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Chapter 1

Search for neutral MSSM Higgs Bosons in

$A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ decays

In light of the recent discovery of a Higgs boson with mass of ~ 126 GeV at LHC [16, 17], it remains an open question whether this new particle is the only missing piece of the electroweak symmetry breaking sector or whether it is one of several Higgs bosons predicted in some theories that go beyond the SM. The most recent measurements [125–128] of its properties shows this new boson to be, within experimental uncertainties, fully compatible with the SM Higgs boson. Nevertheless, such a new particle can also still be accommodated within several theories beyond the standard model (BSM), among all of them, Supersymmetry is a theoretically favoured scenario as the most predictive framework beyond the Standard Model.

This chapter presents the search for the neutral MSSM Higgs bosons decaying into pairs of tau leptons in the fully leptonic final state, published in Ref. [1] as a part of the search for the neutral MSSM Higgs bosons in all final states of the tau leptons decay. The search is based on 20.3 fb^{-1} of 8 TeV data recorded by the ATLAS experiment during 2012 at the Large Hadron Collider. The chapter is organized as follows: a brief summary of the MSSM Higgs sector and an introduction to the analysis strategy is given in Section 1.1, while the event selection and categorization are described in Section 1.2. In Section 1.3 the estimation of the background is described and in Section 1.4 methods to evaluate sys-

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tematic uncertainties are discussed. Finally, in section 1.5, an overview of the statistical methods employed along with the corresponding result of the search are presented.

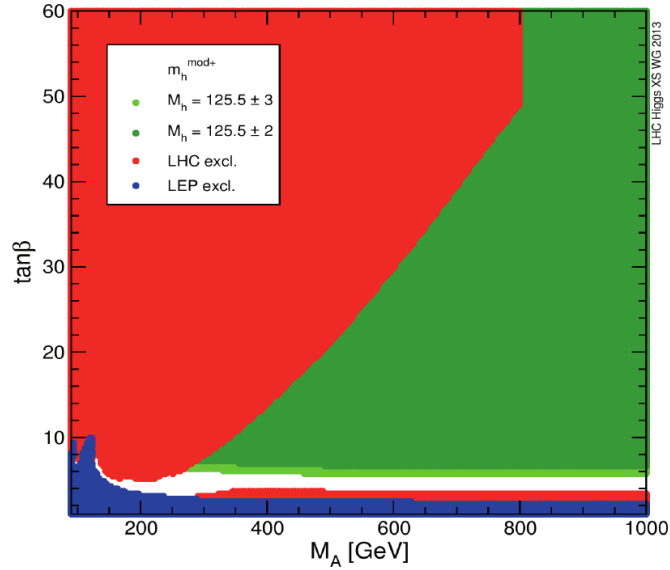


Figure 1.1: Excluded and allowed regions of the $m_A - \tan\beta$ parameter space for the m_h^{mod+} MSSM benchmark scenario. Excluded regions are determined based on direct Higgs boson searches at LEP (blue) and LHC (red). The two green bands correspond to the parameter regions which are compatible with the assumption that the lightest MSSM Higgs boson, h , has a mass respectively of $M_h = 125.5 \pm 2$ (dark green) or 125.5 ± 3 GeV (light green). For more detail see [4].

1.1 Introduction

1.1.1 The Higgs Sector in the MSSM

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

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

Searches for neutral MSSM Higgs bosons have been performed at LEP [64], the Tevatron [65] and the LHC [66,67]. In the following the search for the neutral MSSM Higgs bosons in the final state $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ is presented. This search is complementary to the searches in other $\tau^+\tau^-$ final states characterized by the presence of one or two hadronically decaying τ leptons. Despite of the fact that the $\tau\tau$ branching ratio in $e\mu + 4\nu$ is only 6%, this decay channel provides a sensitivity to the signal comparable to those in other $\tau\tau$ final states, especially for low m_A values. This is mainly due to the high transverse momentum threshold at the trigger level for hadronically decaying τ leptons.

As it is impractical for an experimental search to explore the full parameter space of the MSSM, which has many free parameters, several benchmark scenarios are introduced by fixing all except m_A and $\tan\beta$ parameters to values typical for most interesting physics cases. With the recent Higgs boson discovery, benchmark scenarios of the MSSM have been updated to accommodate for new experimental constraints. As an example, Figure 1.1 shows the currently excluded and allowed regions of the MSSM parameter space for the m_h^{mod+} updated benchmark scenario. In this scenario a large region of the $m_A - \tan\beta$ parameter space is compatible with the assumption that the observed Higgs boson correspond to the supersymmetric SM-like Higgs boson, h . A large part of this parameter space is still experimentally unexplored, this is a strong motivation to pursue the search for additional neutral MSSM Higgs bosons.

1.1.2 Signal and Background Processes

Signal events in which the neutral MSSM Higgs bosons decay through $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ process are characterized 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 contribute to the missing transverse energy in the event. Figure 1.2 shows leading order Feynman diagram for the two considered signal production modes, gluon fusion and in association with b -quarks. The presence (absence) of a b -jet in the final state serves as a main characteristic for the event categorization in the latter (former) case, as described later on.

The described signal topology is common to several other known SM background processes which in general have higher cross sections than the sought signal. The dominant background processes are the $Z/\gamma^* \rightarrow \tau^+\tau^-$ production either via Drell-Yan process or in association with jets and the top quark production ($t\bar{t}$ and single top quark production). Additional significant background contributions originate

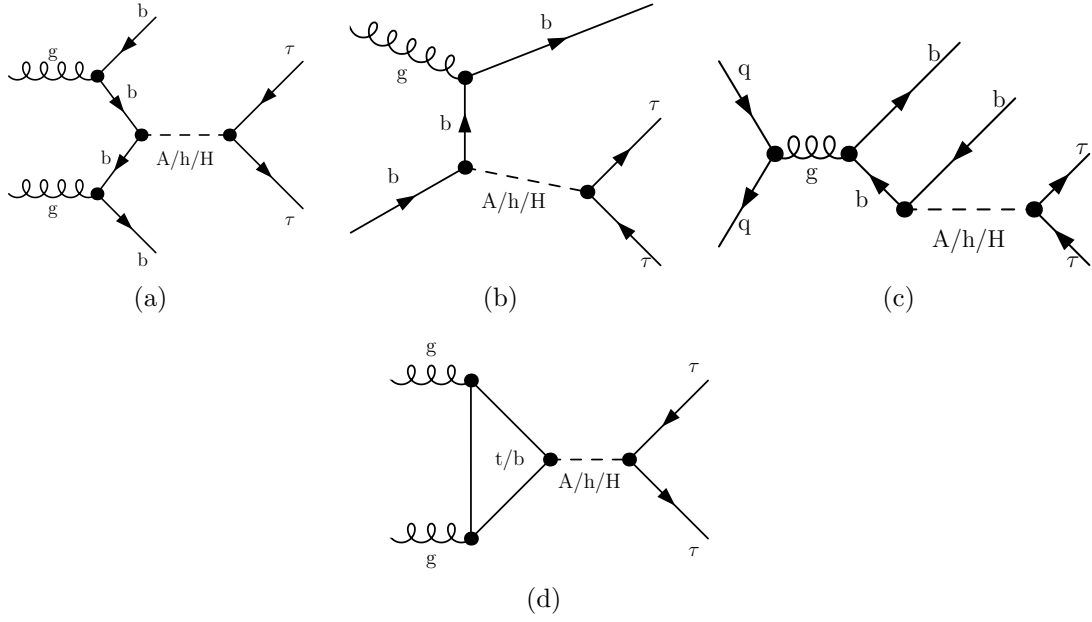


Figure 1.2: Feynman diagram for the production of the neutral MSSM Higgs bosons in association with b -quarks (a,b,c) and via gluon fusion (d) process, subsequent decay in tau lepton pairs is considered.

from the dibosons production (WW , WZ , ZZ) and QCD multi-jet events with non-prompt leptons from hadron decay. 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 1.3. The production cross sections times the relevant branching fraction for signal and background processes are summarized in Table 1.1.

1.1.3 Analysis Strategy

In this thesis a search for the MSSM $A/h/H \rightarrow \tau^+\tau^- \rightarrow e\mu + 4\nu$ decays is presented. The $ee + 4\nu$ and $\mu\mu + 4\nu$ final states are not considered since a large background contribution is expected from $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ 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 the Higgs boson production and decay. The presence of exactly one electron and one muon is required in each event. Electron and muon are required to be isolated and of opposite electrical charge. The events are categorized into two mutually orthogonal event categories. In the so called *b-vetoed* category, the absence of any b-tagged jets is required, thus searching mainly the signal produced 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, searching predominantly signal produced in association with b-quarks. The requirement of a b-jet in the final state suppresses the $Z/\gamma^* \rightarrow \tau\tau$ background. Consequently, $t\bar{t}$ and

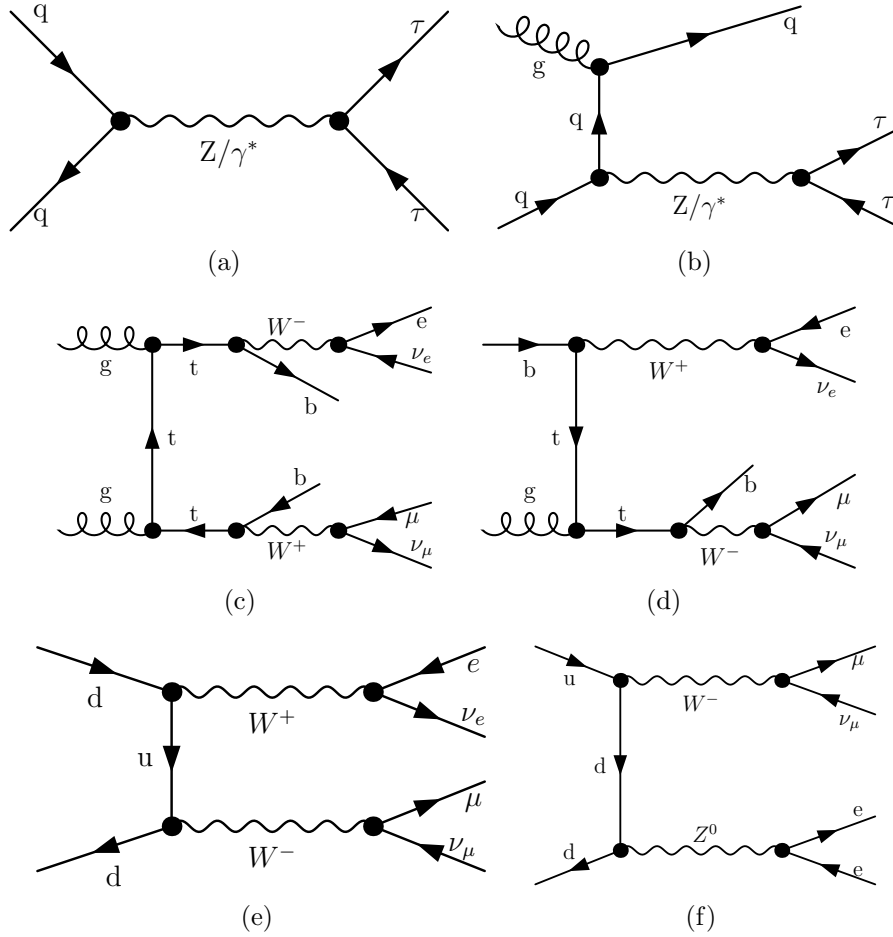


Figure 1.3: Examples of tree level Feynman diagrams for the production and decays of the most relevant backgrounds. The production of $Z/\gamma^* \rightarrow \tau^+\tau^-$ either via Drell-Yan process or in association with jets is shown in (a) and (b), top quark pair and single top quark production in (c) and (d), while examples of WW and WZ production are shown in (e) and (f) respectively.

Process	Cross-section (pb) [\times BR]
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

Table 1.1: The cross sections multiplied by the relevant branching ratios (BR) for signal and the considered background processes. The symbol ℓ stands for $\ell = (e, \mu, \tau)$. 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.

single top quark production are the main background processes in this category. Further selection criteria are introduced in both categories, these are optimized to enhance the signal produced by the corresponding production mode.

The search is performed within the MSSM m_h^{mod} benchmark scenario scanning the $m_A - \tan \beta$ plane in the ranges $90 \leq m_A \leq 300$ GeV and $5 < \tan \beta < 60$. The prediction of the signal event yields and kinematical distributions are evaluated 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 dedicated data control sample since it represent a challenge for simulated events. Contribution of all other background processes is estimated from simulation. The modeling of the background processes is validated using different signal-depleted validation data samples and good agreement is found.

The systematic uncertainties on cross section calculations and the modeling of the detector response taken into account for simulated signal and background processes. For background processes that are measured with data, the uncertainties of the corresponding measurement methods are evaluated.

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

1.1.4 Data and Simulated Event Samples

Data Sample

The presented result are based on proton-proton collision data collected at the LHC during 2012 at a center-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.3 fb^{-1} . The events used in this analysis are recorded using a combination of a single electron and combined electron-muon triggers. Only recorded events in which all relevant components of the ATLAS detector were fully operational are considered. Additional data quality requirements are applied to each event according to [113]. These requirements assure the rejection of 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 [77] and the associated $b\bar{b}A/H/h$ production with SHERPA [78]. The pseudo-scalar Higgs boson samples were generated in the mass range from 90 GeV to 300 GeV assuming $\tan\beta = 20$, all three neutral Higgs bosons ($A/h/H$) are assumed to decay with the same kinematic properties. Appropriate re-weighting of the production cross sections is applied to simulate other $\tan\beta$ values. The m_h^{mod} MSSM benchmark scenario is assumed.

Background Samples

The production of W and Z/γ^* bosons in association with jets was simulated with the ALPGEN [70] generator. The $t\bar{t}$ process was generated using the POWHEG generator. The single top quark production via s-channel and in Wt process were generated using MC@NLO [72], while single top quark production via t-channel was generated with the AcerMC [73] generator. Diboson processes (WW , WZ , ZZ) were generated with the HERWIG [74] generator. For all ALPGEN and MC@NLO event samples described above, the parton shower and hadronisation were simulated with HERWIG and the underlying event activity with the JIMMY [75] programme. Different sets of parton density functions (PDFs) are used depending on the generator: CTEQ6L1 [79] is used by ALPGEN and AcerMC while CT10 [80] is used by SHERPA, POWHEG and MC@NLO.

TAUOLA [82] and PHOTOS [83] are used to model the tau lepton decay and additional photon radiation from charged leptons in the leading-log approximation, respectively.

The ATLAS detector response is simulated for all generated samples using the GEANT4 [84,85] package, the reconstruction of physics objects, described in chapter ??, is performed with the same software used also for the data. The effects of the simultaneous recording of additional proton collisions from the same or neighboring bunch crossings (pile-up) are taken into account in the simulation.

1.2 Event Selection and Categorization

1.2.1 The Common Selection Criteria

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

- (i) A trigger selection, requiring 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. This selection is aimed to reject background from cosmic muons.
- (iii) Exactly one reconstructed “Tight” electron with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. The electron should have $p_T > 15$ or 25 GeV depending on the trigger that selected the event.
- (iv) Exactly one “Combined” muon with $|\eta| < 2.5$ and $p_T > 10$ GeV.
- (v) The electron should be isolated with $E_T^{cone}/p_T < 0.08$ and $P_T^{cone}/p_T < 0.06$.
- (vi) The muon should be isolated with $E_T^{cone}/p_T < 0.04$ and $P_T^{cone}/p_T < 0.06$.
- (vii) Muon and electron should be of opposite charge.
- (viii) Overlap removal between electron, muon, τ_h and jets is performed.
- (ix) The event is rejected if at least one hadronic τ lepton decay is found with the transverse momentum of the corresponding τ -jet $p_T > 15$ GeV.
- (x) To reduce QCD-multijet background contamination, the invariant mass obtained from the sum of the electron and muon four-momenta should be greater than 30 GeV.

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

Events accepted by the common selection criteria are categorized into the *b-tagged* and *b-vetoed* event categories by requiring the presence of exactly one b-tagged jet or the absence of any b-tagged jet in the event, respectively. A jet is considered b-tagged if it has $p_T > 20$ GeV, $|\eta| < 2.5$, $JVF > 0.5$ and it passes the selection of the MV1 b-tagging algorithm at 70% of efficiency for b-quark, ϵ_b^{tt} . Further selection criteria are applied to each category and optimized separately, as described in the following.

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

Table 1.2: Summary of the event selection criteria in the b-tagged and b-vetoed event categories, applied after the common event selection has been performed.

1.2.2 b-vetoed Event Category

A veto on the presence of b-tagged jets in the final state allows for the selection of signal events which are 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 still be discriminated against the signal due to their kinematic properties. The τ leptons from the Higgs boson decay are highly boosted and so are their decay products, this results in significantly different lepton kinematics with respect to diboson or $t\bar{t}$ background processes. Firstly, the electron and muon from Higgs boson decay will be more likely emitted back-to-back. This is illustrated in Figure 1.4(a), showing the angular distance between the two leptons in the transverse plane $\Delta\phi_{e,\mu} = |\phi_e - \phi_\mu|$ for the signal and relevant background processes. Secondly, the neutrinos from the Higgs boson decay will be more likely collinear with the charged leptons, thus, the angular correlation between the direction of the missing transverse energy and the two leptons, derived as:

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

is expected to tend to zero, as is shown in Figure 1.4(b). These two features can be used to discriminate the signal from the W boson, top quark or in dibosons background processes. No further selection criteria are applied in this event category, as it has been shown that no significant improvement of the analysis sensitivity can be achieved. The exact selection criteria are listed in Table 1.2, while in Table 1.3 the predicted number of background and signal events after each stage of selection are reported.

1.2.3 b-tagged Event Category

The request of exactly one b-tagged jet in the b-tagged event category selects predominantly signal events produced in b-quarks associated production mode. Background processes with b-jet activity, as the top quark and single top quark pro-

duction become enhanced compared to the $Z/\gamma^* \rightarrow \tau\tau$ background. Also in this category selection requirement on $\Delta\phi(e - \mu)$ and $\sum \cos \Delta\phi$ are imposed as described for the b-vetoed event category, in order to reduce the top quark and diboson background contributions. Further selection criteria specific for this category are employed as described below.

Given the relatively low jet activity of the signal events, it is possible to discriminate these from top quark production. The top quark processes are very likely to have two or more highly energetic jets in the event, unlike the signal b-jet which are relatively low energetic. Weak jet activity is ensured by requesting the sum of the jets transverse momenta, H_T , in the event to be small. The H_T distribution is shown in Figure 1.4(c). The jets used for the calculation of the H_T value should have $p_T > 30$ GeV, $|\eta| < 4.5$ and $JVF > 0.5$ (if $|\eta| < 2.5$).

Another feature that discriminates top quark pair production from the Higgs boson signal is the higher invariant mass of the former final state, as the highest Higgs mass considered for the presented search is 300 GeV. The sum of electron and muon transverse momenta with E_T^{miss} is used as a corresponding discriminating variable, whose distribution is shown in Figure 1.4(d).

The summary of the exact optimized selection criteria for the b-tagged event category is shown in Table 1.2. In Table 1.4 the predicted number of background and signal events after each stage of selection in the b-tagged event category is reported.

1.2.4 Mass Reconstruction with MMC Technique

Accurate invariant mass reconstruction of a di- τ resonance is a challenging task due to the undetected neutrinos. In the presented analysis a total of four neutrinos are involved in the final state, two for each of the τ lepton decays. The invariant mass depends on eight unknowns given by the two sums of neutrino four-momenta, one for each τ lepton decay. These unknowns can be constrained by four parameters obtained from the measured missing transverse energy and from the τ lepton mass, using the following equations:

$$\begin{aligned} \vec{E}_T^{miss} &= \vec{P}_T^{mis_1} + \vec{P}_T^{mis_2} \\ M_{\tau_i}^2 &= m_{mis_i}^2 + m_{vis_i}^2 + 2\mathbf{P}_{vis_i} \cdot \mathbf{P}_{mis_i} \end{aligned} \quad (1.1)$$

where the index i runs over the two τ leptons in the event. $\vec{P}_T^{mis_i}$, m_{mis_i} and \mathbf{P}_{mis_i} are respectively the transverse momentum, the invariant mass and the four momentum of the pair of neutrinos originating from the decay of the i -th τ lepton with mass M_τ . The subscript *vis* indicates instead quantities related to the charged lepton from the corresponding τ lepton decay. The remaining four degrees of freedom can be further constrained, for example, assuming that the neutrinos are collinear to the electron or muon from the corresponding τ lepton decay. Those approximation, however, introduces limitations on the mass resolution.

In this analysis, the so-called "Missing Mass Calculator" (MMC) algorithm is used to calculate 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 [129].

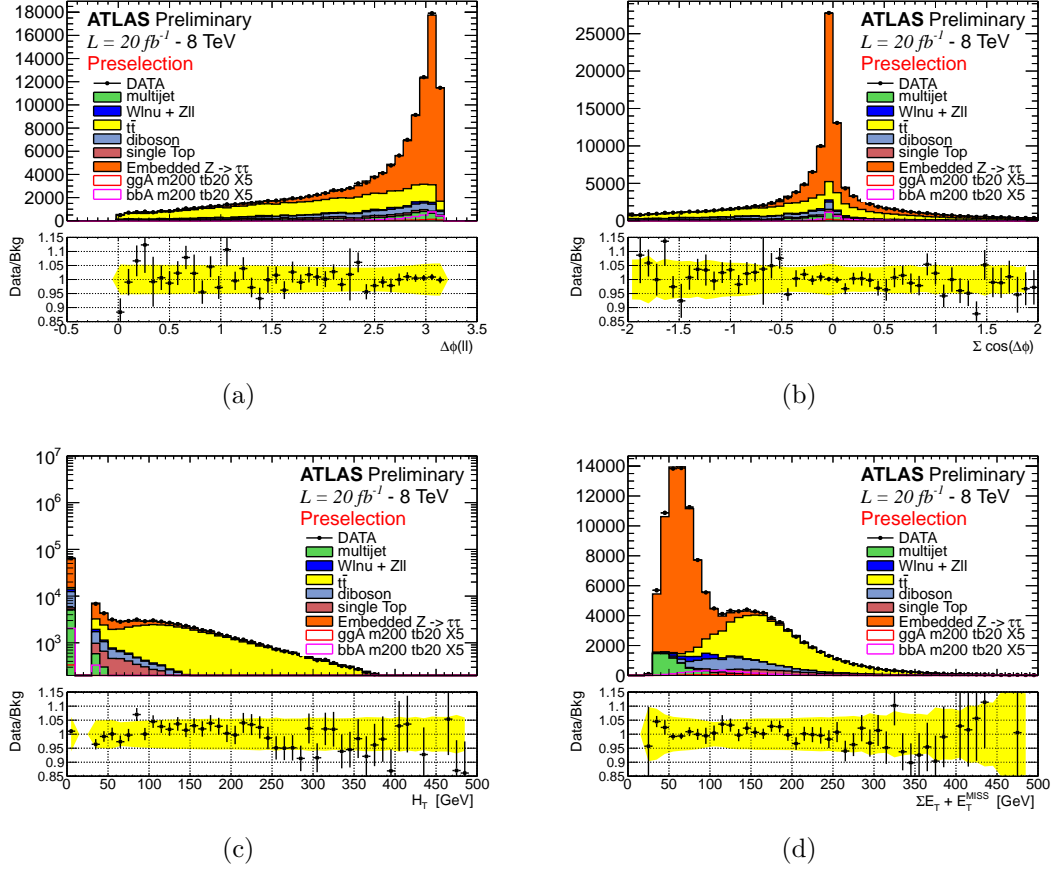


Figure 1.4: Distributions of relevant discriminating variables shown after the common selection has been applied. The prediction of the background model is compared to data. The contribution of the $Z/\gamma^* \rightarrow \tau\tau$ and QCD multi-jet background processes is measured in dedicated signal-depleted control data samples, the prediction for all the other background processes is obtained from simulation. The yellow band represents the total systematic uncertainty for the background model prediction (see Section 1.4).

	Common Selections	$n(\text{b-jet})=0$	$\Delta\phi(e-\mu) > 1.6$	$\sum \cos \Delta\phi > -0.4$
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
Signal			-	-

Table 1.3: Number of observed and predicted signal and background events, after each selection stage in the b-vetoed 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
Signal		-	-	-	-

Table 1.4: Number of observed and predicted signal and background events, after each selection stage in the b-tagged event category.

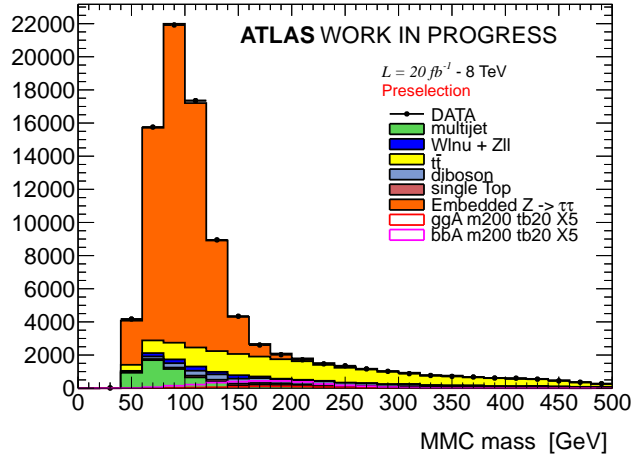
The MMC algorithm solves the equations 1.1 for a set of points in a grid of a four-dimensional parameter space. The four independent variables are chosen to be $m_{mis_i}^2$ and $\cos\theta_i^*$, the latter defined as the angle between the charged lepton from the τ lepton decay and the boost direction of the τ lepton. The di- τ invariant mass in each event is then calculated for each given point of the parameter space. Each solution is weighted by the probability that a τ lepton decay assumes a given configuration. The probability of a given configuration is predicted by means of simulation using PYTHIA generator supplemented with TAUOLA package. The invariant mass of the di- τ system, $m_{\tau\tau}^{MMC}$, is then defined as the maximum of the weighted invariant mass distribution obtained from all scanned points.

The resolution of the missing transverse energy measurement impacts the resolution of the invariant mass obtained with the $m_{\tau\tau}^{MMC}$ method. To improve the E_T^{miss} resolution, a scan over a six-dimensional parameter space is performed in a similar manner as described above. For this purpose, the 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.

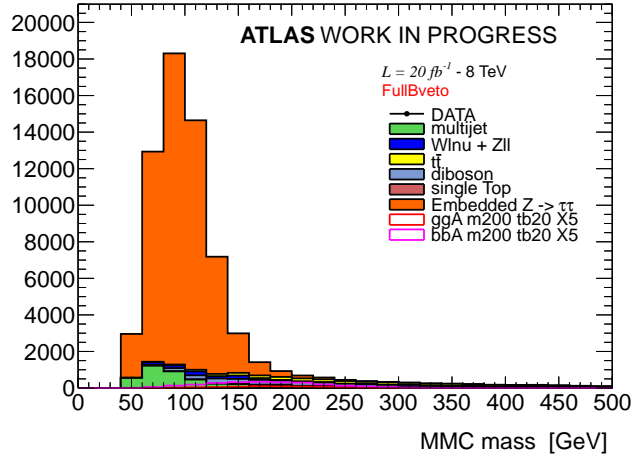
Figure 1.5 shows the $m_{\tau\tau}^{MMC}$ invariant mass distribution after the common selection and after applying the full selection in both event categories.

1.3 Background Prediction and Validation

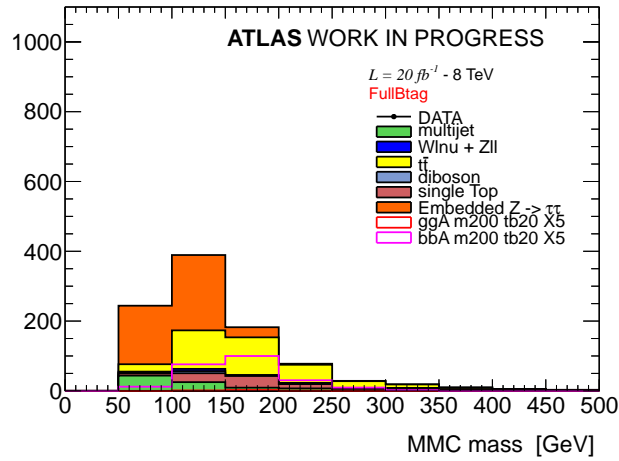
This section describes the strategies for the prediction of the background contributions and validation of these predictions. Monte Carlo simulation is extensively used to model the kinematic properties of the background and signal processes. However, since the simulation of any process is usually prone to systematic uncertainties due to a non-perfect description of the pileup effects, underlying event and detector performance, the background contributions from $Z/\gamma^* \rightarrow \tau\tau$ and QCD multi-jet process are estimated using dedicated signal-free control data samples, as described respectively in section 1.3.3 and 1.3.2. Contributions of other background processes, such as $t\bar{t}$, single top quark, dibosons, $Z \rightarrow \ell\ell + \text{jets}$ (where $\ell = e, \mu$) and $W + \text{jets}$, are estimated from simulation. Given the relatively large $t\bar{t}$ background contribution, a dedicated study to validate this background prediction has been made as described in section 1.3.1.



(a)



(b)



(c)

Figure 1.5: Observed and expected distribution of the invariant di- τ mass $m_{\tau\tau}^{MMC}$ for different stage of analysis selections.

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

Table 1.5: Control data samples for the measurement of the QCD multi-jet background contribution. The samples are defined by the requirements on the relative charge sign of the two leptons (OS,SS) and the isolation criteria applied on them (isolated or anti-isolated). See text.

A good agreement between data and background prediction is found after the common selection, as can be seen in Figure 1.4 and Figure 1.6.

1.3.1 Validation of the $t\bar{t}$ Background Prediction

The background contribution from top quark pair production is estimated using a sample of simulated events generated with POWHEG-PYTHIA Monte Carlo generator. Since this is one of the major background processes for the presented analysis a careful validation of the predicted contribution is needed. For this purpose signal-depleted data validation sample enriched with $t\bar{t}$ events by requiring the presence of exactly two b-tagged jets in all the events passing the common selection. Figures 1.7 and 1.8 show the distributions for a set of kinematic properties and all discriminating variables obtained with this data sample. Good agreement between data and Monte Carlo prediction is found with overall ratio of the observed to the predicted number of $t\bar{t}$ events of $0.998 \pm 0.011(\text{stat.}) \pm 0.110(\text{sys.})$. The total systematic uncertainty on the ratio is dominated by the uncertainty of the b-tagging efficiency.

1.3.2 Multi-jet Background Measurement

The QCD multi-jet process represents an important background, especially in the b-vetoed event category, due to its high cross-section and the relatively low threshold on the lepton p_T used in this analysis. The contribution of this background is evaluated by the so-called ABCD data-driven technique. The ABCD method splits the sample of data events after the common selection into four sub-samples: the signal sample (A), defined by the event selections criteria described in Section 1.2 and three signal-depleted control data sample (B,C,D), which are orthogonal to each other and are enriched in multi-jets 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 1.2.1 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 1.5.

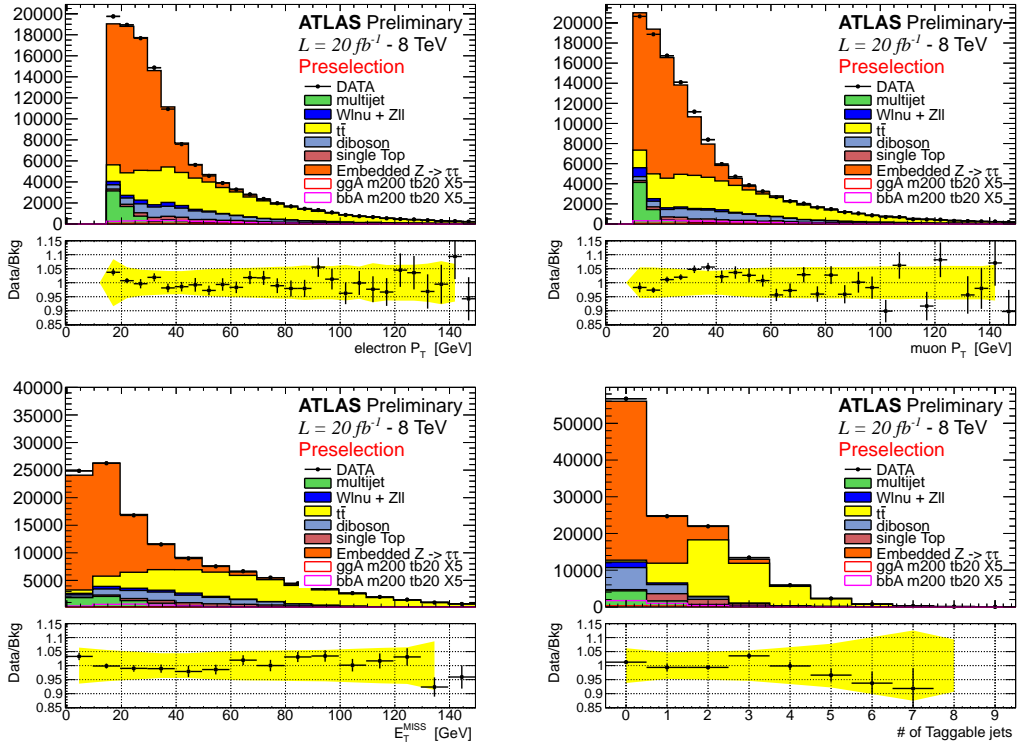


Figure 1.6: Observed and expected distribution of kinematic variables after common selections. The prediction of the background model is compared to data. The contribution of the $Z/\gamma^* \rightarrow \tau\tau$ and QCD multi-jet background processes is measured in dedicated signal-depleted control data samples, the prediction for all the other background processes is obtained from simulation. The yellow band represents the total systematic uncertainty for the background model prediction.

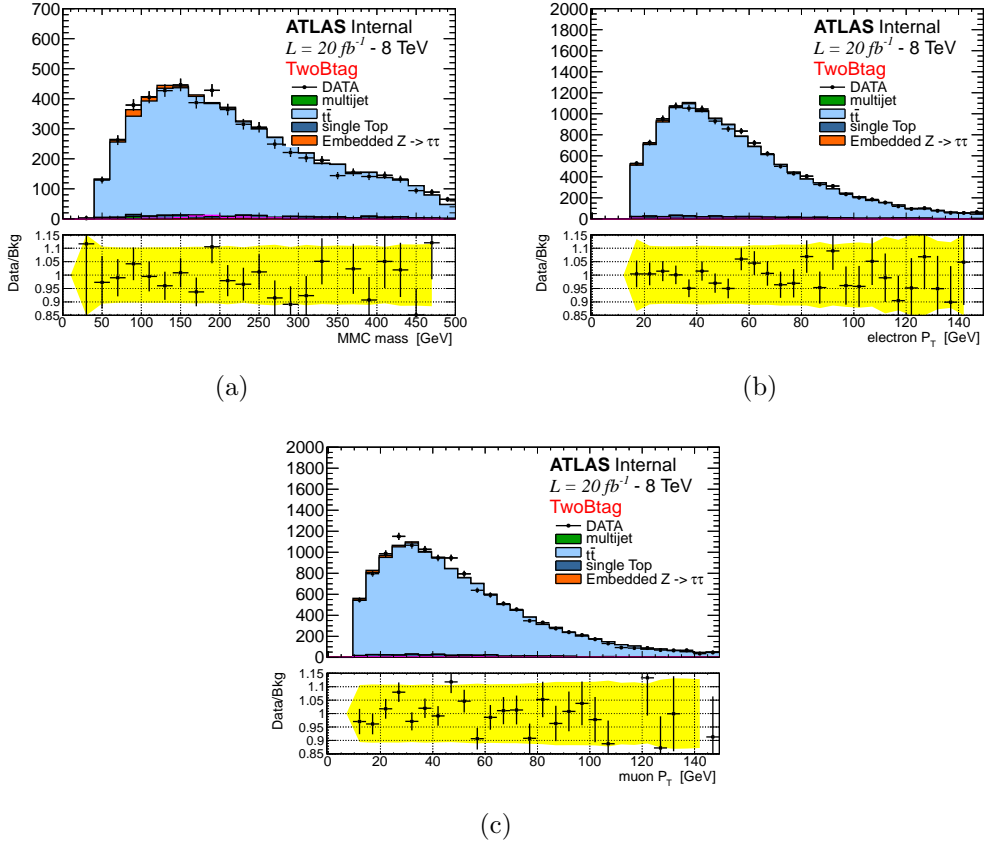


Figure 1.7: Observed and expected distributions of a) the di- τ invariant mass $m_{\tau\tau}^{MMC}$, b) the electron transverse momentum $p_T(e)$ and c) the muon transverse momentum $p_T(\mu)$ in the $t\bar{t}$ validation sample. The error bars on the observed to the predicted events ratio indicates the statistical uncertainty, whereas the yellow band indicates the total systematic uncertainty of this ratio.

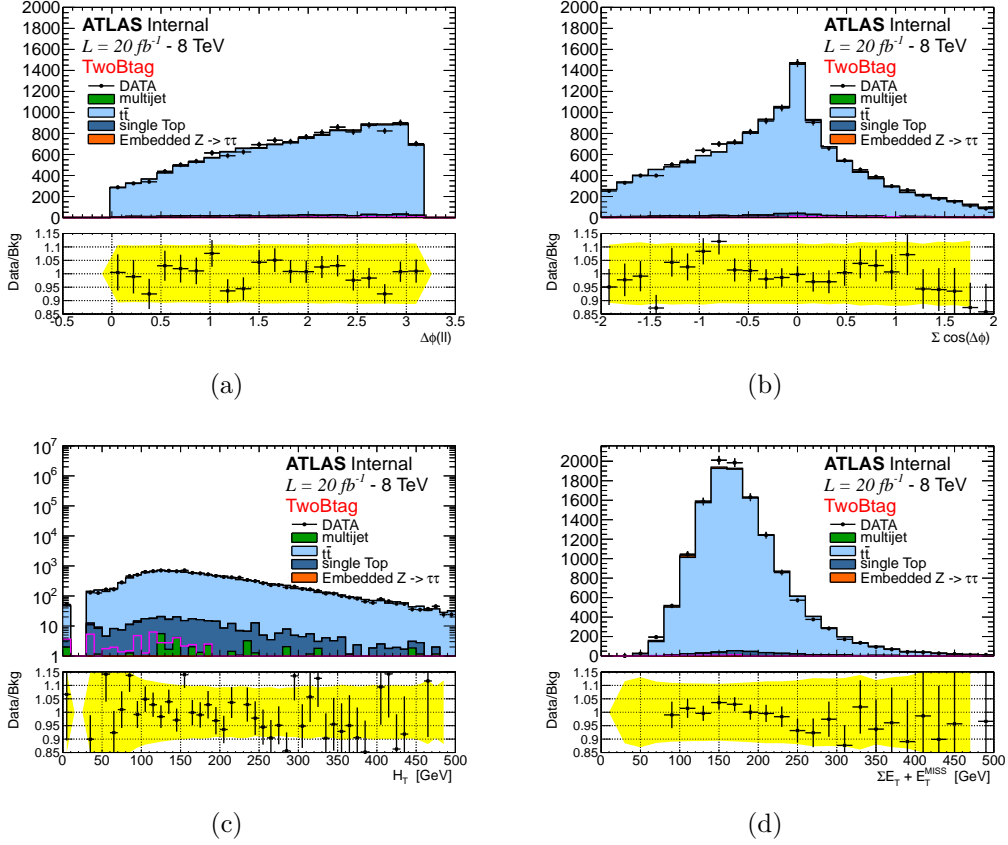


Figure 1.8: Observed and expected distributions of the discriminating variables, (a) $\Delta\phi(e - \mu)$, (b) $\sum \cos \Delta\phi$, (c) $p_{T\mu} + p_{Te} + E_T^{miss}$ and (d) H_T in the $t\bar{t}$ validation sample. The error bars on the observed to the predicted events ratio indicates the statistical uncertainty, whereas the yellow band indicates the total systematic uncertainty of this ratio.

The ABCD method assumes that there is no correlation between the relative charge and lepton isolation in QCD multi-jet events, or in other words that the ratio of OS/SS events is uncorrelated with the lepton isolation criteria. 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, N_D) of multi-jet events in the control samples B, C and D , using the equation

$$N_A = N_B \times \frac{N_C}{N_D} = N_B \times R_{QCD} \quad (1.2)$$

To obtain the pure QCD multi-jet event yields in the data control samples, the contribution from contaminating electroweak (W+jets, Z+jets and dibosons) and top quark processes ($t\bar{t}$, single top quark production) is subtracted in each control sample based on the prediction from simulation. Tables 1.7 and 1.6 show the observed event yield in each control sample at different stages of the event selection along with the predictions of non-QCD background contributions which are subtracted. Signal contamination has been evaluated in all three control samples for different

signal mass points. For the range of m_A and $\tan\beta$ values considered in this analysis, the highest signal contamination is seen in sample B for the mass point $m_A = 300$ GeV and $\tan\beta = 50$, where a contamination of 0.2% is observed².

The modeling of the shapes of kinematic distributions in QCD multi-jet events is given by the data sample B. The events in this sample are expected to have similar kinematic properties as in 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 a shape bias due to isolation requirements at the trigger level, since the single-electron trigger already imposes isolation requirements. Figure 1.9 shows the comparison of the electron p_T distributions in sample B and D. In the latter sample high- p_T electrons are suppressed as they do not pass the trigger selection. Eventually the trigger isolation requirement could also bias the ratio R_{QCD} . This possibility has been carefully studied in a dedicated study as reported in Appendix ???. To a good approximation, the mentioned trigger effects cancel out in the ratio R_{QCD} and no additional systematic uncertainty needs to be taken into account.

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

- $E_T^{miss} < 20$ GeV
- $H_T < 70$ GeV and $p_{T\mu} + p_{Te} + E_T^{miss} < 50$ GeV
- $0 < m_{\tau\tau}^{MMC} < 80$ GeV

This validation sample is 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 1.10 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 1.4.

1.3.3 $Z \rightarrow \tau\tau + \text{Jets}$ Background Measurement

The $Z/\gamma^* \rightarrow \tau\tau$ decays are the major source of background to the presented analysis, calling for its thorough understanding. Unfortunately, for a light Higgs boson, it is impossible to fully discriminate the $Z/\gamma^* \rightarrow \tau\tau$ decays from the signal and thus a dedicated signal-free data control sample cannot be defined. However, thanks to the small Higgs boson coupling to muons, $Z \rightarrow \mu\mu$ decays provide a good starting point to model $Z/\gamma^* \rightarrow \tau\tau$ events based on data. A hybrid approach relying on data and simulation known as the "embedding" is used for this purpose. The $Z \rightarrow \mu\mu$ event

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

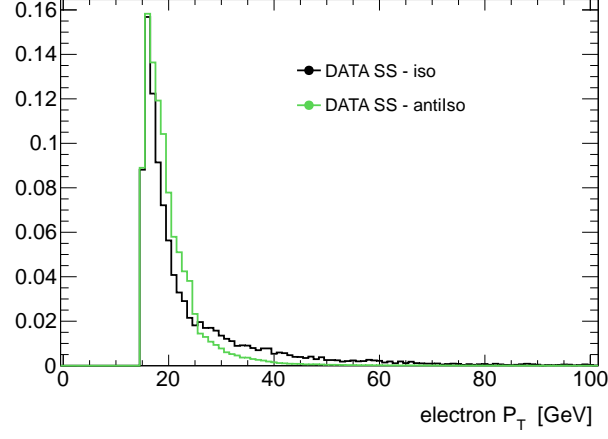
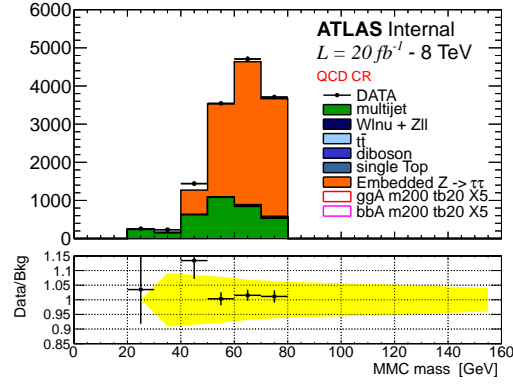


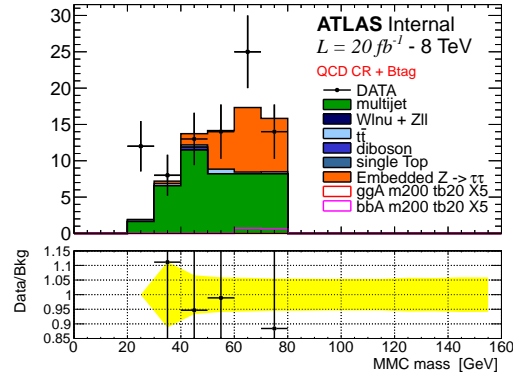
Figure 1.9: Comparison of the electron p_T distribution in control samples B and sample D, showing the bias due to the trigger. The histograms are normalized to the same area.

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	

Table 1.6: Number of observed events and the predicted non-QCD contribution at different stages of the event selections for b-veto category. The error on the R_{QCD} ratio is of statistical nature only.



(a)



(b)

Figure 1.10: $m_{\tau\tau}^{MMC}$ distribution obtained with QCD validation samples defined in Section 1.3.2, without (a) and with an additional requirement of exactly one b-tagged jet in the final state (b).

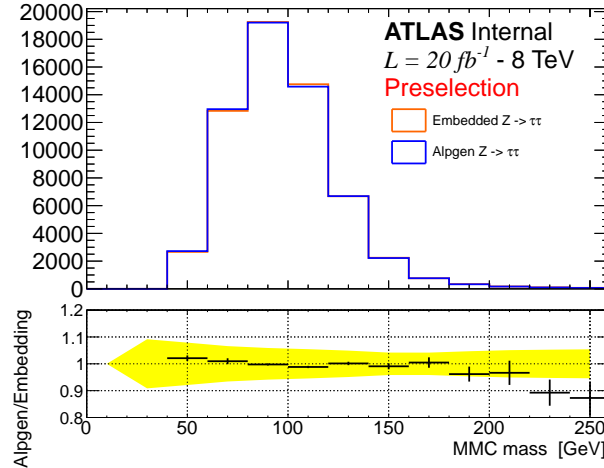


Figure 1.11: Comparison of the $m_{\tau\tau}^{MMC}$ distributions obtained from the ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ simulation and from the embedding technique after the requirements of the common selection has been applied. The yellow band indicates the total systematic uncertainty relative to the ALPGEN simulation sample.

candidates are selected in data. The two muons from the Z decay are then substituted with the decay products from simulated τ lepton decays. The energy deposit in the calorimeter and the reconstructed tracks in a cone of given size around the muon are subtracted and substituted with the corresponding predictions from the τ lepton decay. These τ leptons have the same kinematic properties as the original muons. Further details on the embedding technique may be found in [86, 87].

As the Trigger is not simulated in the described embedded samples, only the shapes of kinematic distributions are modelled by the embedded sample, while the $Z \rightarrow \tau\tau$ event yield is normalized to ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ prediction at a common selection stage. Furthermore, a set of corrections as described in [88], is applied to unfold from the original $Z \rightarrow \mu\mu$ trigger and reconstruction efficiency. 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 [86, 88], demonstrating a reliable performance of the embedding technique and a good description of data. In the context of this analysis, Figures 1.11 and 1.12 show comparisons of various kinematic distributions between data, embedded and ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ events at the common selection stage. No significant differences are seen between for the $m_{\tau\tau}^{MMC}$ distribution. Other relevant discriminating variables, such as the E_T^{miss} and the number of b-jets in the final state, are slightly better described by the embedded $Z/\gamma^* \rightarrow \tau\tau$ sample, as expected due to the imperfect modeling of these variables with simulation.

The embedded sample is based on the selected $Z \rightarrow \mu\mu$ event candidates in data. The $Z \rightarrow \mu\mu$ selection criteria assure a rather pure $Z \rightarrow \mu\mu$ sample. However, further event selection criteria used in the presented analysis, for example the b-tagging requirements, could enhance the contamination of this sample with events

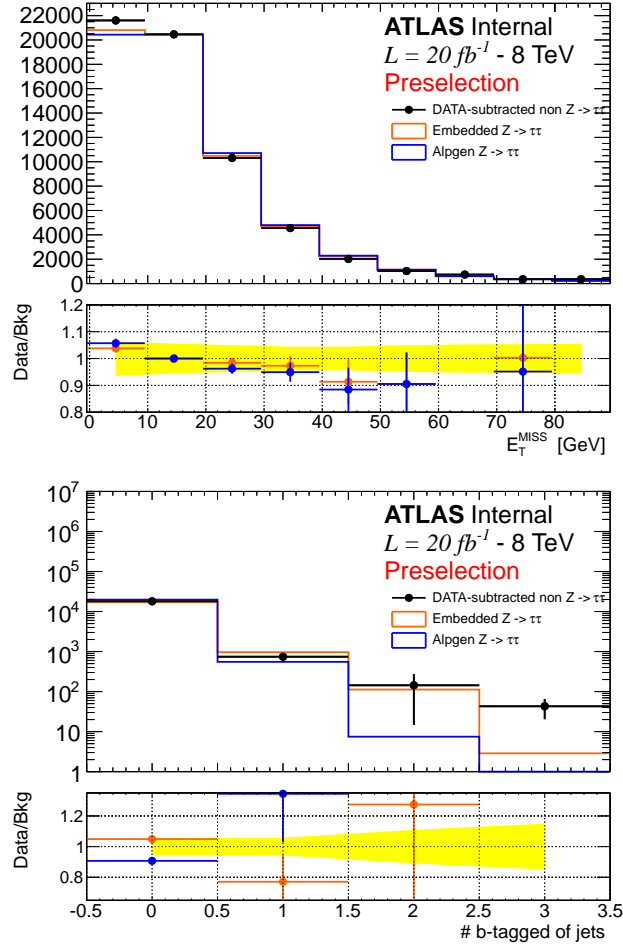


Figure 1.12: Comparison of the (a) E_T^{miss} and (b) b-tagged jet multiplicity distributions in embedded and ALPGEN $Z/\gamma^* \rightarrow \tau\tau$ events after the requirements of the common selection has been applied. Data are superimposed after subtracting the contribution of non- $Z/\gamma^* \rightarrow \tau\tau$ processes. The yellow band indicates the total systematic uncertainty relative to the ALPGEN simulation sample.

from other processes. 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 in a validation sample with two b-tagged jets (as described in Section 1.3.1). These events are assumed to originate solely from the $t\bar{t}$ process and the corresponding yield in the signal sample is extrapolated from simulation. Table 1.8 summarizes the evaluated top quark contamination in the embedded $Z \rightarrow \tau\tau$ sample, separately for the two event categories. The multi-jet contamination can be estimated starting from the yield of embedded events in the sample C defined by 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 sample can be estimated as:

$$N_A^{QCD-emb} = N_C^{QCD-emb} \times \frac{N_B^{\mu\mu}}{N_D^{\mu\mu}} = N_B \times R_{QCD}^{\mu\mu} \quad (1.3)$$

The transfer factor $R_{QCD}^{\mu\mu}$, is evaluated using a di-muon final state with same kinematic selection criteria as for $Z \rightarrow \mu\mu$ candidates entering the embedding procedure. Table 1.9 shows the estimated contamination of QCD multi-jet in the embedded sample. Contamination effects are considered negligible.

1.4 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 ???. The uncertainties due to such corrections are referred to as detector-related systematic uncertainties and are addressed in section 1.4.1. For all process 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 given analysis selection criteria and are described in section 1.4.2. Further systematic uncertainties related to the background measurements with dedicated control data are described in Sections 1.4.3 and 1.4.4.

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 statistical interpretation of data. Systematic uncertainties that the shape of the mass distribution are documented in appendix ???. 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.

1.4.1 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

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	

Table 1.7: Number of observed events and the predicted non-QCD contribution at different stages of the event selections for b-tag category. The error on the R_{QCD} ratio is of statistical nature only.

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

Table 1.8: Evaluation of the $t\bar{t}$ contamination in the embedded $Z \rightarrow \tau\tau$ sample using a two b-tag validation sample. The transfer factor is a multiplicative factor obtained from simulation that allows to extrapolate the measurement from the validation sample into the signal sample.

	Yield of embedded events 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 1.9: Evaluation of the QCD multi-jet contamination in the embedded $Z \rightarrow \tau\tau$ sample using the control sample with OS anti-isolated events (sample C). The transfer factor $R_{QCD}^{\mu\mu}$ is the multiplicative factor that allows to extrapolate the measured events in control sample C into the signal sample. The transfer factor is evaluated using di-muon events with same kinematic properties as the $Z \rightarrow \mu\mu$ candidates entering the embedding procedure.

of those parameters correspond to a nuisance parameter in the probability model used for the statistical interpretation as described in Section 1.5. Each parameter is varied independently by one standard deviation up or down 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 1.11 and 1.10 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"), the second related to electron energy scale and resolution corrections. The energy scale uncertainties are described by a set of six different nuisance parameters [101]. 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 [112] related to different effects and jet energy components. For example the sensitivity to pileup effects or to the flavor composition of the jet are considered separately. 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 Tables 1.11 and 1.10 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 [116, 117], ranging from 5-10% in dependence 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% [118]. E_T^{miss} uncertainties are independently propagated through the analysis and are added in quadrature, this final term is referred as the "MET" uncertainty.

1.4.2 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 1.13. 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 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 is not affected by these systematic uncertainties, as an example see Figure 1.13, only the variation in the acceptance is considered as a systematic uncertainty. The

b-vetoed event category, Uncertainties on event yields (%)					
Source	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 1.10: 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).

b-tagged event category, Uncertainties on event yields (%)					
Source	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 1.11: Impact of the experimental systematic uncertainties on the event yields in different simulated samples in the b-tagged 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 $\tan\beta = 20$.

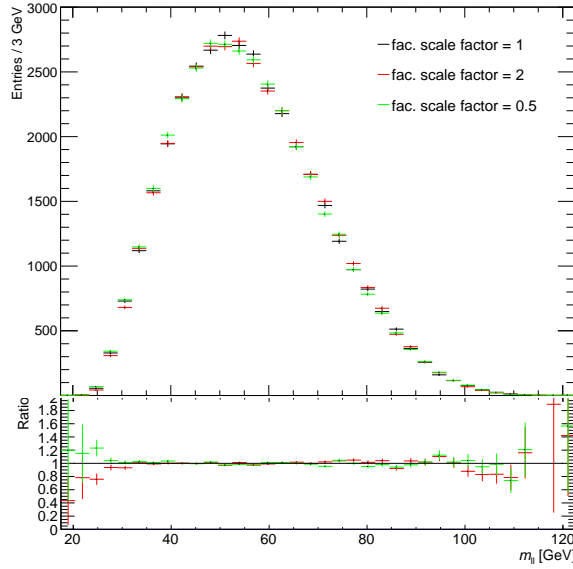


Figure 1.13: Distribution of the invariant mass of all visible τ -lepton decay products for different choices of the factorisation scale. The shown distribution is for gluon fusion produced signal in the b-vetoed event category.

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% [136]. 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% [137]. The acceptance uncertainties on dibosons and single top quark production are estimated to be 2% [136].

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 [139], where the b-tagging is performed by identifying the b-quarks and applying weights according to the measured ATLAS b-tagging efficiencies [116]. 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 varies from 4% to 30% depending on M_A , production process and on the analysis category.

1.4.3 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 $Z \rightarrow \mu\mu$ 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

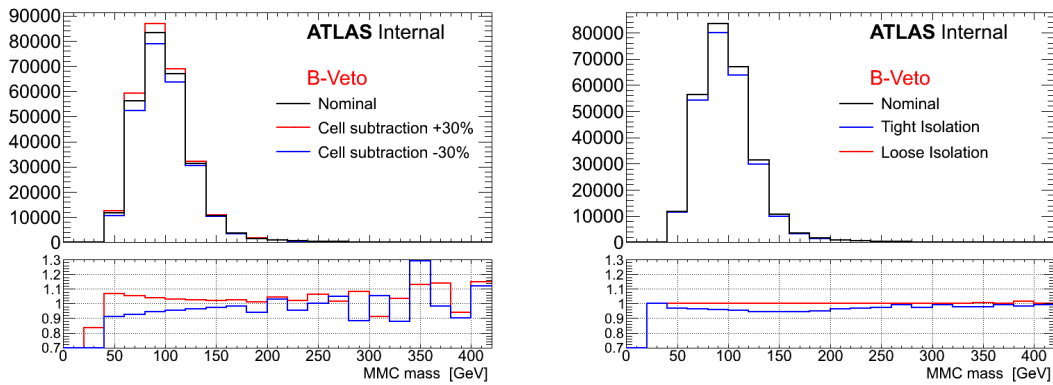


Figure 1.14: Impact of EMB_MFS (left) and EMB_ISO (right) systematic uncertainties on the $m_{\tau\tau}^{MMC}$ mass distribution for in the embedded sample. Significant impact is observed only in the b-vetoed event category.

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 1.14.

In the sample of $Z \rightarrow \mu\mu$ candidates used for the embedding, only a loose requirement on the muon track isolation is applied. A different muon isolation requirement 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 $Z \rightarrow \mu\mu$ 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 1.14.

Finally, because the normalization of the embedded sample is determined from the simulated ALPGEN sample, the uncertainties on the relative cross section in the two event category and luminosity uncertainty 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.

1.4.4 QCD Multi-Jet Systematic Uncertainties

The QCD multi-jet background is estimated via the ABCD method, as described in Section 1.3.2. 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 1.15 shows the R_{QCD} factor, i.e. the ratio between the QCD yields in data samples C and D, as a function of the 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

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 1.12: 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.

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 1.15 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 1.15 are obtained after common selection. Similar results after the full analysis selection in the two event categories are shown in Appendix ??.

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 1.12 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 1.16. 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 ?? and is found to be negligible.

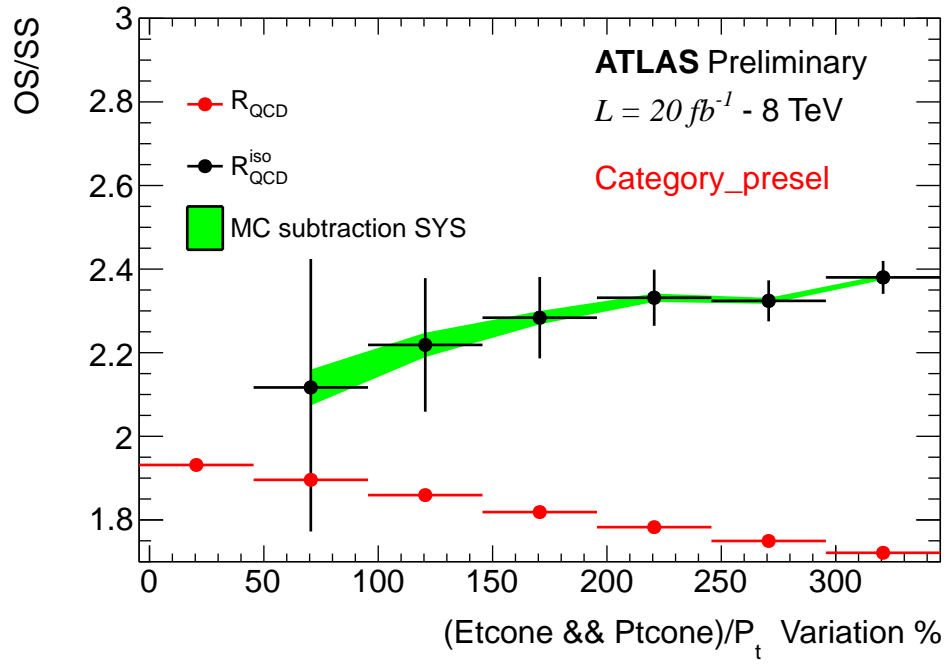


Figure 1.15: Transfer factors R_{QCD} and R_{QCD}^{iso} (see text) as a function of the sliding lepton isolation thresholds. The thresholds are varied in percentages relative to the nominal lepton isolation threshold (value of zero on the plot). The common selection are applied.

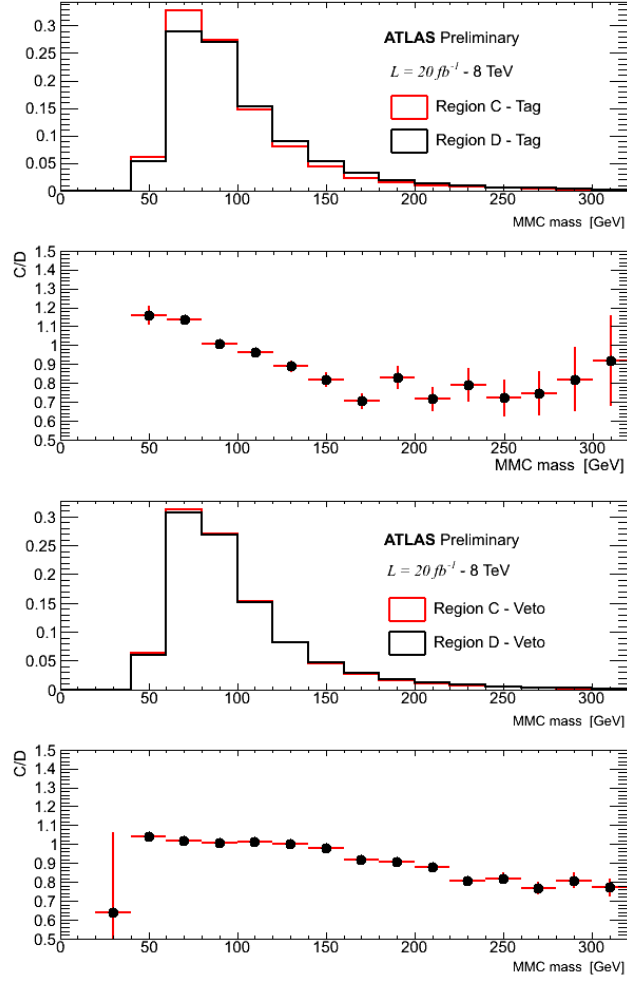


Figure 1.16: Differences in the shape of the invariant $m_{\tau\tau}^{MMC}$ mass distribution in data samples C and D shown separately for the b-tagged and b-vetoed event categories. The data samples C and D are normalised to the same number of events.

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

1.5 Results

1.5.1 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 [140]. The statistical procedures described in the following are implemented in the software packages described in [141–143].

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} :

$$\mathcal{L}(\mathcal{D} \mid \mu, \boldsymbol{\theta}) = \text{Pois}(\mathcal{D} \mid \mu \cdot s(\boldsymbol{\theta}) + b(\boldsymbol{\theta})) \cdot \prod_{j,i} \mathcal{G}(\theta_j^{sys} \mid 0, 1) \cdot \Gamma(\theta_i^{stat} \mid \beta_i) \quad (1.4)$$

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 distributions. The function $\mathcal{G}(\theta_j^{sys} \mid 0, 1)$ 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

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.

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 1.4. The function $\Gamma(\theta_i^{stat}|\beta_i)$ is an extended gamma function⁴ 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 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 (1.4) 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 $m_{\tau\tau}^{MMC}$ 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 analyzed separately. The actual implementation in the likelihood function of the ABCD method follows that suggested in [134] and it is described in more detail in Appendix ??.

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 [140] 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 slit into component which are fully or uncorrelated or they are defined as to either fully correlated or uncorrelated. The choice of the above options is made by always selecting the most conservative assumption.

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* [144]:

$$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(\mathcal{D} \mid \mu, \hat{\boldsymbol{\theta}}_\mu)}{\mathcal{L}(\mathcal{D} \mid \hat{\mu}, \hat{\boldsymbol{\theta}})} \quad \text{with the constraint} \quad 0 \leq \hat{\mu} \leq \mu. \quad (1.5)$$

\mathcal{L} is the likelihood function defined in equation (1.4), $\hat{\mu}$ 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

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

of μ . \tilde{q}_μ is increasing with increasing disagreement between data and the given hypothesis with a signal strength μ . 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 time, asymptotic approximation formulas described in [144] 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 observe 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 $CL_s = p_{s+b}/p_b$ [145, 146].

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 value 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.

1.5.2 Exclusion Limits on the Signal Production

The statistical procedure described in section 1.5.1 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 neutran 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 $\tan\beta = 5$

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

Sample	b-tag category			b-veto category		
	N(event)	Stat.	Syst.	N(event)	Stat.	Syst.
$Z/\gamma^* \rightarrow \tau\tau$	418	± 6	$^{+27}_{-27}$ (7%)	54680	± 60	$^{+3500}_{-3500}$ (6%)
$t\bar{t}$	330	± 10	$^{+37}_{-35}$ (11%)	2159	± 25	$^{+280}_{-300}$ (14%)
Multijet	101	± 15	$^{+15}_{-15}$ (15%)	3930	± 330	$^{+590}_{-590}$ (15%)
Other	114	± 9	$^{+12}_{-12}$ (11%)	4450	± 110	$^{+250}_{-250}$ (6%)
Total	963	± 21	$^{+50}_{-50}$	65220	± 360	$^{+3600}_{-3600}$
Signal	144	± 7	$^{+24}_{-33}$	2028	± 27	$^{+150}_{-100}$
Data	-	-	-	-	-	-

Table 1.14: 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). The numbers in parentheses indicate the systematic uncertainty in percent. 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.

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 $m_{\tau\tau}^{MMC}$ 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 1.14 compares the expected and the observed event yields in the two event categories at the final stage of the cut event selection. Additionally, Figure 1.17 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 1.18. 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 $90 < m_A < 200 \text{ GeV}$. The observed limit is presently unknown.

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

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

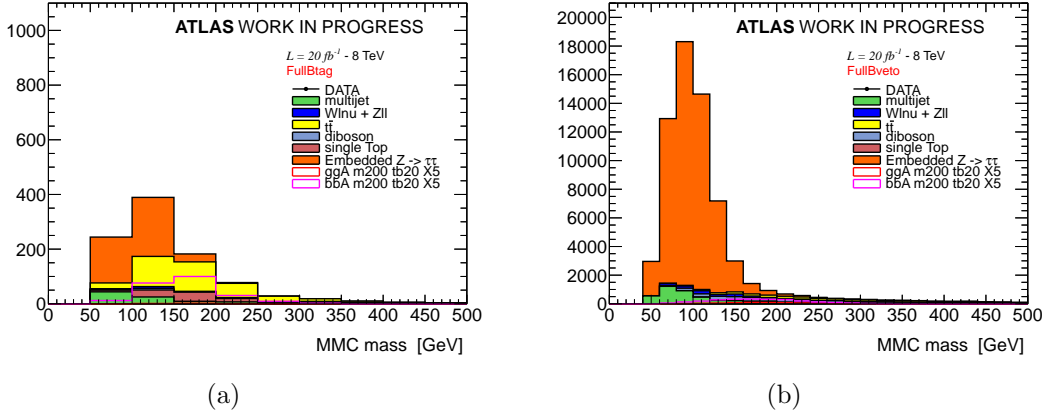


Figure 1.17: $m_{\tau\tau}^{MMC}$ mass distribution for (a) the b-tagged event category and (b) the b-vetoed event category after the full event selections.

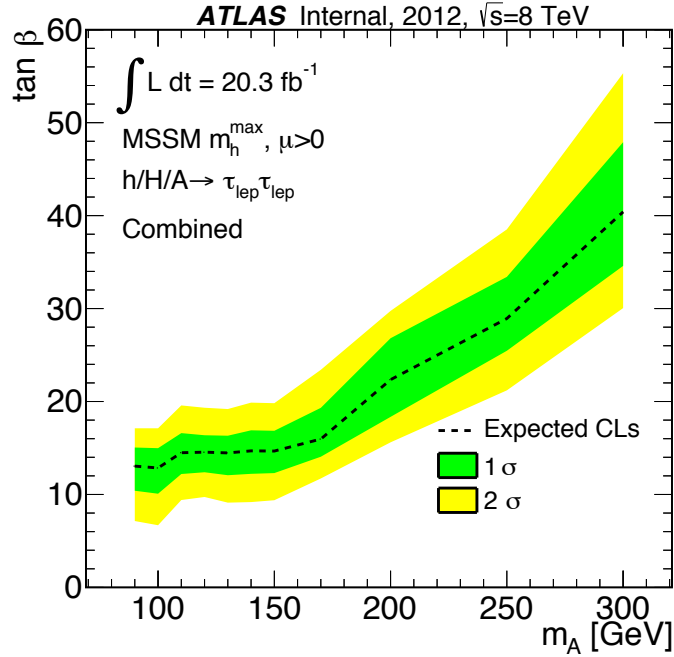


Figure 1.18: Expected and observed exclusion limits at the 95% CL_s confidence-level for MSSM Higgs bosons production interpreted in the $m_A - \tan\beta$ parameter space of the m_h^{mod} scenario. Combined result of the b-tagged and b-vetoed category is shown.

Figure 1.19: Limits on the production of a scalar particle decaying to a di-tau pair and produced in association with b quarks (left) or via gluon-gluon fusion (right). Still not produced...

$pp \rightarrow gg \rightarrow \phi$ 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 1.19. The limits in the production in association with b-quarks and via gluon fusion are shown separately. More information on the limit setting procedure and its validation can be found in Appendix ??.

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