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

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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 $m_{\text{h}}^{\text{max}}$ 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 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]. The neutral Higgs bosons will be collectively referred to as $\Phi^0$ in this paper, unless specified otherwise. 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.

In the MSSM, Neutral Higgs production $pp \to \Phi^0 + X$ at the LHC is dominated by $b\bar{b}$-associated production, where $\Phi^0$ is produced together with a $b\bar{b}$ pair, $b\bar{b}\Phi^0$ (Fig. 1(a)), and the gluon-gluon ($gg$) fusion process, $gg\Phi^0$ (Fig. 1(b)). The associated production dominates over the $gg$ fusion process at large values of $\tan\beta$ due to the enhance of coupling to $b$-quarks. Results of previous searches for the MSSM neutral Higgs bosons performed at LEP, Tevatron and LHC can be found in [3, 4, 5, 6]. Despite its lower branching ratio, the $\Phi^0 \to \mu^+\mu^-$ decay 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 $A^0 \to \mu^+\mu^-$ in the ($m_{A^0}, \tan\beta$) plane is presented in Fig. 1. 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.

The analysis is sensitive to both production mechanisms, $b\bar{b}$-associated and gluon-gluon fusion production and is performed using proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ data corresponding to an integrated luminosity of 4.96 fb$^{-1}$. The results and the calculation of the exclusion limits rely on estimating the background from data. Monte Carlo (MC) simulation is used to estimate the signal selection efficiency and cross-check the data-driven background estimation methods.

2. The CMS Detector and Event Selection

A detailed description of the CMS detector can be found elsewhere [7]. The central feature of the CMS apparatus is a superconducting solenoid, providing a 3.8 T magnetic field. Within the field
volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). The tracks can be reconstructed with transverse momentum \( p_T \) as low as 100 MeV/c and a \( p_T \) resolution of 1% at 100 GeV/c. The energy resolution achieved by ECAL is \( 3%/\sqrt{E_T/\text{GeV}} \) while in HCAL it is \( 100%/\sqrt{E_T/\text{GeV}} \). Muons are measured in gas-ionization detectors embedded in the steel return yoke.

The process \( \Phi^0 \rightarrow \mu^+\mu^- \) is characterized by the presence of two oppositely-charged muon tracks with high \( p_T \). The events are assigned to one of the following three non-overlapping categories. Category 1 contains 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. 1(a). In Category 2 are selected the events where no b-jet candidate is reconstructed, but an additional third muon, \( \mu_{3rd} \), in the event is required as a signature of the b-quark semileptonic decay. Such events are also candidates for the process \( \Phi^0 b\bar{b} \). The events that do not belong to Category 1 or Category 2 are forming the Category 3. This sample contains candidates of the gg-fusion process shown in Fig. 1(b).

The dataset is collected using a trigger that requires at least one muon candidate with a \( p_T \) above 24 GeV/c for the first part of the 2011 data sample and 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).

Muon candidates are reconstructed using both the tracker and the muon chamber information. The muons are required to be in the pseudorapidity range \( |\eta| < 2.1 \) and most energetic muon must have \( p_T > 30 \text{ GeV}/c \), whereas the second muon \( p_T > 20 \text{ GeV}/c \). A series of quality criteria presented in [8] need to be fulfill by the muon track in order to be accepted as good reconstructed candidates. The signal events have a rather small missing energy \( (E_T^{\text{miss}}) \) in the plane transverse to the beam direction. The analysis uses Particle Flow (PF) objects [9] to reconstruct jets and determine the \( E_T^{\text{miss}} \) in the event. The selection cut \( E_T^{\text{miss}} < 30 \text{ GeV} \) is applied, as it provides a strong rejection of the \( t\bar{t} \) background, but still preserves most of the signal events.

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 [10]. Jets are reconstructed using the anti-\( k_T \) jet selection algorithm [11] with a radius of 0.5 in the \( |\eta_{\text{jet}}| < 2.4 \) region with \( p_T > 20 \text{ GeV}/c \). In addition they should be well separated from the muon track by a distance of \( \Delta R_{\mu-jet} > 0.5 \) in pseudorapidity and azimuthal angle. To perform the b-tag, 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 for the whole jet. Events that fail the b-tag selection are classified in Category 2 if an additional muon candidate, \( \mu_{3rd} \), is found in the event. In signal events produced in association with \( b\bar{b} \), the \( \mu_{3rd} \) is expected to be produced in \( b \)-hadron semileptonic decays. It is required to have a \( p_T > 3 \text{ GeV}/c \) in \( |\eta| < 2.4 \) range, be well separated with respect to each of the two hard muons, \( \Delta R > 0.5 \), and fulfill additional track quality cuts [8].

In Fig. 2 the di-muon invariant mass distribution is shown for each of the three categories, both for data and simulated backgrounds. The expected di-muon distribution for the decay \( \Phi^0 \rightarrow \mu^+\mu^- \), with \( m_{A_0} = 150 \text{ GeV}/c^2 \) and \( \tan\beta = 30 \) is superimposed for illustration. Signal events were simulated using Pythia [12] over a large range of values of \( m_{A_0} \) and \( \tan\beta \).

After the selection mentioned before, most of the remaining background events are due to the Drell-Yan process. The \( b\bar{b}Z^0 \) process is the irreducible background for \( b\bar{b}\Phi^0 \) associated production. Another important source of background is \( t\bar{t} \) production (for Category 1) and \( W^\pm W^\mp \) production.
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(for Category 3), with t-quark or W bosons decays leading to muons in the final state. Other less important sources of background that were still considered in the analysis, are the \(Z^0\) (\(\tau^+\tau^-\), \(e^+e^-\)) or \(W^\pm\) plus jets production processes, \(W^\pm Z^0\), \(Z^0 Z^0\), QCD and single \(t\) production [8].

3. Background Estimation and Exclusion Limits

The search for a Higgs signal and the exclusion limit calculation are performed using a data driven approach with the background contribution determined from a fit to the data. 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. The distribution is modeled by the function \(F_{\text{sig}}\), which is a linear combination of three Breit-Wigner (BW) functions normalized to unity, taking into account the experimental resolution. The relative contribution of the three functions, \(F_{\text{BW} h^0}\), \(F_{\text{BW} H^0}\) and \(F_{\text{BW} A^0}\) is parametrised as:

\[
F_{\text{sig}} = a \cdot F_{\text{BW} h^0} + b \cdot F_{\text{BW} H^0} + (1 - a - b) \cdot F_{\text{BW} A^0}
\]

The parameters that represent the mass and width of the three BW functions, and the relative contribution of the three Higgs bosons are determined from the fit on simulated signal events.

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 \(1/M_{\mu^+\mu^-}^2\). Defining \(x = M_{\mu^+\mu^-}\), the function describing the background is:

\[
F_{\text{bkg}} = e^{\lambda x} \left( f_{\text{BW} Z^0} \frac{\Gamma_{Z^0}}{N_{\text{norm}1}} \cdot \frac{1}{x - M_{\mu^+\mu^-}^2 + \frac{\Gamma_{Z^0}^2}{4}} + (1 - f_{\text{BW} Z^0}) \cdot \frac{1}{1\text{GeV}/c^2} \cdot \frac{1}{x^2} \right)
\]

where \(e^\lambda(x)\) describes the exponential part of the parton density function and \(N_{\text{norm}i}\) 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 \(F_{\text{bkg}}\). The detector resolution is included in the fitted width. The function used to fit the data is \(F = N \cdot (1 - f_{\text{Background}}) \cdot F_{\text{sig}} + f_{\text{Background}} \cdot F_{\text{bkg}}\). The term \(f_{\text{Background}}\) and the quantities \(f_{\text{BW} Z^0}\) 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 from

\[\text{Figure 2: The } \mu^+\mu^- \text{ invariant mass distribution for Category 1 (a), 2 (b) and 3 (c). The expected signal for the decay } \Phi^0 \to \mu^+\mu^- \text{, with } m_{\Phi^0} = 150 \text{ GeV}/c^2 \text{ and } \tan \beta = 30 \text{ is superimposed.}\]
the number of events in data with $100 < f < 120$.

The term of background events determined from the histogram of Fig. 3 (a) within one standard deviation.

A test of the fit stability is illustrated in Fig. 3(b) where the expected signal for $m_A^0 = 140$ 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. 3(a) within one standard deviation. The term $f_{\text{Signal}}$ is calculated as the ratio between the number of selected MC signal events and the number of events in data with $100 < M_{H^+H^+} < 300$ GeV/$c^2$. This ensures that the background calculation is robust against the possible presence of signal events in the data.

**Category 1** with the signal hypothesis $m_A^0 = 140$ GeV/$c^2$ and $\tan \beta = 50$ is shown in Fig. 3(a). A test of the fit stability is illustrated in Fig. 3(b) where the expected signal for $m_A^0 = 140$ 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. 3(a) within one standard deviation.

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.

The systematic uncertainty of the fit method is found to vary between 1% and 6% for different $m_A^0$ values. Additional dominant uncertainties [8] are due to measurement of the $E_T^{\text{miss}}$ (1.8%), the
b-tagging (3.6%), the integrated luminosity (2.2%), the parton distribution function (up to 3%), the
renormalization and factorization scale (from 5% to 13%) as well as the theoretical cross-section
(from 16% to 20%) which is needed when limits in terms of tan\(\beta\) and \(m_{A^0}\) are calculated.

No evidence for the neutral MSSM Higgs bosons was found therefore exclusion limits are
calculated. The confidence level (CL) of the exclusion limit in the \((m_{A^0}, \tan\beta)\) plane is calculated,
using the Asymptotic CL algorithm [13] 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 certain region in the \((m_{A^0}, \tan\beta)\) parameter plane.

In Fig. 4 the combined exclusion limits are presented. The results for each category alone can be
seen in [8]. No deviation from the +2\(\sigma\) uncertainty band is observed.

4. Conclusions

The search for the neutral MSSM Higgs bosons \(A^0, h^0\) and \(H^0\) decaying to \(\mu^+\mu^-\) is performed
assuming the \(m_{h^\text{max}}\) scenario. The proton-proton collisions data analyzed here were recorded at
\(\sqrt{s} = 7\) TeV with the CMS detector and correspond to 4.96 fb\(^{-1}\). No evidence of the MSSM \(m_{h^\text{max}}\)
scenario Higgs boson production is found within the sensitivity of the analysis.

The exclusion limits are obtained by fitting the background contribution from data while the
Monte Carlo simulation is used only to compute the expected signal contribution. The analysis
excludes at 95% CL in the \(m_{h^\text{max}}\) scenario values of \(\tan\beta\) between 16 and 26 for Higgs mass 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\(^2\).

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