CMS Physics Analysis Summary

Search for Neutral MSSM Higgs Bosons in the $\mu^+\mu^-$ final state with the CMS experiment in $pp$ Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

This paper presents a search for production of neutral Higgs bosons predicted by Supersymmetry using the $\mu\mu$ decay channel. The data from proton-proton collisions at $\sqrt{s} = 7$ TeV were recorded in 2011 with the CMS detector and correspond to an integrated luminosity of 4.96 fb$^{-1}$. The search is sensitive to SUSY Higgs boson production in association with a $b\bar{b}$ pair and via the gluon-gluon fusion process. In the $m_{h_{1}}^{\text{max}}$ scenario, this analysis excludes values of $\tan\beta$ between 16 and 26, at the 95% CL, for Higgs masses from 115 to 175 GeV/$c^2$. Less stringent limits in terms of $\tan\beta$ (between 26 and 40) are determined for higher values of the Higgs mass up to 300 GeV/$c^2$. 
1 Introduction

In the minimal supersymmetric extension of the standard model (MSSM), the Higgs sector contains two Higgs boson doublets. One doublet couples to the up-type and the other one to the down-type fermions. After electroweak symmetry breaking, five physical Higgs bosons remain. They are the CP-odd neutral scalar $A^0$, two charged scalars $H^\pm$ and the two CP-even neutral scalars $h^0$ and $H^0$ [1, 2]. Unless specified otherwise, the neutral Higgs bosons $h^0$, $A^0$ and $H^0$ will be collectively referred to as $\Phi^0$ in this analysis.

The phenomenology of the MSSM Higgs sector can be effectively described using only two parameters: $m_{A^0}$, the mass of the neutral scalar $A^0$, and $\tan \beta$, the ratio of the vacuum expectation values of the two doublets. The masses of the other four Higgs bosons can be expressed as a function of these two parameters. At large values of $\tan \beta$, if $m_{A^0} < 130 \text{ GeV/c}^2$, the masses of $A^0$ and $h^0$ are nearly degenerate. Conversely, if $m_{A^0} > 130 \text{ GeV/c}^2$, then the masses of $H^0$ and $A^0$ are nearly degenerate whereas $m_{h^0} \approx 130 \text{ GeV/c}^2$. The position of the crossover point depends mostly on the nature of the mass mixing in the stop sector. The relations between the masses of the MSSM Higgs bosons, computed in the framework of the MSSM $m_{h^0}^{\text{max}}$ scenario [1, 2], are shown in Fig. 1a.

The dependence of the $A^0$ width, $\Gamma_{A^0}$, on $m_{A^0}$ for different values of $\tan \beta$ is shown in Fig. 1b. The kinks observed for $m_{A^0} \sim 300 \text{ GeV/c}^2$ are due to the opening of the $t\bar{t}$ decay channel.

In the MSSM, Neutral Higgs production $pp \rightarrow \Phi^0 + X$ at the LHC is dominated by two processes: $b\bar{b}$-associated production, where $\Phi^0$ is produced together with a $b\bar{b}$ pair, $b\bar{b}\Phi^0$ (Fig. 2a), and the gluon-gluon ($gg$) fusion process, $gg\Phi^0$ (Fig. 2b).

The coupling $g$ of the MSSM Higgs boson to $b$-quarks is enhanced at large values of $\tan \beta$ with respect to that of the standard model Higgs:

$$g_{b\bar{b}H}^{\text{MSSM}} = \tan \beta \cdot g_{b\bar{b}H}^{\text{SM}} \quad (1)$$

In this case associated production dominates over the $gg$ fusion process.

Figure 1: The Higgs bosons masses in the MSSM $m_{h^0}^{\text{max}}$ scenario (a). The $A^0$ width, $\Gamma_{A^0}$, as a function of $m_{A^0}$ for various $\tan \beta$ values (b).
Figure 2: The Higgs bosons production processes in the MSSM: (a) $b\bar{b}$-associated production and (b) gluon-gluon fusion.

Results of previous searches for the MSSM neutral Higgs bosons performed at LEP, Tevatron and LHC can be found in [3–7]. Despite their lower branching ratios, the $\Phi^0 \rightarrow \tau^+\tau^-$ and $\Phi^0 \rightarrow \mu^+\mu^-$ decay channels provide higher sensitivity in experimental searches at LHC than $\Phi^0 \rightarrow b\bar{b}$, for which the background from the QCD multijet production is overwhelming. While the process $\Phi^0 \rightarrow \tau^+\tau^-$ has a branching ratio larger by a factor $(m_\tau/m_\mu)^2$ and provides better sensitivity in terms of limits, the $\Phi^0 \rightarrow \mu^+\mu^-$ channel has a cleaner experimental signature due to the full reconstruction of the final state. The $A^0$ production cross sections multiplied by the branching ratio $A^0 \rightarrow \mu^+\mu^-$ in the $(m_{A^0}, \tan\beta)$ plane is presented in Fig. 3.

In the context of the MSSM $m_\mu^{\text{max}}$ scenario, this paper describes the results of a search for neutral Higgs bosons $\Phi^0$ with the CMS detector at the LHC using the decay process $\Phi^0 \rightarrow \mu^+\mu^-$. The analysis is performed using proton-proton collision data sample corresponding to an integrated luminosity of 4.96 fb$^{-1}$. The analysis is sensitive to both production mechanisms, $b\bar{b}$-associated and gluon-gluon fusion production.

The results of the analysis and the calculation of the exclusion limits rely on estimating the expected background from data. Monte Carlo (MC) simulation is used to estimate the selection efficiency for the signal process and as a guidance in developing background estimation methods. Once the background estimation methods are defined, the data are used to control and...
2 The CMS Detector

A detailed description of the CMS detector can be found elsewhere [8]. The central feature of the CMS apparatus is a superconducting solenoid, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). The solenoid allows tracks with transverse momentum ($p_T$) as low as 100 MeV/$c$ to be reconstructed, and the tracker provides a $p_T$ resolution of 1% at 100 GeV/$c$. The energy resolution achieved by ECAL is $3\%/\sqrt{E_T}/$GeV while in HCAL it is $100\%/\sqrt{E_T}/$GeV. Muons are measured in gas-ionization detectors embedded in the steel return yoke.

3 Event Selection

The process $\Phi^0 \rightarrow \mu^+ \mu^-$ is experimentally characterized by the presence of two oppositely-charged muon tracks with high transverse momentum $p_T$. The two tracks are isolated from the other particles and jets in the event, and their invariant mass would correspond to the mass of the $\Phi^0$ boson. Such events also have a rather small missing energy ($E_{T\text{miss}}$) in the plane transverse to the beam direction. In the events where the $\Phi^0$ boson is produced in association with a $b\bar{b}$ pair, the $b$-quarks fragment into jets that can be identified by an appropriate $b$-tagging algorithm. Therefore the analysis requires events with two oppositely-charged isolated muons and with small $E_{T\text{miss}}$, to suppress the background from $t\bar{t}$ events. The events are assigned to one of the following three non-overlapping categories:

- **Category 1**: events with at least one jet tagged as a $b$-jet candidate. In this category, $b$-tagging enhances the amount of signal events with respect to the Drell-Yan background. Such events are candidates for the process $\Phi^0 b\bar{b}$ shown in Fig. 2a, with the subsequent decay $\Phi^0 \rightarrow \mu^+ \mu^-$. 

- **Category 2**: events where no $b$-jet candidate is reconstructed. The presence of an additional third muon $\mu_{3\text{rd}}$ in the event is required as a signature of the $b$-quark semileptonic decay. Such events are also candidates for the process $\Phi^0 b\bar{b}$, with the subsequent decay $\Phi^0 \rightarrow \mu^+ \mu^-$. 

- **Category 3**: events that do not belong to Category 1 or Category 2. This sample contains candidates of the $gg$-fusion process shown in Fig. 2b, with the subsequent decay $\Phi^0 \rightarrow \mu^+ \mu^-$. 

The dataset is collected using a trigger that requires at least one muon candidate with a transverse momentum $p_T$ above a defined threshold $p_{T\text{min}}$. This analysis uses the (unprescaled) muon trigger in the pseudorapidity range $|\eta| < 2.4$ with $p_{T\text{min}} = 24$ GeV/$c$ for the first part of the 2011 data sample, and with $p_{T\text{min}} = 30$ GeV/$c$ within $|\eta| < 2.1$ for the second part.

Each event is required to contain at least one well reconstructed primary vertex (PV) characterized by $|z_{PV}| < 24$ cm, where $z_{PV}$ is the distance of the PV from the nominal center of the CMS detector along the beam axis.

Muon candidates are reconstructed using both the tracker and the muon chamber information. The muons are required to be in the pseudorapidity range $|\eta| < 2.1$, with at least 11 hits in the tracker detector (strips and pixel) and at least one hit in the pixel detector. The $\chi^2/ndf$ of the global fit must be smaller than 10. The transverse and longitudinal impact parameters of
the track relative to the selected PV must be $|d_{xy}| < 0.02$ cm and $|d_z| < 15$ cm, respectively, in order to discard muon particles from cosmic rays events. The transverse momentum of the most energetic muon must have $p_T > 30$ GeV/$c$, whereas the second muon must have $p_T > 20$ GeV/$c$. Muon tracks are required to be isolated from the rest of the event activity. For this purpose an isolation variable is constructed using the sum of the transverse momenta of the particles reconstructed in the tracker and the transverse energy deposited in the calorimeter towers within a cone around the muon direction defined by $\Delta R = \sqrt{\Delta \eta^2 + \Delta \varphi^2} = 0.3$. This sum is corrected for pile-up effects as a function of the median $p_T$ of the jets [9] and the contribution of the muon is excluded. The muon is accepted if this corrected sum is less than 10% of the muon transverse momentum.

The analysis uses Particle Flow (PF) objects [10] to reconstruct jets and determine the $E_{T}^{\text{miss}}$ in the event. A correction for the jet resolution difference between data and simulation, and for Z-recoil is applied [11] to the simulated events. The selection cut $E_{T}^{\text{miss}} < 30$ GeV is applied, as it provides a strong rejection of the $t\bar{t}$ background, but still preserves most of the signal events.

A b-tagging algorithm [12] is used to identify jets that are likely to arise from the hadronization of $b$-quarks. Jets are reconstructed using the anti-$k_T$ jet selection algorithm [13] with a radius of 0.5. Their transverse momentum must be $p_{T\,\text{jet}} > 20$ GeV/$c$ in the pseudorapidity region $|\eta_{\text{jet}}| < 2.4$. In addition they should not contain the two leading muon candidates. This is achieved by requiring that the jet is separated from the muon track by a distance $\Delta R_{\mu\,-\text{jet}} = \sqrt{\Delta \eta^2 + \Delta \varphi^2} > 0.5$, where $\Delta \eta$ and $\Delta \varphi$ are the differences in pseudorapidity and azimuthal angle between the muon track and the jet direction.

To perform the $b$-tag and select events that belong to Category 1, tracks associated to a jet are ranked according to their impact parameter significance, $d$. The second largest $d$ in the jet is taken as the discriminator variable $d_{b\,-\text{tag}}$ for the whole jet. The event is considered $b$-tagged if it contains at least one reconstructed jet with $d_{b\,-\text{tag}} > 1.7$. In Fig. 4, the distribution of the $b$-tag discriminator variable $d_{b\,-\text{tag}}$ for the jet with the highest $p_T$ in the event is shown. The data are superimposed on the simulation for the expected background contributions. The expected $d_{b\,-\text{tag}}$ distribution for MC signal simulation is also shown.

Events that fail the $b$-tag selection are classified in Category 2 if an additional muon candidate, denoted as $\mu_{3\text{rd}}$, is found in the event. In signal events produced in association with $bb$, the $\mu_{3\text{rd}}$ is expected to be produced in $b$-hadron semileptonic decays and characterized by relatively low transverse momentum. The selection requires the muon to have a transverse momentum $p_T > 3$ GeV/$c$, a pseudo-rapidity $|\eta| < 2.4$ and a separation with respect to the two hard muons, $\Delta R > 0.5$. Additional quality cuts are applied to the track reconstructed in the Strips and Pixels detectors: more than 10 hits in total and more than 1 hit in the Pixel detector, track $\chi^2/ndf$ less than 1.8, $|d_{xy}| < 3.0$ cm and $|d_z| < 30$ cm.

Di-muon events not classified in Category 1 or Category 2 are assigned to Category 3.

In Fig. 5 the di-muon invariant mass distribution is shown for each of the three categories as well as the sum of the three distributions, both for data and simulated backgrounds. The expected di-muon distribution for the decay $\Phi^0 \to \mu^+\mu^-$, with $m_{\Phi^0} = 150$ GeV/$c^2$ and $\tan \beta = 30$ is superimposed for illustration.

Signal events were simulated using Pythia [14] over a large range of values of $m_{\Phi^0}$ and $\tan \beta$, as summarized in Table 1.

After the selection mentioned before, most of the remaining background events are due to the Drell-Yan process. In particular the $b\bar{b}Z^0$ process is an irreducible background for $b\bar{b}\Phi^0$ asso-
Figure 4: Distribution of the $b$-tag discriminator variable, $d_{b\text{-tag}}$, of the jet with highest transverse momentum in the event. Data and background simulation are superimposed. The expected $d_{b\text{-tag}}$ distribution for the signal process is also shown.

Associated production. Another important source of background is $t\bar{t}$ production (for Category 1) and $W^\pm W^\pm$ production (for Category 3), with $t$-quark or $W$ bosons decays leading to muons in the final state. These types of events were simulated using the program MadGraph [15]. Other less important sources of background that were still considered in the analysis, are the $W$ or $Z$ plus jets production processes $Z^0 \rightarrow \tau^+\tau^-$, $Z^0 \rightarrow e^+e^-$, $W^\pm Z^0$, $Z^0Z^0$, $W^\pm \rightarrow \ell^+\ell^-$ ($\ell = e, \mu, \tau$, QCD and single $t$ production. They were generated with MadGraph, Powheg [16] and Pythia. The decays of the $\tau$ were generated with Tauola [17]. These types of events are found to contribute in a negligible way to the three event categories, compared to the dominant $Z^0 \rightarrow \mu^+\mu^-$ background. Nevertheless it should be stressed that in the exclusion limits calculation the MC simulations of the various background processes are not used, but a fit is performed on data in order to estimate the background.

4 Selection Efficiency

While background shapes and normalizations are obtained from the data, selection efficiencies for signal events have to be determined using the simulation. This is the input from the simulation in the exclusion limits. This section describes the estimation of the selection efficiencies for signal events, using simulation with appropriate corrections to compensate for deficiencies in the description of data.

The trigger efficiency is measured with a tag & probe (TP) method using a clean sample of $Z^0 \rightarrow \mu^+\mu^-$ events. After correcting for small background contamination, the efficiency is measured in two dimensional bins of $p_T\mu$ and compared with the simulation predictions.

A muon candidate is considered as a tag muon if it fulfills all selection criteria already presented and fires the requested trigger. Probe muons are those which fulfill all selection criteria and together with the tagged muon have an invariant mass between 60 and 120 GeV/c$^2$. After the invariant mass selection some events can have more than one $Z^0$ candidate. Events with more than two probe muons are discarded. In the case of events with two probe muons, if
Figure 5: The $\mu^+\mu^-$ invariant mass distribution for Category 1 (a), 2 (b), 3 (c) and the sum of them (d). The expected di-muon invariant mass distribution for the decay $\Phi^0 \rightarrow \mu^+\mu^-$, with $m_{\Phi^0} = 150 \text{ GeV}/c^2$ and $\tan \beta = 30$ is superimposed.
only one satisfies the tag requirements, this one will be considered for the efficiency estimation. Otherwise, a random decision is made and only one of the probe muons is considered. The combinatorics are also considered, if both muons fulfill the tag condition they are counted twice in the numerator and the denominator. The trigger efficiency is measured with the same method also for the simulated events. These estimations are used to correct the event efficiency as measured from simulation taking into account the combinatorics at the trigger level and the $p_T\mu$-$\eta_\mu$ bin of each muon. The difference comes from the fact that in MC only one version of the trigger was simulated.

A muon candidate is built matching the track from the tracker detector (tracker muon) and the track from the muon chambers (standalone muon). The matching efficiency between the tracker and the standalone muon track to form a muon candidate is tested on data and simulation using a TP method, where the tagged track is a muon candidate that fulfills all the muon selection criteria presented before. Then a standalone muon track is searched as a probe in events where its combination with the tagged track has an invariant mass between 60 and 120 GeV/$c^2$. The efficiency is tested by measuring the fraction of probe muons in which the standalone track has the proper matching with a tracker muon track. The estimation is performed both on data and simulated events independently. The two estimations are consistent within 0.1%. Similar results are obtained for the tracker muon reconstruction and muon isolation. The efficiency for reconstructing a standalone muon is different by up to $7 \pm 0.6\%$ between data and MC, and therefore, a correction factor is applied. The efficiency for each event is calculated using the product of individual muon efficiencies according to the $p_T\mu$-$\eta_\mu$ bin of each muon, their efficiencies were multiplied given correction factor for each event. The statistical uncertainties on the correction factors were found to be 0.1%, in agreement with [18], and used as a systematic uncertainty on the signal estimate.

A tag & probe technique is used to control the modelling of the $b$-tagging description in the simulation. Within the sample of events with a muon pair having an invariant mass $M_{\mu^+\mu^-} > 60$ GeV/$c^2$, events with two jets of which at least one is $b$-tagged are selected. In these events the presence of a second $b$-tagged jet was searched for and the ratio $r_{T-P}^{b} = N_{2-tag}/N_{1-tag}$ was computed, where $N_{1-tag}$ is the number of events with at least one $b$-tagged jet and $N_{2-tag}$ is the number of events with two $b$-tagged jets. The estimation is performed on two separate samples: one with events having a transverse missing energy $E_T^{miss} < 30$ GeV, corresponding to the selection cut applied in the analysis, leading to a moderate amount of true $b$-jets, and one sample with $E_T^{miss} > 50$ GeV, that is enriched in $t\bar{t}$ events and thus with a high content of $b$-hadron decays. The ratio $r_{T-P}^{b}$ is measured both on data and simulation. The good agreement between data simulation in both cases is also consistent with the observation from [12]. The difference in the ratio $r_{T-P}^{b}$ is $3.6 \pm 3.4\%$ for the sample with $E_T^{miss} < 30$ GeV and $3.2 \pm 0.3\%$ for the sample with $E_T^{miss} > 50$ GeV. The difference between data and simulation was assigned as a systematic uncertainty as reported in Sec. 5.

The overall selection efficiency for the process $\Phi^0 \rightarrow \mu^+\mu^-$ depends significantly on the mass of the $\Phi^0$ boson and weakly on $\tan\beta$. In Fig. 6 the overall efficiency at the end of the analysis chain, for simulated samples of $b\bar{b}A^0$, $A^0 \rightarrow \mu^+\mu^-$ signal events is presented in the $\tan\beta$ and $m_{A^0}$ plane. Results for each of the three categories of events used in this analysis are shown separately.

5 Systematic Uncertainties

In this section the systematic uncertainties considered in the analysis are discussed in detail.
Effects due to the knowledge of the jet energy scale (JES) are estimated directly from the signal simulation considering a 5% calibration uncertainty on the measurement of the jet energy using the calorimeters (absolute scale), with an additional 2% uncertainty per unit of rapidity (relative scale) [19]. The systematic uncertainty is given by the ratio of the number of selected events before and after application of a Gaussian smearing. The uncertainty is not dependent on the invariant mass of the di-muon system. The total uncertainty due to JES is determined by the quadratic sum of the absolute and relative JES uncertainties. The JES systematic uncertainties are estimated for each of the three categories. They are considered separately in the limit calculation done for each category alone, while in the combined limit the anticorrelation is considered. If the JES is increased, then the systematic error for Category 1 is positive, while the ones for Category 2 and 3 are negative.

The simulated samples are reweighted according to the pile-up conditions present in the data. For these samples, the yield of signal events normalized to the integrated luminosity is found to be constant within 1%. Therefore, a systematic uncertainty of 1% is assigned to account for the uncertainty on the pile-up correction in the simulation.

The $E_T^{\text{miss}}$ measurement has an uncertainty of 5% as presented in [20]. To evaluate the effect of this uncertainty, the $E_T^{\text{miss}}$ in simulated events is subjected to a Gaussian smearing of 5% and the resulting efficiency is compared with the reference result. This process is repeated for a wide range of values of $\tan \beta$ and Higgs boson masses. The deviations in the selection efficiency relative to the nominal $E_T^{\text{miss}}$ value are within ±1.8%, and this is assigned as a systematic uncertainty.

The systematic uncertainty due to the $b$-tagging is taken as the difference between data and simulation determined to be 3.6% (see Sec. 4).

An imprecise modeling of the invariant mass resolution in the simulation can affect the signal efficiency. As the MSSM Higgs boson masses studied in this analysis are in the approximate range of 100-300 GeV/$c^2$, muons from $Z^0$ decay are used to estimate possible discrepancies between simulation and data. The di-muon spectrum around the $Z^0$ peak is fit using a Breit-Wigner function convoluted with a Gaussian function to account for the mass resolution. In this procedure the intrinsic width of the $Z^0$ boson is set constant to 2.4952 GeV/$c^2$ [21] in the Breit-Wigner function. The Gaussian width $\sigma$ is used as a free parameter. The procedure is applied to data and simulation separately. The differences between MC and 2011 data are $0.20 \pm 0.28\%$ and $2.6 \pm 1.8\%$ before and after $b$-tagging. Because these differences are consistent with 0 it is
considered that the resolution differences between data and MC simulations can be neglected.

The uncertainty on the efficiency of the detection of $\mu_3$rd candidates is estimated to be $\pm 1.2\%$, as explained in [22] and references therein.

The integrated luminosity systematic uncertainty is 2.2% as estimated in [23]. The uncertainty estimated for the choice of the PDFs and of $\alpha_s$ varies from 1 to 3% depending on $\tan \beta$ and the production mechanism, while for the renormalization and factorization scale, it varies from 5 to 13%. These uncertainties were estimated as explained in [24] and the scale uncertainty is mainly affecting the case when a Higgs boson is produced in association with jets.

Table 2 summarizes the systematic uncertainties that affect the determination of the signal efficiency. Whenever meaningful, their breakdown among the three event categories is also shown. These uncertainties are taken into account in the calculation of the exclusion limits described in Sec. 6. The uncertainty on the production cross-section of the three MSSM neutral Higgs bosons varies between $-20\%$ and $+16\%$ depending on the values of $m_{A^0}$ and $\tan \beta$ and is used only in the calculation of the $\pm 1\sigma$ and $\pm 2\sigma$ error bands of the exclusion limits in the $(m_{A^0}, \tan \beta)$ plane.

6 Results

The search for a Higgs signal and the exclusion limit calculation is performed using a data driven approach with the background contribution determined from a fit to the data as described in the next paragraph.

The shape of the expected signal ($A^0, h^0$ or $H^0$), for the various values assumed for $m_{A^0}$ and $\tan \beta$ is determined by a fit to the invariant mass distribution of the simulated signal events that pass the selection criteria. The distribution is modeled by the function $F_{\text{sig}}$, which is a linear combination of three Breit-Wigner (BW) functions normalized to unity, one for each Higgs boson taking into account its experimental resolution. The relative contribution of the three functions, $F_{BW\mu^0}$, $F_{BW\mu^0}$ and $F_{BW\mu^0}$ is parametrised as:

$$F_{\text{sig}} = a \cdot F_{BW\mu^0} + b \cdot F_{BW\mu^0} + (1 - a - b) \cdot F_{BW\mu^0}$$

(2)

The parameters that represent the mass and width of the three BW functions, and the relative contribution of the three Higgs bosons, $a$, $b$ and $(1 - a - b)$, are determined from the fit on simulated signal. An example is shown in Fig. 7a for $m_{A^0} = 140$ GeV/$c^2$ and $\tan \beta = 50$.

For each signal choice a linear combination of the functions describing the expected Higgs boson contribution and the background is fit to the data. In this procedure the parameters that describe the shape of the signal, determined in the previous step, are kept constant and only the relative amount of signal to background is varied. As the Drell-Yan is the dominant background process, the background fit function model is given by a BW function plus the photon exchange term proportional to $1/\mu^2 + \mu^+\mu^-$. Defining $x = M_{\mu^+\mu^-}$, the function describing the background, $F_{\text{bg}}$ is:

$$F_{\text{bg}} = e^{\lambda x} \left( \frac{f_{BWZ^0}}{N_{\text{norm}1}} \cdot \frac{\Gamma_{Z^0}}{(x - M_{Z^0})^2 + \frac{\Gamma_{Z^0}^2}{4}} + \frac{(1 - f_{BWZ^0})}{N_{\text{norm}2}} \cdot \frac{1 \text{GeV} / c^2}{x^2} \right)$$

(3)

where $e^{\lambda(x)}$ describes the exponential part of the parton density function and $N_{\text{norm}1,2}$ is given by the integral of corresponding function in the chosen mass range.
The parameters $\Gamma_{Z^0}$ and $M_{Z^0}$ are previously determined from a fit of the di-muon invariant mass around the $Z^0$ peak for each category of events. They are used as fixed parameters in $F_{\text{bkg}}$. In Fig. 7b the fit performance for events of Category 1 at the $Z^0$ resonance is shown. The detector resolution is included in the fitted width.

The function used to fit the data is therefore:

$$F = N \cdot \left[ (1 - f_{\text{Background}}) \cdot F_{\text{sig}} + f_{\text{Background}} \cdot F_{\text{bkg}} \right]. \quad (4)$$

The term $f_{\text{Background}}$ and the quantities $f_{BWZ^0}$ and $\lambda$ contained in $F_{\text{bkg}}$ are left to vary, whereas all previously determined parameters related to $F_{\text{sig}}$ are kept constant. The parameter $N$, the normalization factor, multiplied with $f_{\text{Background}}$ returns the number of expected background events. An example of the fit for data events with the signal hypothesis $m_{A^0} = 140 \text{ GeV}/c^2$ and $\tan \beta = 50$ is shown in Fig. 7c for events of Category 1.

A test of the stability of the fit results is illustrated in Fig. 7d where the expected signal for $m_{A^0} = 140 \text{ GeV}/c^2$ and $\tan \beta = 50$ is artificially added to the data. In this case the quantity $f_{\text{Background}}$ determined from the fit, multiplied by the number of events in the histogram, reproduces the expected number of background events determined from the histogram of Fig. 7c to within one standard deviation. The term $f_{\text{expected}}$ is an estimation of the expected signal calculated as the ratio between the number of selected MC signal events and the number of events in data with $100 < M_{\mu^+\mu^-} < 300 \text{ GeV}/c^2$. This ensures that the background calculation is robust against the possible presence of signal events in the data.

A further test on the stability of the determination of $f_{\text{Background}}$ is performed to estimate uncertainties related to the fit procedure. For given $m_{A^0}$ and $\tan \beta$ values, the number of background events estimated from $F_{\text{bkg}}$ in the region $m_{h^0} \pm 3 \cdot \Gamma_{h^0}$, $m_{H^0} \pm 3 \cdot \Gamma_{H^0}$ and $m_{A^0} \pm 3 \cdot \Gamma_{A^0}$, where the presence of the signal is expected, is computed. The number of background events is also determined in the case that the same mass regions are excluded from the fit range. Comparing the two results, the observed differences are found to vary between 1% and 6% for different $m_{A^0}$ values.

The additional uncertainty on the signal and background shape due to the statistical uncertainties of the fit parameters is also considered.

The confidence level (CL) of the exclusion limit in the $(m_{A^0}, \tan \beta)$ plane is calculated, using the Asymptotic CL algorithm [26] for events of Category 1, 2 and 3. The value of $\tan \beta$ at which the CL exceeds 95% is chosen for each mass point to perform the final limit calculation.

The limit on the rate is then transformed into a limit on the cross section times the branching ratio to muons. Using this limit on the cross section and the knowledge of the cross section in the MSSM, the limit can be projected on $\tan \beta$ to exclude a region in the $(m_{A^0}^0, \tan \beta)$ parameter plane.

Results are shown in Fig. 8, 9 and 10 for the three event categories. In Fig. 11 the combined exclusion limits are also presented. No deviation from the $+2\sigma$ uncertainty band is observed. Due to the limited statistics, the results for Category 2 are shown for a smaller invariant mass range.

## 7 Conclusions

The search for the neutral MSSM Higgs bosons $A^0$, $h^0$ and $H^0$ decaying to $\mu^+\mu^-$ is performed assuming the $m_{h^0}^{\text{max}}$ scenario. The data from proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ were
recorded in 2011 with the CMS detector and correspond to an integrated luminosity of 4.96 fb$^{-1}$.

For events with two oppositely charge muons in the $|\eta| < 2.1$ region and with high transverse momenta, $p_T > 20$ GeV/$c$ and at least one with $p_T > 30$ GeV/$c$, the study was performed on three separate categories of events. Events of Category 1 contain at least one $b$-tagged anti-$k_T$ jet with $p_T > 20$ GeV/$c$ and $|\eta| < 2.4$, to select the Higgs boson produced in association with a $b\bar{b}$ pair. If a $b$-tagged jet is not reconstructed, but an additional low transverse momentum muon is detected, the event belongs to Category 2. Such events can still contain semi-leptonic decays of $b$ hadrons, thus representing $b\bar{b}$ associated production. The gluon-gluon fusion production, where no $b$-quark is produced, is studied with events from the Category 3, i.e. those events that are not included in the previous two categories. No evidence of the MSSM $m_{h}^{max}$ scenario Higgs boson production is found within the sensitivity of the analysis.

The exclusion limits are obtained by fitting the background contribution directly from data. The Monte Carlo simulation is used to compute the expected signal contribution. The analysis excludes at 95% CL in the $m_{h}^{max}$ scenario values of $\tan\beta$ between 16 and 26 for Higgs masses from 115 to 175 GeV/$c^2$. Less stringent limits in terms of $\tan\beta$ (between 26 and 40) are determined for higher values of the Higgs mass up to 300 GeV/$c^2$. 


References


Table 1: The $m_{A^0}$ and $\tan \beta$ values for which the signal event samples were simulated.

<table>
<thead>
<tr>
<th>$m_{A^0}$ [GeV/c^2]</th>
<th>$m_{A^0}$ step [GeV/c^2]</th>
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</tr>
<tr>
<td>200-300</td>
<td>25</td>
<td>5-55</td>
<td>5</td>
</tr>
<tr>
<td>300-500</td>
<td>50</td>
<td>5-55</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2: Sources of systematic uncertainties and the corresponding relative errors for the efficiency of analysis selections. The Q-scale stands for renormalization and factorization scale. This and the PDF and $\alpha_s$ uncertainties are describing only the signal acceptance. Theoretical uncertainties on the cross-section, including effects related to PDF choice, $\alpha_s$ and the Q-scale, are considered as an additional systematic uncertainty when setting limits in terms of $\tan \beta$ and $m_{A^0}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT &amp; $\mu$ Rec. Eff.</td>
<td>±0.1</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>±1.8</td>
</tr>
<tr>
<td>JES (Cat.1)</td>
<td>$^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>JES (Cat.2)</td>
<td>$^{+0.02}_{-0.04}$</td>
</tr>
<tr>
<td>JES (Cat.3)</td>
<td>$^{+0.4}_{-0.2}$</td>
</tr>
<tr>
<td>$b$-tag</td>
<td>±3.6</td>
</tr>
<tr>
<td>$\mu_{3\sigma}$ as in [22]</td>
<td>±1.2</td>
</tr>
<tr>
<td>pile up</td>
<td>±1</td>
</tr>
<tr>
<td>integrated luminosity</td>
<td>±2.2</td>
</tr>
<tr>
<td>PDF and $\alpha_s$</td>
<td>±1 to ±3</td>
</tr>
<tr>
<td>Q-scale</td>
<td>±5 to ±13</td>
</tr>
<tr>
<td>$\sigma_{A^0/H^0/H^0}$</td>
<td>$^{+16}_{-20}$</td>
</tr>
</tbody>
</table>

$m_{A^0}$ and $\tan \beta$ dependent [25] (not for $\sigma \times B.R.$ vs. $m_{A^0}$)
Figure 7: Fit of the invariant mass distribution of the expected signal for \(m_{A^0} = 140 \text{ GeV}/c^2\) and \(\tan \beta = 50\) (a). Fit of the di-muon invariant mass around the \(Z^0\) peak to determine the mass and width of the BW function, for events of Cat. 1 (b). Fit of the di-muon spectrum of data from Cat. 1 (c). A test of the fit procedure is illustrated in (d) where the expected Monte Carlo signal is artificially added to the data. The term \(\frac{f_{\text{expected}}}{f_{\text{Signal}}}\) is an estimation of the expected signal calculated as the ratio between the number of selected MC signal events and the number of events in data with \(100 < M_{\mu^+\mu^-} < 300 \text{ GeV}/c^2\). For all distributions the difference between the fit results and the data is shown in the \(\Delta N\) distribution.
Figure 8: The exclusion limit for the MSSM production cross-section times the B.R. at 95% CL (a) and its projection in the \((m_{A^0}, \tan \beta)\) plane (b) for Category 1. The excluded regions are above the curves.

Figure 9: The exclusion limit for the MSSM production cross-section times the B.R. at 95% CL (a) and its projection in the \((m_{A^0}, \tan \beta)\) plane (b) for Category 2. The excluded regions are above the curves.
Figure 10: The exclusion limit for the MSSM production cross-section times the B.R. at 95% CL (a) and its projection in the \(m_{A^0}, \tan \beta\) plane (b) for Category 3. The excluded regions are above the curves.

Figure 11: The combined exclusion limit for the MSSM production cross-section times the B.R. at 95% CL (a) and its projection in the \(m_{A^0}, \tan \beta\) plane (b). The excluded regions are above the curves.