employment of Track-jet for the MSSM Higgs Boson Search

The impact of the track-jets selection on the search for the neutral MSSM Higgs bosons is tested in a preliminary study and reported in the following. Common selection criteria,², as defined in Section 5.2.1, are applied to simulated signal and background samples with the following modifications concerning the jets on which b-tagging procedure is applied (taggable jets):

- Calorimeter jets should have $|\eta| < 2.5$ and $20 < p_T < 50$ GeV.

²This study has not been updated with the latest version of the object reconstruction selections and corrections, a difference of the order of 10% is expected with respect the numbers in table 5.4.

- Track-jets should have $|\eta| < 2.5$ and $5 < p_T < 33$ GeV.
- The b-tagging algorithm applied on the above jets is "IP3D+SV1" at a working point with a $\epsilon_b^{t\bar{t}} = 70\%$ tagging efficiency.

The minimum transverse momentum for which calorimeter jet are calibrated is 20 GeV, track-jets instead can safely access transverse momentum up to 5 GeV. The event yields expected for the $pp \rightarrow b(b)A/h/H$ signal process, $Z/\gamma^* \rightarrow \tau\tau$ and $t\bar{t}$ background processes (the two most important background contributions in the b-taged event category) are reported in Table 6.2. The yields are normalized to an integrated luminosity of $1 fb^{-1}$. In addition to the event yields after the common selection stage other b-tagging related selection requirements are applied to study the impact of the replacement of calorimeter with track-based jets. As expected, after requiring exactly one b-tagged jet, the track-jets reconstruction results in a higher signal efficiency with a relatively similar rejection (10% higher) of top quark background compared to calorimeter-based jet reconstruction. However, lower transverse momentum threshold for the track-jets implies higher mistagging rates, as can be seen from an increase of $Z/\gamma^* \rightarrow \tau\tau$ background. This may also lead to a strong contamination of the QCD multi-jet background, even tough this is a minor background contribution in b-taged event category.

In conclusion, the neutral MSSM Higgs boson search presented in the previous chapter may be improved if track-jet reconstruction is applied instead of calorimeter based one. The sensitivity³ to the signal can be improved in this event category by about a factor two. However, to exploit the full power of this technique a dedicated calibration of the b-tagging algorithms is needed for the track-jets. Additional improvements of the b-tagging algorithms for low p_T b-jets are also desirable. Furthermore, systematic uncertainties of track-jet reconstruction need to be evaluated. A preliminary study, addressing some of the most important of such systematic uncertainies is reported in section 6.3.

³Note that the sensitivity is estimate according to the s/\sqrt{b} ratio (where s and b are the signal and background yield respectively), considering a counting experiment without systematic uncertainties and with only two background processes, this corresponds to the maximal possible sensitivity achievable with the current b-tagging performance.

Selection	Signal $bbA/H/h$		$Z/\gamma^* \rightarrow \tau\tau$		$t\bar{t}$	
Common Selection	127.2 ± 2.2		3017 ± 8		2066 ± 5	
	Calo. jet	Track-jet	Calo. jet	Track-jet	Calo. jet	Track-jet
At least one tagable jet	47.3 ± 0.8	106.9 ± 1.8	1146 ± 3	2513 ± 7	1804 ± 4	2014 ± 5
Exactly one jet matched to a b-hadron	18.4 ± 0.3	46.7 ± 0.8	4.5 ± 0.3	18.2 ± 0.5	1054 ± 3	959.1 ± 2.3
Exactly one b-tagged jet	10.2 ± 0.1	21.0 ± 0.6	37.3 ± 0.5	107 ± 1	777 ± 4	630 ± 4

Table 6.2: Event yield for the signal and dominant background processes after different event selection requirements. The yields are shown separately for the calorimeter and the track-based jet reconstruction. The Higgs boson produced in association with b-quarks is simulated for $\tan\beta = 20$ and $m_A = 150$ GeV. The yields are normalized to an integrated luminosity of $1 fb^{-1}$.

6.3 Systematic Uncertainties of Track-jet Reconstruction

There are several sources of systematic uncertainties of the track-jet reconstruction that may contribute to the mismodeling of physics observables. These effects are briefly summarized in the following with an emphasis on uncertainties of the energy scale and reconstruction efficiency.

Uncertainty on the properties of simulated track-jets can arise from the Monte Carlo generator configurations, depending on the particular choice of PDF and fragmentation functions, or details of the parton shower and underlying event modeling, which have a significant impact on physics objects with low transverse momentum. These uncertainties can be evaluated by means of a dedicated analysis with the Rivet package [141]. They depend on the particular use of track-jets and need to be evaluated case by case.

Energy scale and resolution of single tracks is found to be very well modeled by simulation for tracks above 500 MeV [151]. Thus, uncertainty on the track-jet energy scale and resolution that arise from the mismodeling of the pattern recognition procedure are considered to be negligible.

In a dense track environment different tracks may share same hits, leading to a degradation of the track momentum resolution, fake tracks and losses of track reconstruction efficiency. Mismodeling of the hit sharing among several tracks may in general affect the track-jet energy scale, resolution and reconstruction efficiency. Such effects has been studied in [153], where energy scale uncertainties for calorimeter jets is measured based on associated tracks. It has been shown that effects due to the merging of track hits are negligible for jets with $p_T < 300$ GeV.

Mismodeling of the inner detector material budget leads to the mismodeling of the track reconstruction efficiency, which strongly affects also the track-jets reconstruction. A methodology to estimate the uncertainty of the energy scale and reconstruction efficiency for track-jets due to the mismodelling of the material budget is studied for the first time and presented in section 6.3.1.

6.3.1 Material Budget Uncertainty on Track-Based Jets Reconstruction

An obvious but rather inconvenient way to estimate the uncertainty due to the mismodeling of the inner detector material budget is to simulate the Monte Carlo samples relevant for a given analysis using several different ID material budgets. It

can be shown that the mismodeling of material budget primarily influence the track reconstruction efficiency (see section 6.3.2). An alternative approach is therefore to modify the track reconstruction efficiency in a given sample according to the corresponding uncertainty [152, 154] and build track-jets from such new collection of tracks. A tool has been developed which randomly removes tracks according to the uncertainty on reconstruction efficiency. The track-jets which are build from this subset of tracks are called in the following *inefficient* track-jets.

The standard and inefficient track-jets are compared in a simulated sample of minimum bias processes. A set of "isolated" track-jet with cone size $\Delta R = 0.4$ are selected, where the isolation means that no other track-jet should be reconstructed within an angular distance of $\Delta R = 1$. Inefficient track-jets are then matched with the original track-jet in the same event, the matching fails if no inefficient track-jet is found within a cone of size $\Delta R = 0.8$ around the original track-jet. The impact of tracking inefficiency on track-jet energy scale and reconstruction efficiency is presented respectively in Figure 6.7 and 6.8. These results are based on the current knowledge of the inner detector material budget [152]. Since track-jets are required to have at least two tracks at reconstruction level, if a track is lost that jet cannot be reconstructed anylonger, therefore for track-jet with two tracks the only effect is a loss of reconstruction efficiency. For track-jets with low transverse momentum, uncertainty on the material budget translates into an energy scale shift of 2-4% and in a reduction of the mean number of tracks.

This method can only simulate excess of material (reduced track efficiency) but not a lack of material (increased track efficiency). However, for the latter case a symilar, symmetric impact is expected.

6.3.2 Validation of the Track Subtraction Method

The method described in section 6.3.1 depends strongly on the assumption that hadronic secondary interactions within the inner detector material lead manly to the loss of some tracks and only in a marginal way to a decrease of the track quality. As a consequence, the misodeling of the material budget is expected to influence mainly the track reconstruction efficiency. In this section, the impact of the material budget uncertainty on the track momentum resolution and fake rate is evaluated using a simulated sample of minimum bias events, in which additional material is added to the ID increasing uniformly of 10% the interaction length.

For this study, the track selection is performed as in Section 6.1. Furthermore a

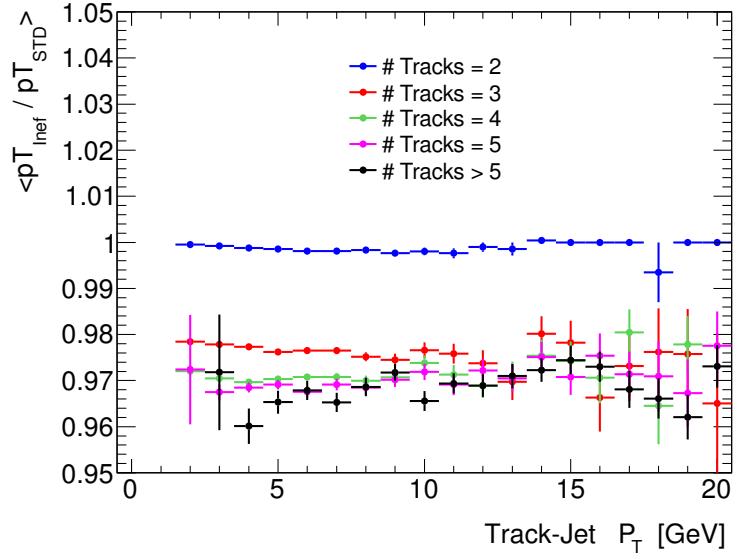


Figure 6.7: Inefficienct track-jets are matched with standard track-jets. The average transverse momenta of the inefficient track-jet $p_{T\,inef}$ relative to the corresponding standard track-jet $p_{T\,std}$ is shown as a function of the p_T and number of associated tracks of the standard track-jet.

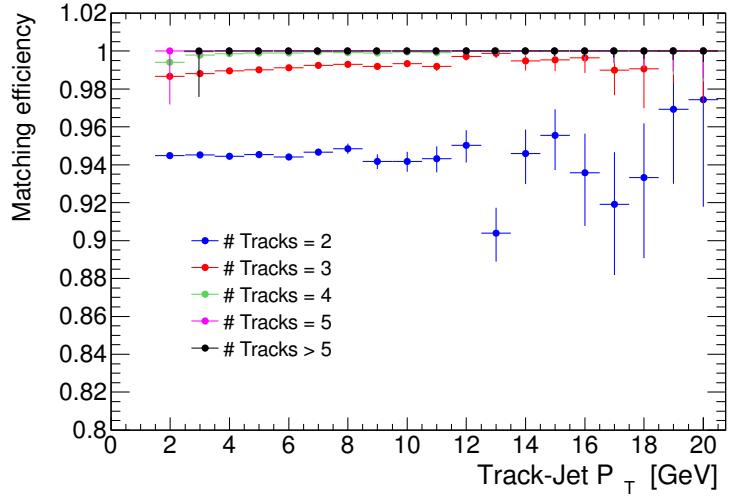


Figure 6.8: Inefficienct track-jets are matched with standard track-jets. The matching efficiency is shown as a function of the p_T and number of tracks associated with the standard track-jet.

track should be matched within a cone $\Delta R < 0.1$ with a stable⁴ simulated particle which alone should be causing at least 80% of all the track hits. Tracks that do not fulfill these requirements are considered as fake tracks. Fake tracks originate from a random combination of hits generated by different particles. The track fake rate defined as the ratio between the number of fake tracks and the total number of selected tracks is about 1-3% and is shown in Figure 6.9. The additional material leads to a total increase of the track fake rate by about one permille. The track energy resolution as shown in Figure 6.10 is about 1% for a large range of track p_T values, the total degradation of the resolution in the presence of additional ID material is also of the order about one permille. The deterioration of the track energy resolution and fake rate due to the additional material budget is therefore negligible compared to the impact on the track reconstruction efficiency of about 1-2%. Decrease in the track reconstruction efficiency has a strong impact on the track-jet energy scale. Figure 6.11 shows the ratio of the track reconstruction efficiency for the primary particles assuming the nominal and additional material budget.

Reconstruction of inefficient track-jets in a sample with nominal material budget is also directly compared to the track-jets reconstruction in a sample with added additional ID material. Track-jet are matched to truth-jet (as described in section 6.2) in order to determine the track-jet reconstruction efficiency and energy scale, shown respectively in Figure 6.12 and 6.13. Inefficient track-jets reproduce correctly the impact of additional material, giving in most of the cases a conservative estimate of the corresponding systematic uncertainties.

⁴This refers to a generator level stable and interacting particle, i.e. a charged particle with decay length greater than 1m. Also stable particles from secondary interactions are considered.

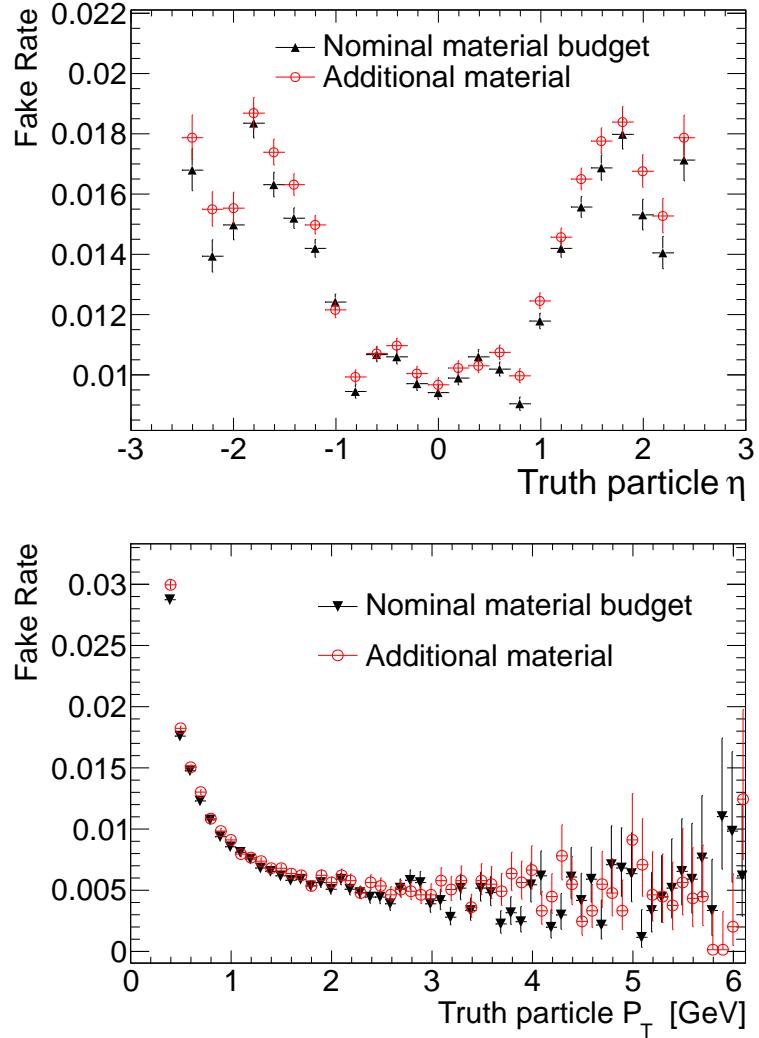


Figure 6.9: Track fake rate as a function of the associated truth particle η (left) and p_T (right). The results are shown for the two simulated samples of minimum bias processes, one with a nominal material budget and one with 10% additional inner detector material.

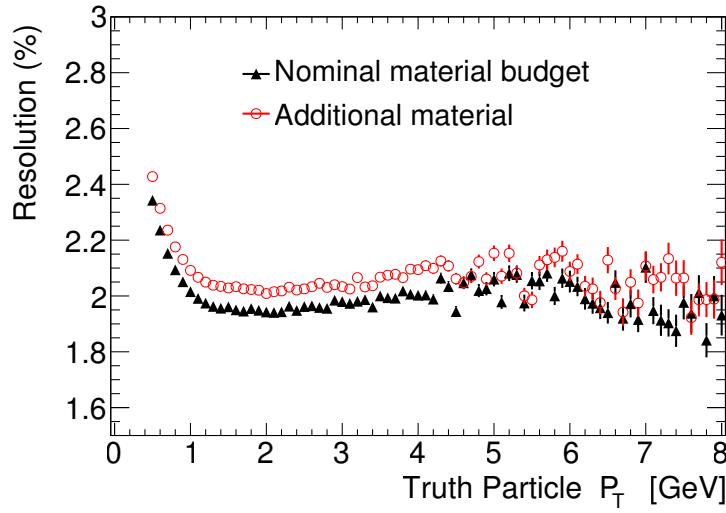


Figure 6.10: Track momentum resolution relative to the matched truth particle as a function of truth particle p_T . The results are shown for the two simulated samples of of minimum bias processes, one with a nominal material budget and one with 10% additional inner detector material.

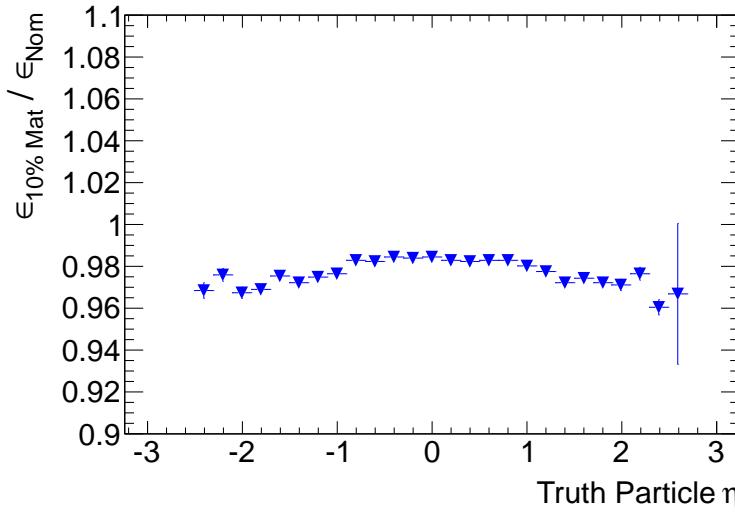


Figure 6.11: Ratio of track reconstruction efficiencies relative to primary truth particles as a function of truth particle η . The ratio is shown for efficiency measured in minimum bias samples with the nominal material budget (ϵ_{Nom}) and in the sample with 10% of additional material ($\epsilon_{10\%Mat}$).

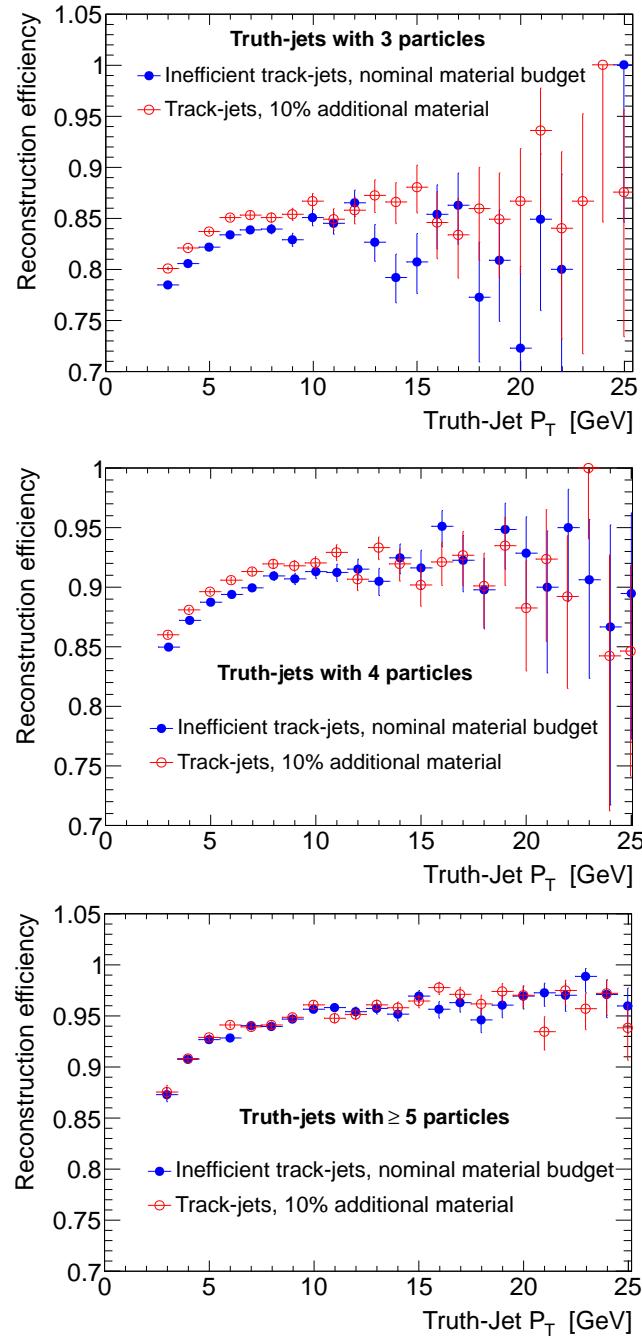


Figure 6.12: Jet reconstruction efficiency relative to truth-jet for inefficient track-jets reconstructed in a minimum bias sample with nominal material budget and for the nominal track-jet reconstruction in a sample with 10% additional material. Result are shown separately for truth-jet consisting of 3,4 and ≥ 5 truth particle.

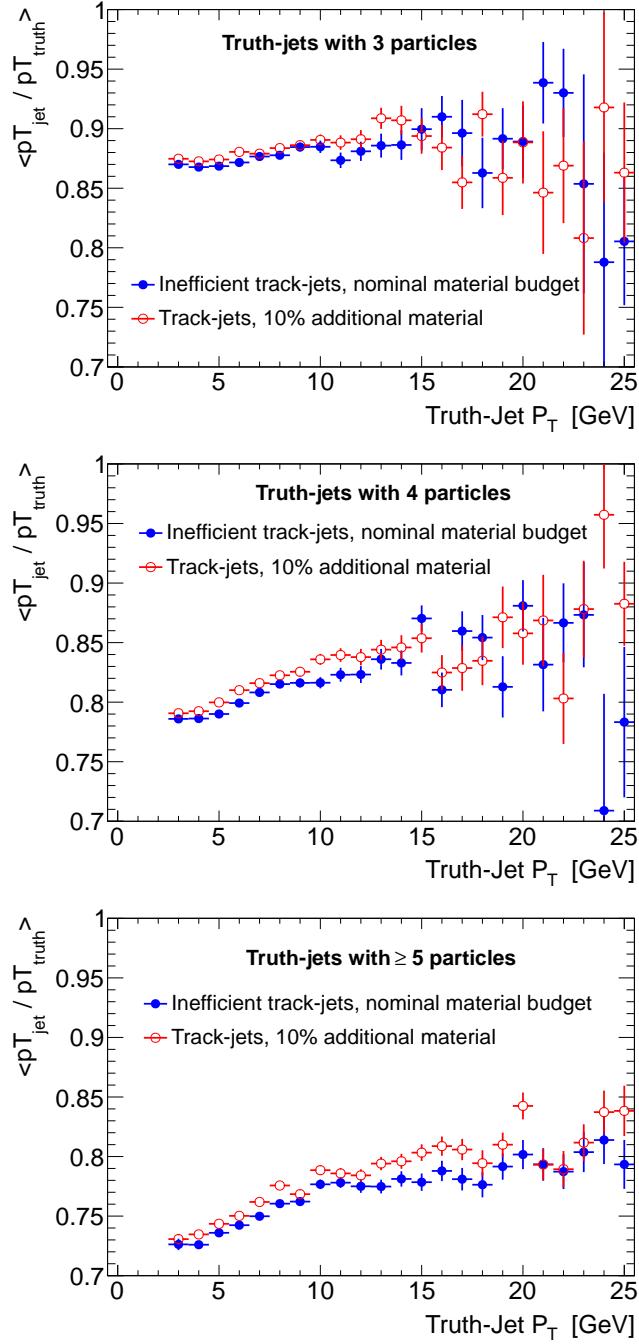


Figure 6.13: Fraction of the jet transverse momentum relative to truth-jet transverse momentum shown for inefficient track-jets reconstructed in a minimum bias sample with nominal material budget and for the nominal track-jet reconstruction in a sample with 10% additional material. Result are shown separately for truth-jet consisting of 3,4 and ≥ 5 truth particle.

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Appendix A

QCD Trigger bias

The single electron trigger (`EF_e24vhi_medium1`) used in this analysis includes the following isolation cut: $p_T(\text{cone})20/p_T < 0.1$. This means that the kinematical distributions in the anti-isolated ABCD regions will be biased due to a reduced efficiency for high p_T electrons. This unwanted feature may potentially effect the R_{QCD} factor, as the OS/SS ratio may differ due to different p_T spectrum. To check the effect on R_{QCD} the ABCD method has been repeated using the `EF_e24vh_medium1` trigger, which doesn't include isolation and hence is prescaled in 2012 8 TeV data. The prescale of a factor around 100 has been taken in consideration using trigger information stored in D3PD. Figure A.1 shows $p_T(\text{cone})$ distribution for the standard and test triggers. The comparable event yields in the region $p_T(\text{cone})20/p_T < 0.1$ show that the prescale normalisation for the test trigger has been correctly accounted for.

Figure A.2 shows the behaviour of R_{QCD} factor as a function of isolation variable for the two triggers under test. As the deviations are within statistical uncertainty, we conclude that the isolation requirement used at trigger level does not influence the OS/SS ratio. Hence no further systematic uncertainty is assigned.

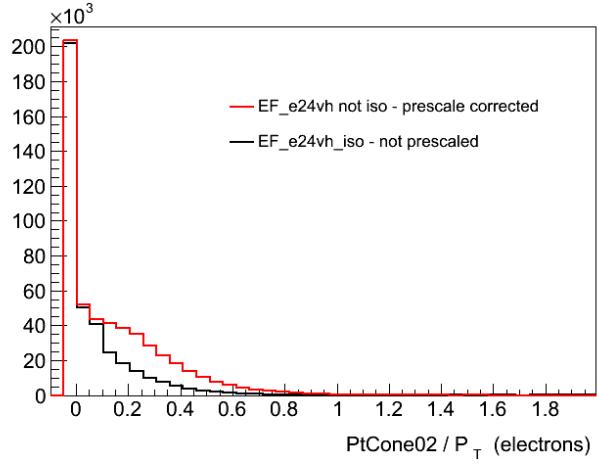


Figure A.1: $p_T(\text{cone}) / p_T$ distribution for the analysis standard trigger and its prospective without isolation requirement, this second trigger is rescaled according to prescales information.

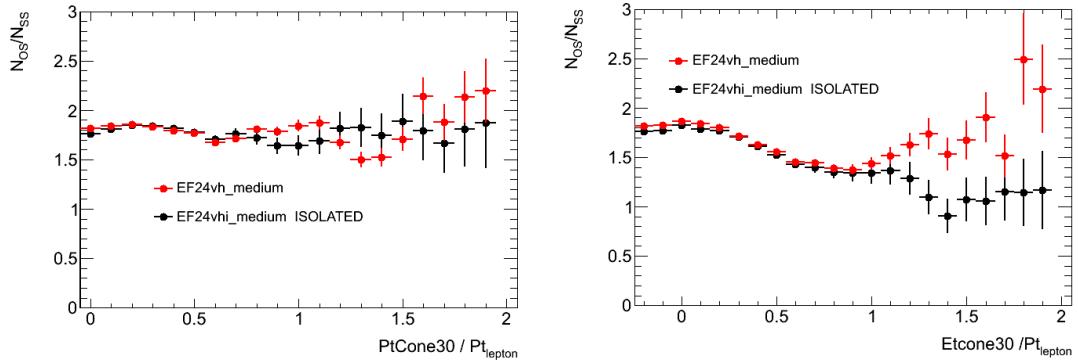


Figure A.2: R_{QCD} as a function of (a) $p_T(\text{cone}) / p_T$ and (b) $E_T(\text{cone}) / \text{PT}$ for the electron triggers with and without isolation requirement.

Appendix B

QCD Additional Plots

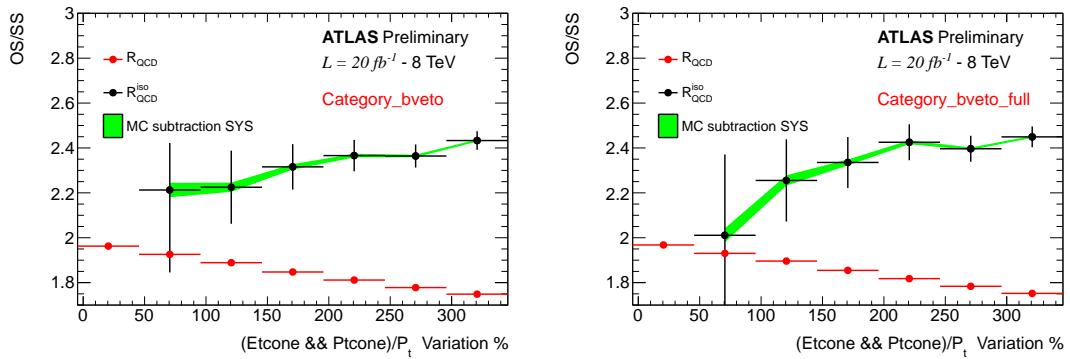


Figure B.1: OS/SS ratio as a function of lepton isolation variable selections (a) after the requirement of zero b-jets and (b) for the full b-veto selection. The isolation selections are varied as a percentage relative to the standard lepton isolation cut values (0 in the plot). The red points show the anti-isolated scale factor R_{QCD} , i.e. the ratio between regions C and D. The black points show the isolated SF, which is defined as the ratio between region \hat{A} and \hat{B} , where the leptons have isolation values larger than the nominal value but smaller than the sliding cut.

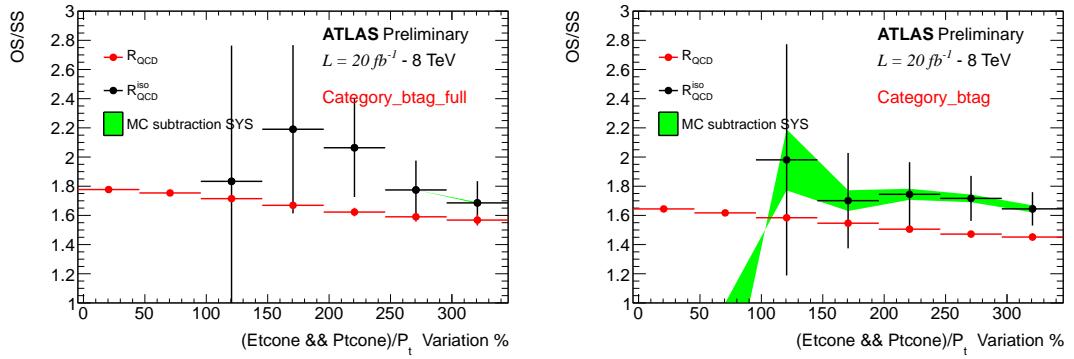


Figure B.2: OS/SS ratio as a function of lepton isolation variable selections (a) after the requirement of one b-jet and (b) for the full b-tag selection. The isolation selections are varied as a percentage relative to the standard lepton isolation cut values (0 in the plot). The red points show the anti-isolated scale factor R_{QCD} , i.e. the ratio between regions C and D. The black points show the isolated SF, which is defined as the ratio between region \hat{A} and \hat{B} , where the leptons have isolation values larger than the nominal value but smaller than the sliding cut.

Appendix C

Limits cross checks and additional plots

C.1 The ABCD Method

The actual implementation in the limit framework of the ABCD method follows that suggested in [136]. The control data samples B,C and D are considered as additional channels to be statistically combined to two the signal event category. Three free parameters are fitted in B,C and D channels which are: the number of multi-jet events in the data sample B, N_B^{QCD} , the factor R_{QCD} and the factor that extrapolates from isolated to anti-isolated data control samples R_{BD} . Neglecting signal contributions, the following equations can be written for the event yield of the B,C and D control data samples:

$$N_B = N_B^{BKG} + N_B^{QCD}$$

$$N_C = N_C^{BKG} + N_B^{QCD} \times R_{QCD} \times R_{BD}$$

$$N_D = N_D^{BKG} + N_B^{QCD} \times R_{BD}$$

where N^{BKG} represent the prediction of non-QCD background in the relative data samples. The estimate of multi-jet event yield in the signal sample will be then $N_B^{QCD} \times R_{QCD}$. This method is particularly powerful because in the best fit of R_{QCD} the statistical and systematics uncertainty for non-QCD backgrounds and data are considered.

C.2 Additional Limit Checks

During the limit derivation, the systematic uncertainties (translated in term of nuisance parameter) are fitted to the data, several checks have been performed to ensure the quality of our statistical model. If some of the nuisance parameters are significantly different from their nominal value (ie before fit), it can be symptomatic of an important mis-modelling and must be carefully scrutinised. Also the correlation between the nuisance parameter and the signal strength (which reflects the degeneracy of the fit) is an important element to keep under control, in fact it reflects how well the data can constraint the nuisance parameters. Finally, to have a feeling of the behaviour of the likelihood at its minimum one can check the negative log likelihood profile in each nuisance parameter direction. We performed all this checks using the package NuisanceCheck-00-00-05 described in [156].

The signal and background model with the signal normalisation free (unconditional fit) is fitted to the data, in the following example plots the signal is assumed for the mass point $m_A = 120$ GeV, $\tan\beta = 20$, The difference between the post fit and pre-fit value of the nuisance parameter along with their errors is shown in figure C.1-C.3, respectively for the b-veto, b-tag channel and the combination between them. Figure C.4-C.6 shows the correlation matrix between the nuisance parameters respectively for the veto category, tag category and the combination between the two channels. Figure C.7-C.9 shows the behaviour of the likelihood at its minimum for each of the nuisance parameters (while a nuisance parameter is investigated the other are kept constant) for the combination between the channels.

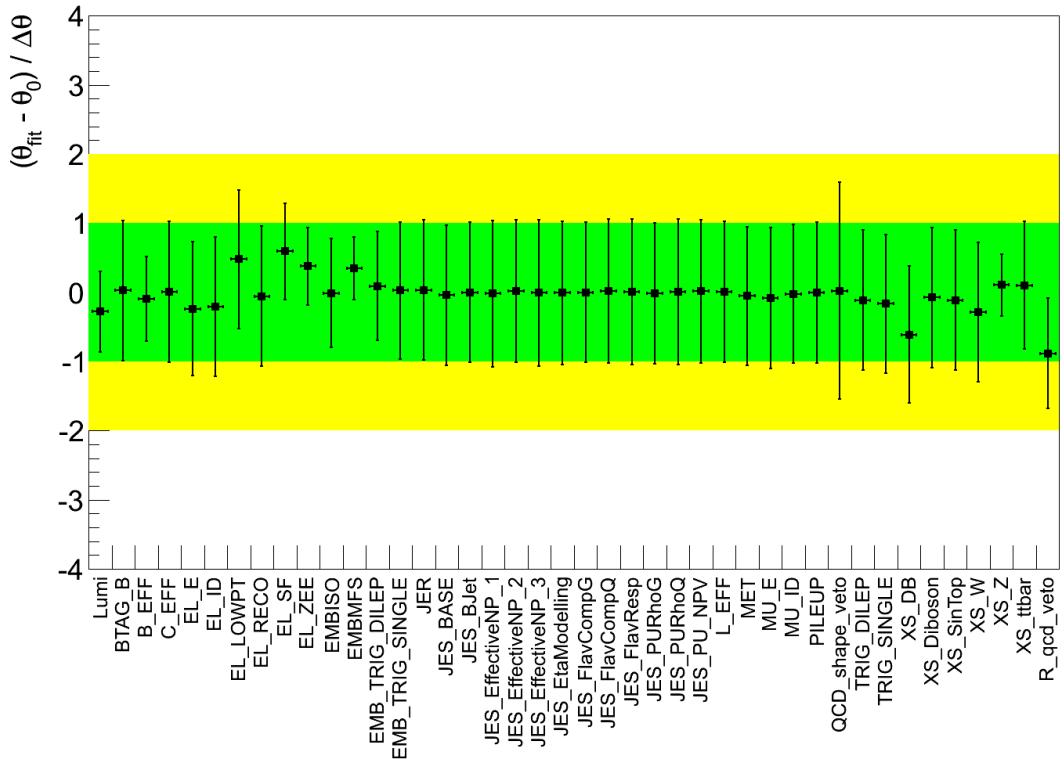


Figure C.1: Pulls for nuisance parameter considered in the fit, mA = 120 GeV, $\tan\beta = 20$, for the veto channel.

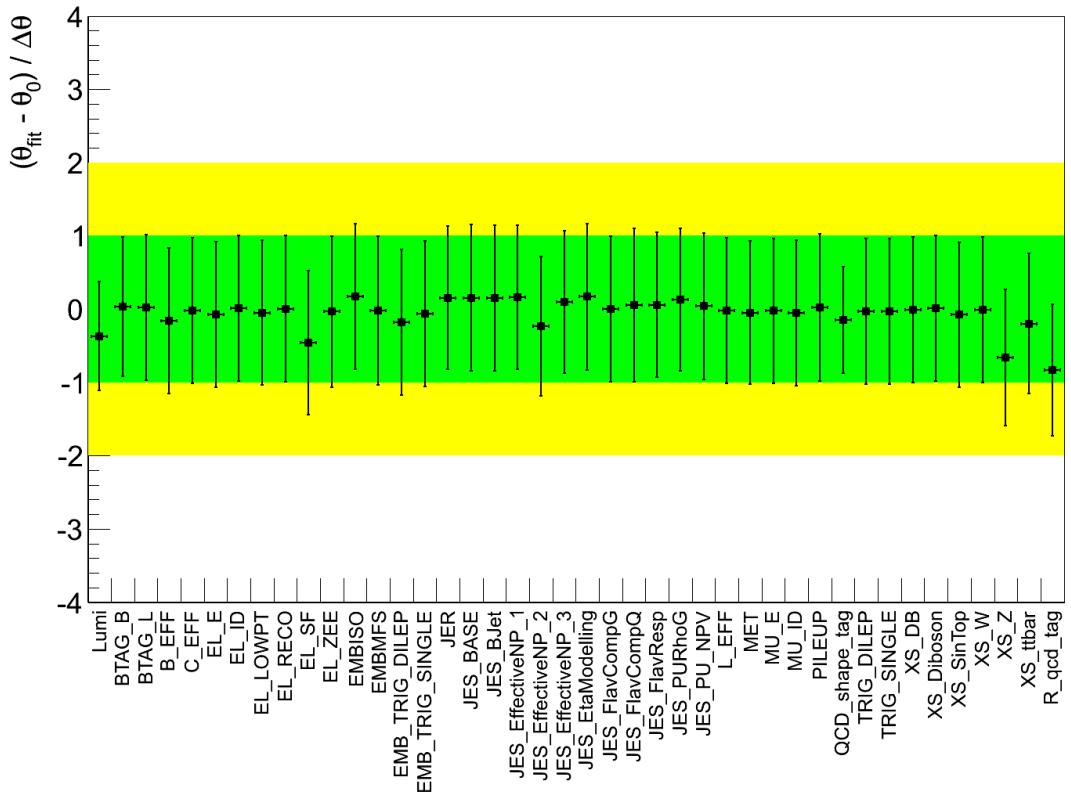


Figure C.2: Pulls for nuisance parameter considered in the fit, mA = 120 GeV, $\tan\beta = 20$, for the tag channel.

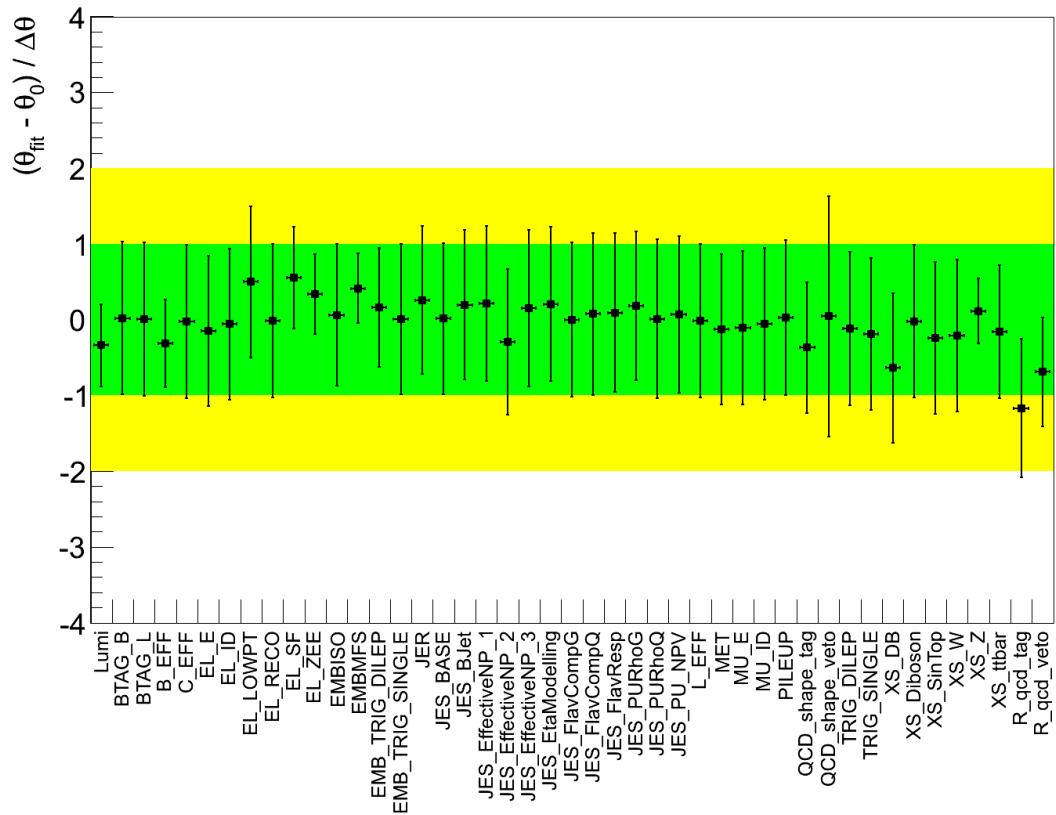


Figure C.3: Pulls for nuisance parameter considered in the fit, mA = 120 GeV, $\tan\beta = 20$, combination between the two channel.

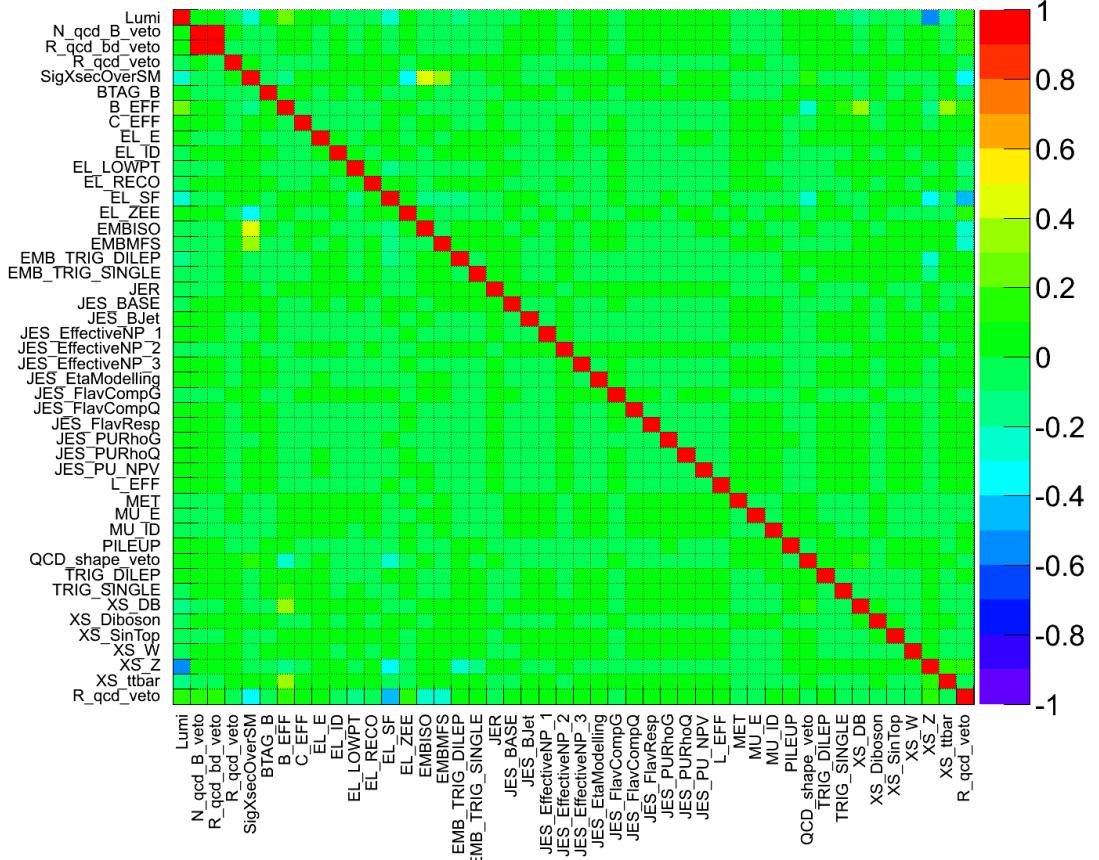


Figure C.4: Correlation matrix for nuisance parameters considered in the fit. The point $m_A = 120$ GeV and $\tan\beta = 20$ is considered for the tag channel.

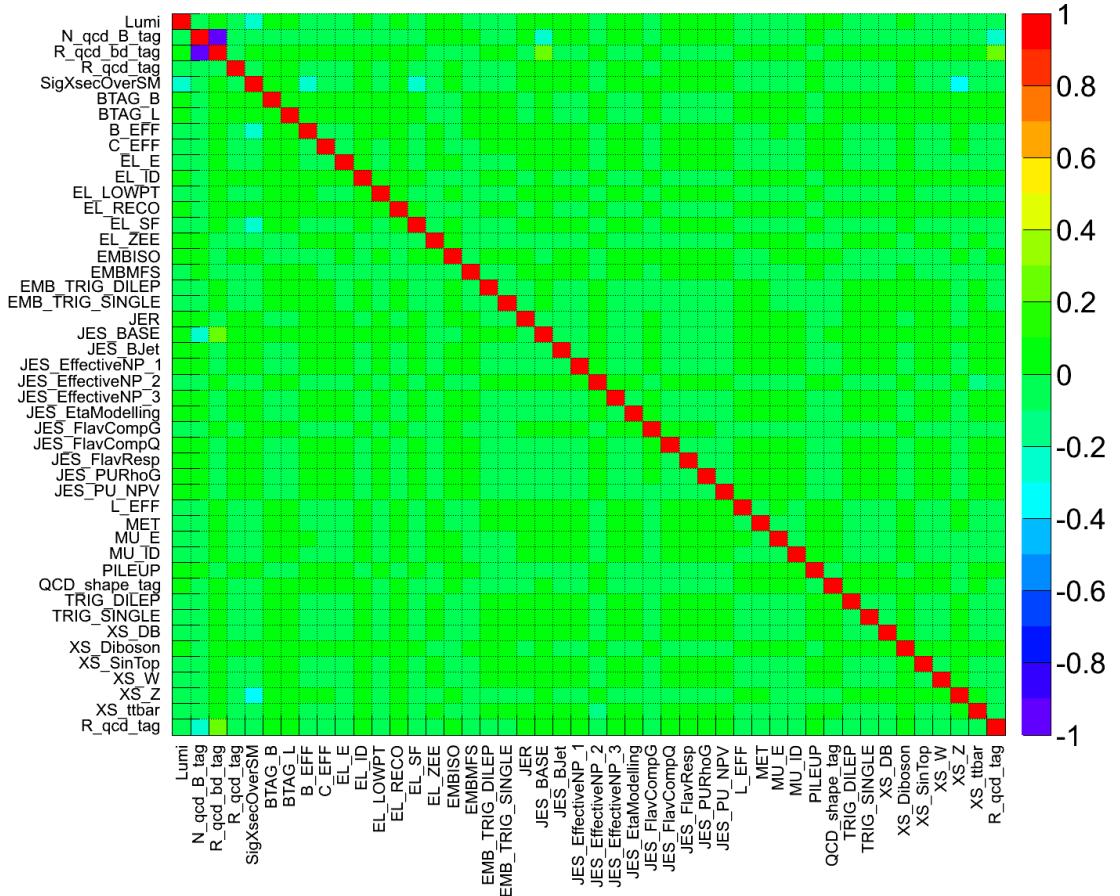


Figure C.5: Correlation matrix for nuisance parameters considered in the fit. The point $m_A = 120$ GeV and $\tan\beta = 20$ is considered for the tag channel.

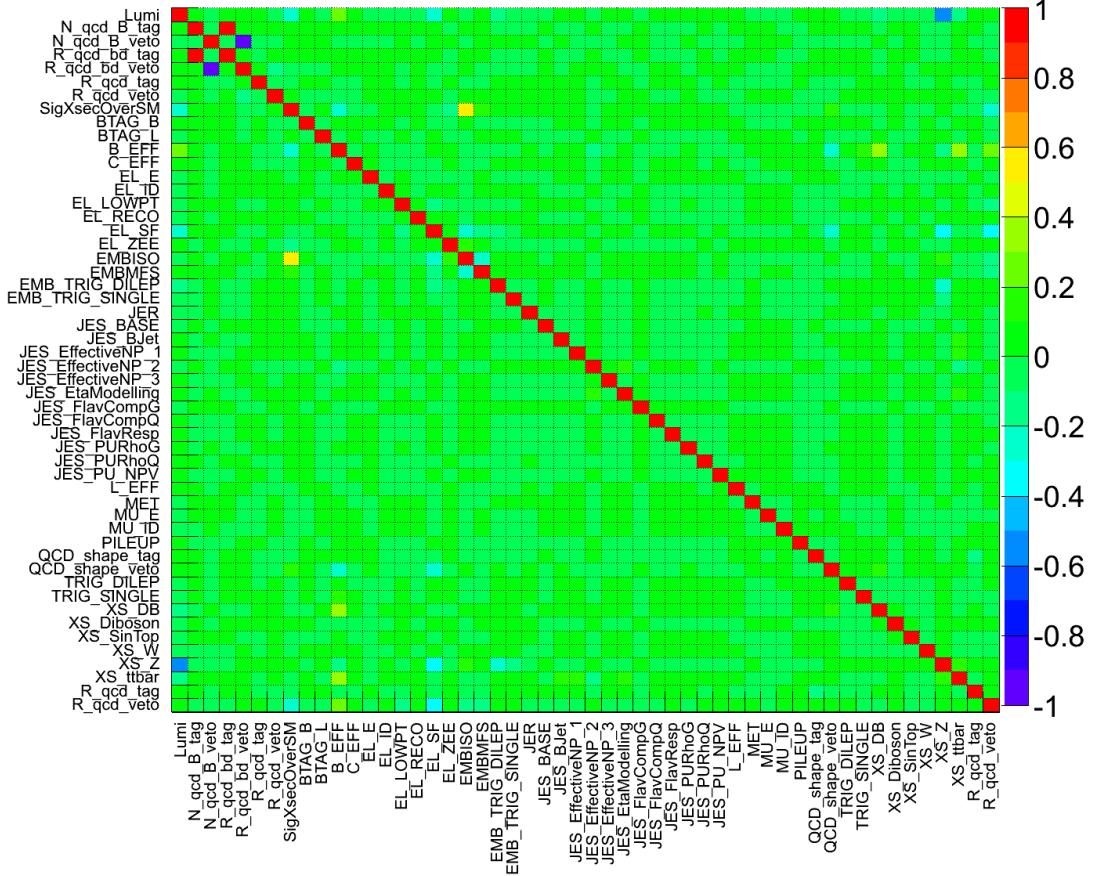


Figure C.6: Correlation matrix for nuisance parameters considered in the fit. The point $m_A = 120$ GeV and $\tan\beta = 20$ is considered for the combination of the b-tag and b-veto channels.

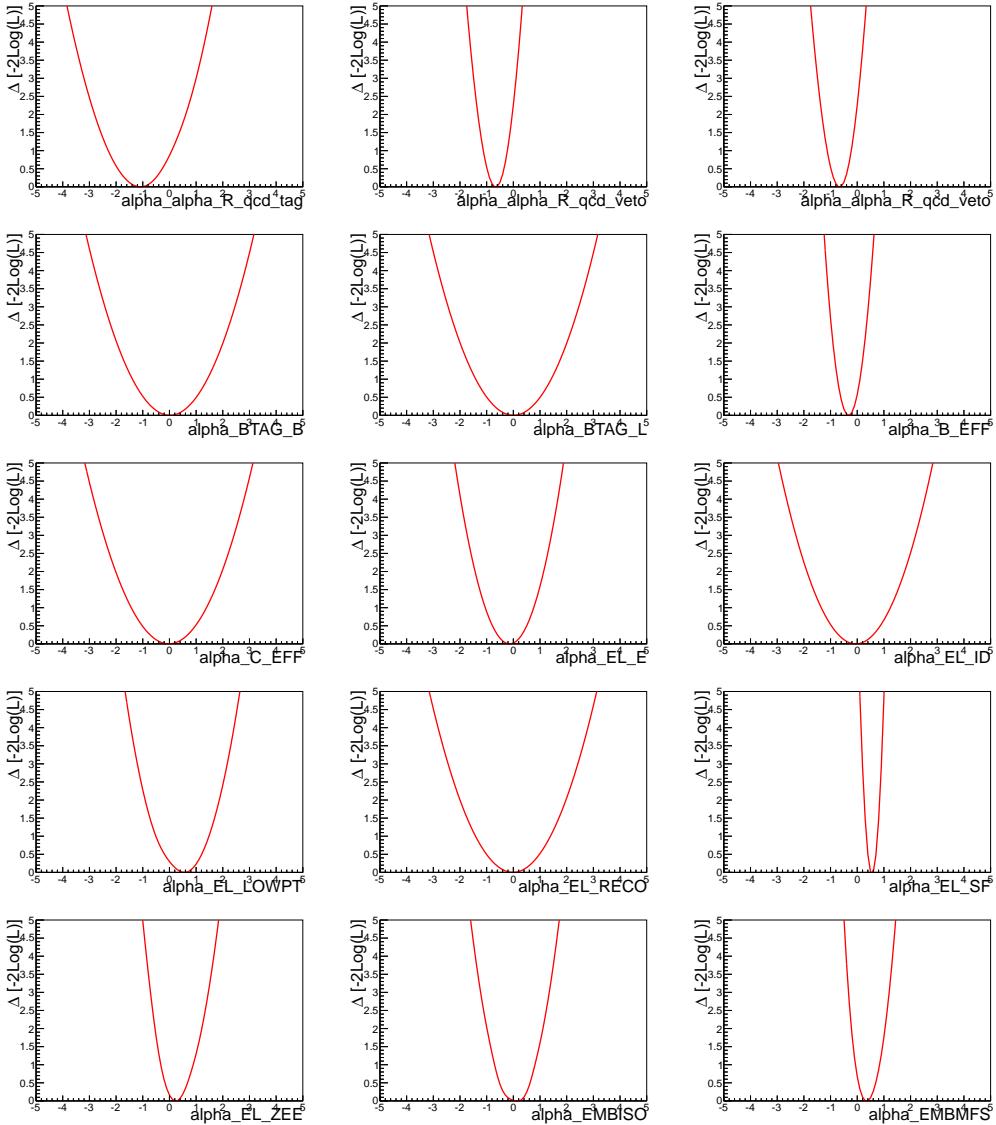


Figure C.7: Likelihood scans for nuisance parameter considered in the fit, mA = 120 GeV, $\tan\beta = 20$, combination between the two channel.

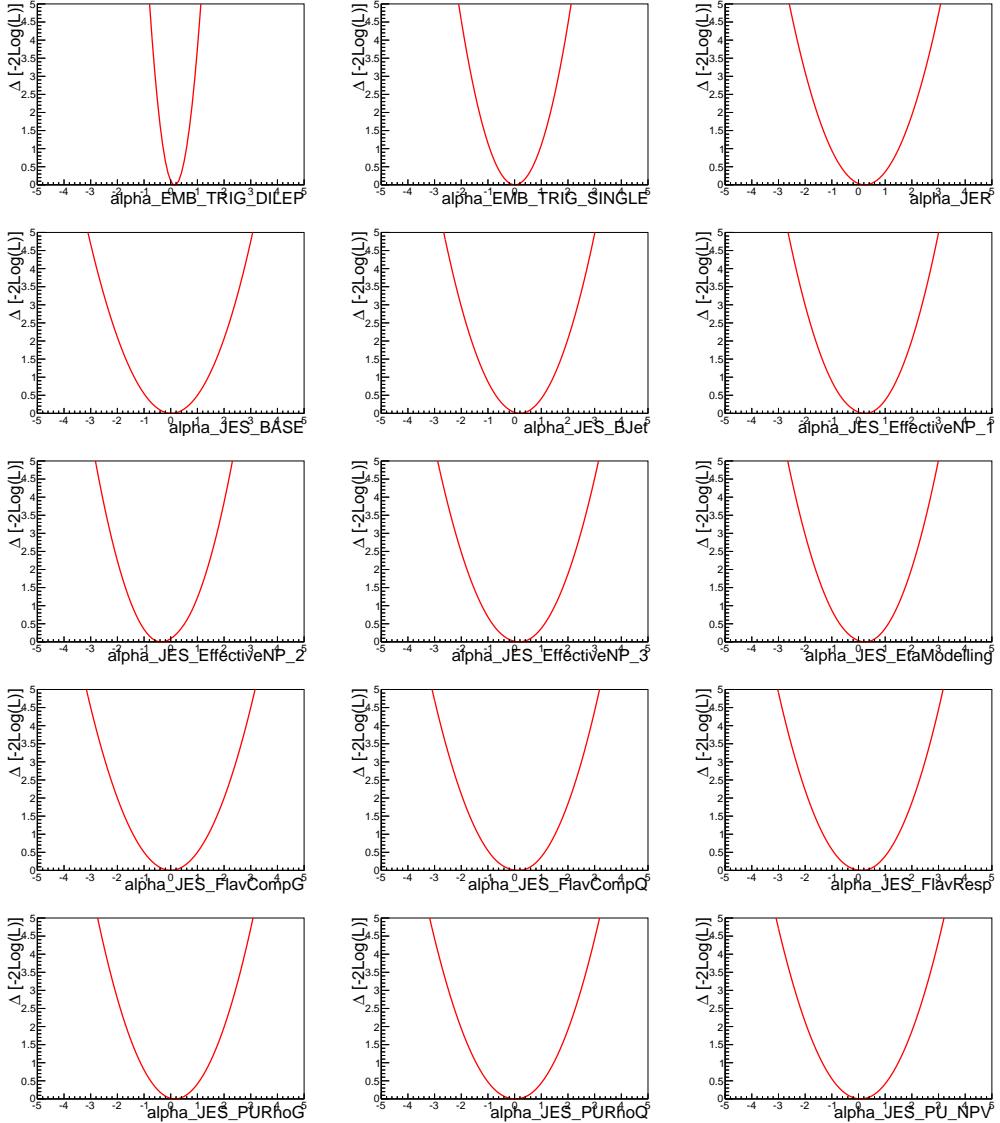


Figure C.8: Likelihood scans for nuisance parameter considered in the fit, mA = 120 GeV, $\tan\beta = 20$, combination between the two channel.

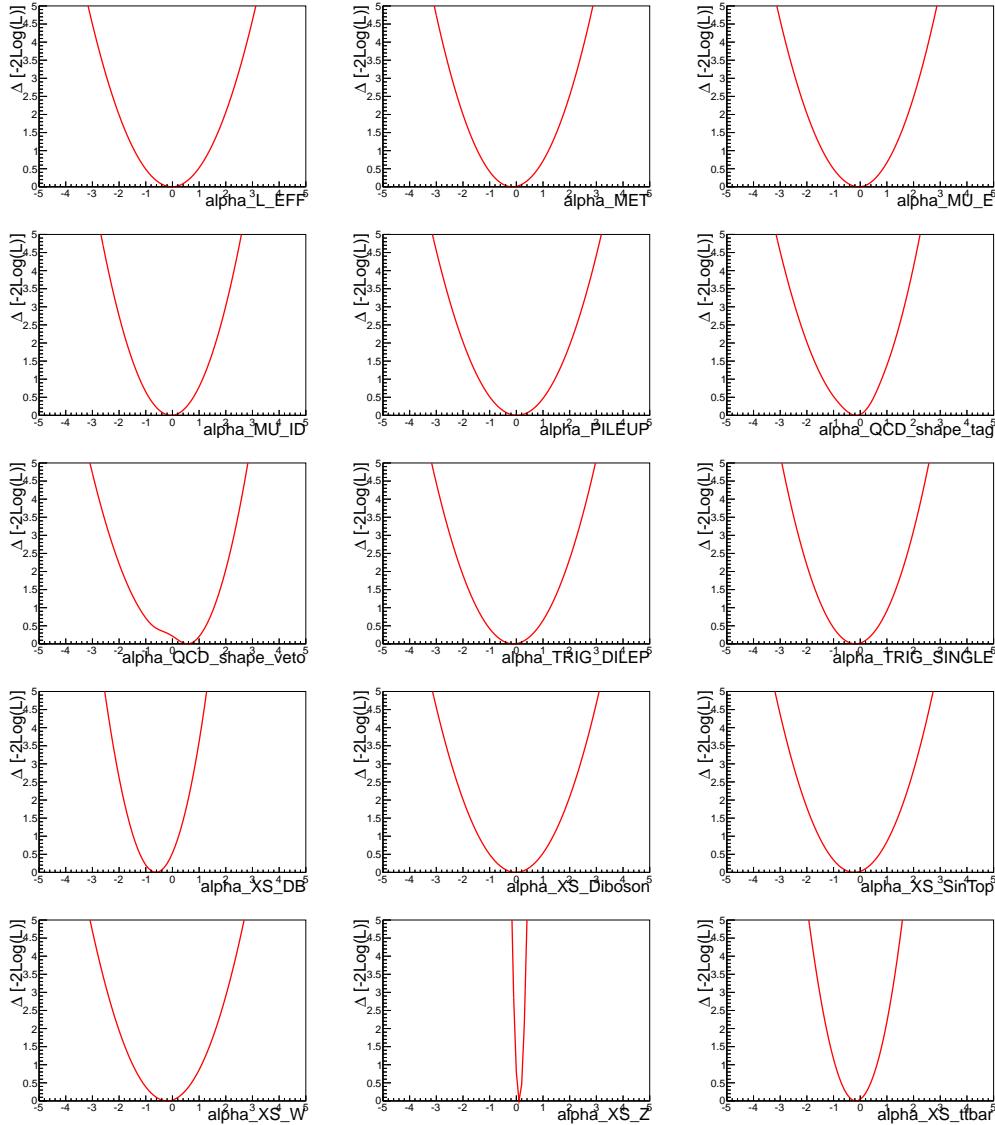


Figure C.9: Likelihood scans for nuisance parameter considered in the fit, mA = 120 GeV, $\tan\beta = 20$, combination between the two channel.

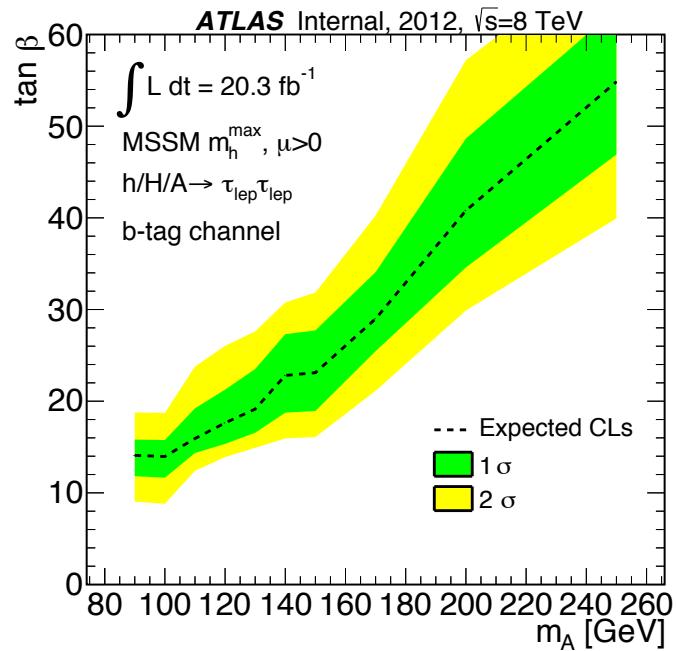


Figure C.10: Expected exclusion limits, using the b-tag channel, for MSSM Higgs boson production in the MSSM m_A vs $\tan \beta$ parameter space.

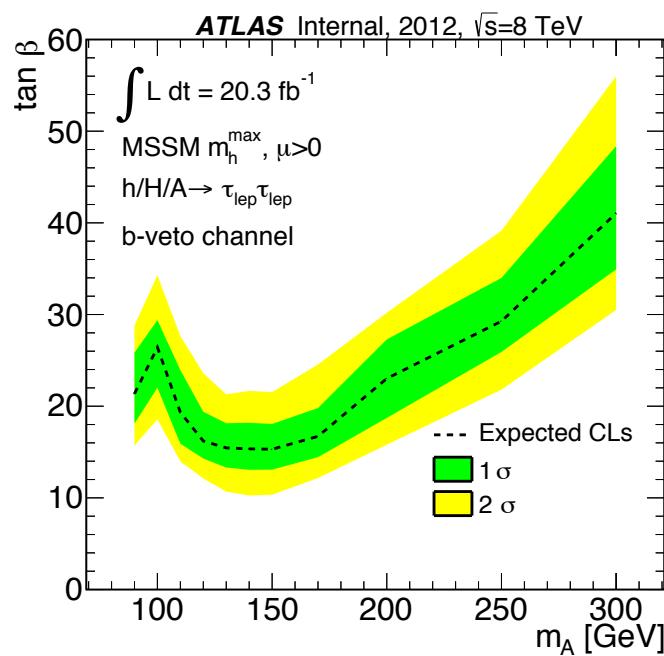


Figure C.11: Expected exclusion limits, using the b-veto channel, for MSSM Higgs boson production in the MSSM m_A vs $\tan \beta$ parameter space.

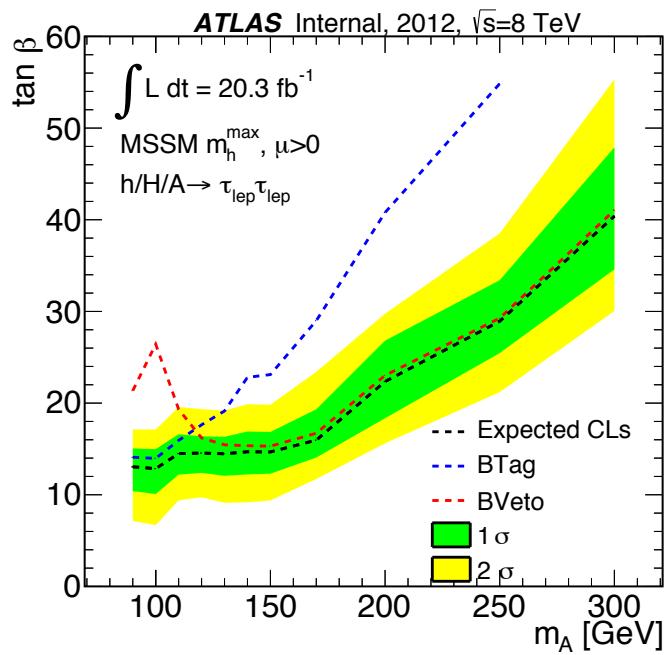


Figure C.12: Expected exclusion limits for MSSM Higgs boson production in the MSSM m_A vs $\tan \beta$ parameter space. Limits are compared for the b-tag and b-veto channel with the combined limit from both channels.

C.3 Shape Systematics

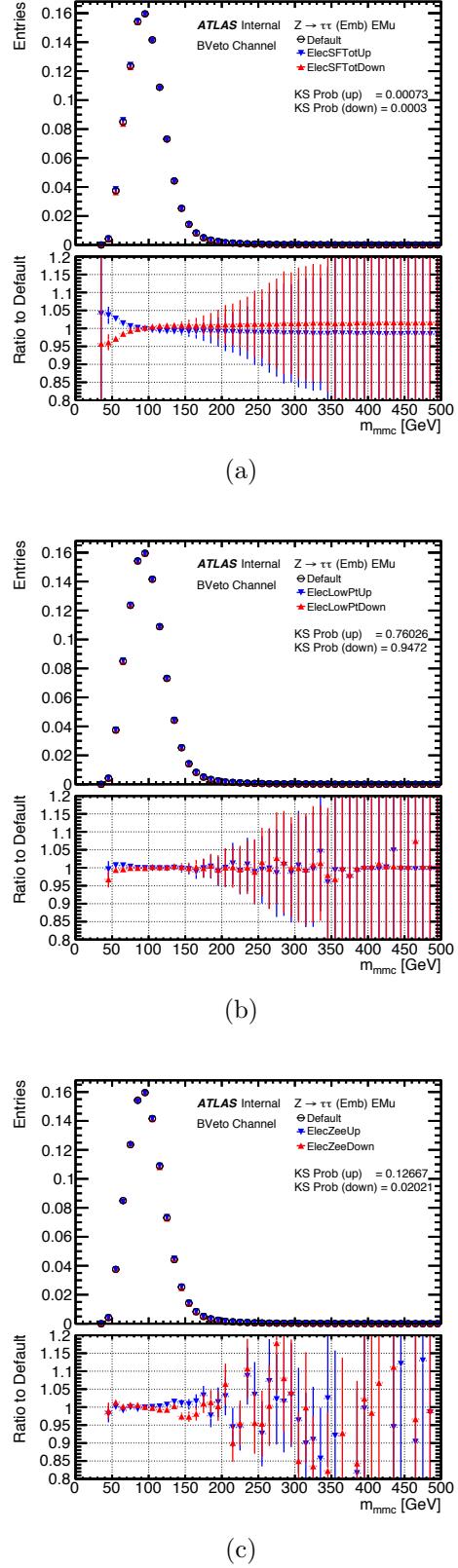


Figure C.13: Effect on the $m_{\tau\tau}^{MMC}$ distribution of the embedding sample due to the (a) the electron reconstruction and identification systematics, (b) the electron low p_T energy scale systematic and (c) the electron Zee energy scale systematic. The plots are made after the full b-veto category selection.