Search for Neutral MSSM Higgs Bosons Decaying to \( \tau \nu \) in pp Collisions at \( s = 7 \) and \( 8 \) TeV

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Search for neutral MSSM Higgs bosons decaying to $\mu^+\mu^-$ in pp collisions at $\sqrt{s} =$ 7 and 8 TeV

CMS Collaboration

CERN, Switzerland

ABSTRACT

A search for neutral Higgs bosons predicted in the minimal supersymmetric standard model (MSSM) for $\mu^+\mu^-$ decay channels is presented. The analysis uses data collected by the CMS experiment at the LHC in proton–proton collisions at centre-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 5.1 and 19.3 fb$^{-1}$, respectively. The search is sensitive to Higgs bosons produced either through the gluon fusion process or in association with a $b\bar{b}$ quark pair. No statistically significant excess is observed in the $\mu^+\mu^-$ mass spectrum. Results are interpreted in the framework of several benchmark scenarios, and the data are used to set an upper limit on the MSSM parameter $\tan \beta$ as a function of the mass of the pseudoscalar A boson in the range from 115 to 300 GeV. Model independent upper limits are given for the product of the cross section and branching fraction for gluon fusion and $b\bar{b}$ quark associated production at $\sqrt{s} =$ 8 TeV. They are the most stringent limits obtained to date in this channel.

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1. Introduction

The predictions of the standard model (SM) [1–7] of fundamental interactions have been confirmed by a large number of experimental measurements. The observation of a new boson with a mass of 125 GeV and properties compatible with those of the SM Higgs boson [8–10] confirms the mechanism of the electroweak symmetry breaking (EWSB). Despite the success of this theory in describing the phenomenology of particle physics at present collider energies, the mass of the Higgs boson in the SM is not protected against quadratically divergent quantum-loop corrections at high energy. Supersymmetry (SUSY) [11,12] is one example of alternative models that address this problem. In SUSY, such divergences are cancelled by introducing a symmetry between fundamental bosons and fermions.

The minimal supersymmetric extension of the standard model (MSSM) [13,14] predicts the existence of two Higgs doublet fields. One doublet couples to up-type and one to down-type fermions. After EWSB, five physical Higgs bosons remain: a CP-odd neutral scalar $A$, two charged scalars $H^\pm$, and two CP-even neutral scalar particles $h$ and $H$. The neutral bosons $h$, $A$, and $H$, will be generally referred to as $\phi$ collectively in this paper, unless differently specified.

At lowest order in perturbation theory, the Higgs sector in the MSSM can be described in terms of two free parameters: $m_A$, the mass of the neutral pseudoscalar $A$, and $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets. The masses of the other four Higgs bosons can be expressed in terms of these two parameters and other measured quantities, such as the masses $m_W$ and $m_Z$ of the $W$ and $Z$ bosons, respectively. In particular, the masses of the neutral MSSM scalar Higgs bosons $H$ and $h$ are given [13] by

$$m_{H,h} = \left[ \frac{1}{2} \left( m_A^2 + m_Z^2 \pm \left( (m_A^2 + m_Z^2)^2 \right. \right. \right. \right.$$

$$\left. \left. \left. - 4m_A^2m_Z^2\cos^2 2\beta \right) \right]^{1/2} \right]^1/2$$

(1)

The A and H bosons are degenerate in mass above 140 GeV and for small $\cos \beta$ (large $\tan \beta$) values. This expression also provides an upper bound on the mass of the light scalar Higgs boson, corresponding to $m_h \leq m_Z\cos 2\beta$. The value can become as large as $m_h \approx 135$ GeV once radiative corrections are taken into account [15].

The main production mechanisms for the three neutral $\phi$ bosons at the LHC are the associated production with $b\bar{b}$ quarks (AP), given at the leading order by the Feynman diagram shown in Fig. 1 (top), and the gluon fusion (GF) process, shown in Fig. 1 (bottom) [16–18]. The GF process with virtual $t$ or $b$ quarks in the...
part of the $m_A$–$\tan \beta$ parameter space is excluded within the $m_{h_{\text{FP}}}$
scenario, and new benchmarks were therefore proposed in which the
MSSM parameters are adjusted to have $m_h$ in the interval 122 to
128 GeV, but with a wider range of $\tan \beta$ and $m_A$ values [19,
31,32]. To do this, the $m_{h_{\text{FP}}}$ scenario was reformulated in two
versions, $m_{h_{\text{FP}}}^{\text{mod}+}$ and $m_{h_{\text{FP}}}^{\text{mod}−}$, corresponding to different values of
the top squark mixing parameter. Other recently proposed scenarios
[31] are the light top squark (light stop) model, which results in
a modified GF rate, and the light tau slepton (light stau) model,
which yields a modified $h \to γγ$ branching fraction. Such mod-
elves are expected mainly to affect the Higgs boson production cross
section and not the kinematic properties of the events. A list of the
parameters of the various scenarios can be found in Ref. [23]. The
results presented in this paper are obtained in the framework of
the MSSM $m_{h_{\text{FP}}}^{\text{mod}−}$ scenario. Comparisons are also made with other
benchmarks.

2. The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting
soyoid of 6 m internal diameter, providing a magnetic field
at 3.8 T. Within the solenoid volume are a silicon pixel and strip
tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL),
and a brass and scintillator hadron calorimeter (HCAL), each com-
prised of a barrel and two endcap sections. Muons are measured
in gas-ionization detectors embedded in the steel flux-return yoke
outside the solenoid. Forward calorimetry extends the coverage
provided by the barrel and endcap detectors up to pseudorapidity
$|η|<5$. A detailed description of the CMS detector, together with a
definition of the coordinate system and kinematic variables, can be
found in Ref. [33]. The CMS offline event reconstruction creates a
global event description using the particle flow (PF) technique [34].
The PF event reconstruction attempts to reconstruct and identify
each particle with an optimized combination of all subdetector in-
formation. The missing $p_T$ vector is defined as the projection on
the plane perpendicular to the beams of the negative vector sum
of the momenta of all reconstructed particles in an event. Its mag-
nitude is referred to as $E_{\text{miss}}^\text{jet}$.

An average of 9 and 21 pp collisions take place in any LHC
bunch crossing, respectively at 7 and 8 TeV, because of the large
luminosity of the machine and the size of the total inelastic cross
section. These overlapping events (pileup) are characterized by
small-$p_T$ tracks, compared to the particles produced in a $φ \to
μ^+μ^−$ event, and their presence can degrade the detector capa-
ability to reconstruct the objects relevant for this analysis. The primary
vertex is chosen from all reconstructed interaction vertices as the
one with the largest sum in the squares of the $p_T$ of the associ-
ated tracks. The charged tracks originating from another vertex are
then removed.

Offline jet reconstruction is performed using the anti-$k_T$
clustering algorithm [35,36] with a distance parameter of 0.5. The jet
momentum is defined by the vectorial sum of all the PF particles
momenta in the jet, and found in simulation to be within 5% to
10% of the true hadron-level momentum, with some $p_T$ and $η$
dependence. Extra energy coming from pileup interactions affects
the momentum measurement. Corrections to the measured jet energy
are therefore applied. They are derived from event simulation, and
confirmed with in-situ measurements using energy balance in dijet
and Z/photons + jet events [37].

Muons are measured in the pseudorapidity range $|η|<2.4$, us-
ing detection planes based on three technologies: drift tubes, cath-
ode strip chambers, and resistive-plate chambers. Matching muons
to tracks measured in the silicon tracker provides relative $p_T$ reso-
lutions for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel

loop is dominant at small and moderate values of $\tan \beta$. At large
$\tan \beta$ the coupling of $φ$ to down-type quarks is enhanced relative
to the SM [19] and the AP process becomes dominant. Similarly, the
coupling of the $φ$ boson to charged leptons is also enhanced at large
$\tan \beta$.

This paper reports on a search for the MSSM neutral Higgs bosons
produced either by the AP or GF mechanisms, where the
Higgs bosons decay via $φ \to μ^+μ^−$. The analysis is sensitive to
all three bosons, h, H, and A in the mass range between 115 and
300 GeV. The search is performed by the CMS collaboration using
data recorded in pp collisions at the LHC, corresponding to an
integrated luminosity of 5.1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 19.3 fb$^{-1}$at
$\sqrt{s} = 8$ TeV. The common experimental signature of the two
processes is a pair of oppositely charged muons with high transverse
momentum ($p_T$) and a small imbalance of $p_T$ in the event. The AP
process is characterized by the presence of additional jets originating
from $b$ quarks ($b$ jets), whereas the events with only jets from
light quarks or gluons are sensitive to the GF production mecha-
nism. The presence of a signal would be characterized by an excess
of events over the background in the dimuon invariant mass corre-
spor ding to the $φ$ mass value.

Although the product of the cross section and the branching
fraction for the $μ^+μ^−$ channel is a factor $10^3$ smaller than for the
Corrections

Fig. 1. Leading-order diagrams for the main production processes of MSSM Higgs
bosons at the LHC (top) in association with $b\bar{b}$ production and (bottom) through
gluon fusion.
and better than 6% in the endcaps. The $p_T$ resolution in the barrel is better than 10% for muons with $p_T$ up to 1 TeV [38].

3. Simulated samples

Simulated samples are used to model the signal and to determine the efficiency of the signal selection. Background samples are also simulated to optimize the selection criteria. The normalization and distribution of the background events are measured from data.

The signal samples are generated using the Monte Carlo (MC) event generator PYTHIA 6.424 [39] for a wide range of $m_A$ and tan $\beta$ values, as listed in Table 1, for the AP and the GF production mechanisms. The $\phi$ production cross sections and their corresponding uncertainties are provided by the LHC Higgs Cross Section Working Group [16–18]. The cross sections for the GF process in the $m_{\text{max}}$ scenario are obtained using the HIGLU program [40,41], based on next-to-leading order (NLO) quantum chromodynamics (QCD) calculations. The SUSHI program [42] is used for the other benchmarks. For the AP process, the four-flavor NLO QCD calculation [43, 44] and the five-flavor next-to-next-to-leading order (NNLO) QCD calculation are implemented in MAD@NLO [45] and combined using the Santander matching scheme [46]. The Higgs Yukawa couplings computed with the FeynHiggs program [47] are used in the calculations. The decay branching fractions to muons in the different benchmark scenarios are obtained with FeynHiggs and HDECAY [48]. Further details on signal generation can be found in Refs. [16–18].

The values of $m_A$ predicted by FeynHiggs differ typically by a few GeV from those computed with PYTHIA. The invariant mass spectrum of the h boson is therefore shifted to match the FeynHiggs prediction. The small difference between PYTHIA and FeynHiggs in assessing the width of the h boson is of the order of 100 MeV, and therefore neglected, since the experimental mass resolution is at least one order of magnitude larger. The PYTHIA parameters used to simulate the signal are those for the $m_{\text{max}}$ scenario. Since for a given set of $m_A$ and tan $\beta$ values, the kinematic properties of the final state are the same for all the scenarios, the simulated samples based on the $m_{\text{max}}$ benchmark are also used to check the validity of the other models. Further details on this procedure and the related systematic uncertainties are discussed in Section 7.

The main source of background for the $\phi$ production and decay to $\mu^+\mu^-$ is Drell–Yan muon-pair production, $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$. Another background is from oppositely charged muon pairs produced in decays of top quarks in $t\bar{t}$ production. These events are simulated using the MadGraph 5.1 [49] generator. Other background processes such as $W^+W^-, W^+Z, Z\gamma$ and ZZ are generated with PYTHIA. The MC samples also include simulated pileup events to reproduce the overlapping pp interactions present in the data. All generated events are processed through a detailed simulation of the CMS detector based on GEANT4 [50] and are reconstructed with the same algorithms used for data.

4. Event selection

The experimental signature of the MSSM Higgs bosons decay considered in this analysis is a pair of oppositely charged muons with high $p_T$. The invariant mass of the pair corresponds to the mass of the $\phi$ boson within the experimental resolution. Moreover, the process is characterized by a small $E_T^{\text{miss}}$ in the event. If the $\phi$ boson is produced in association with a $b\bar{b}$ pair, the presence of at least one $b$ quark jet is expected.

The details of the event selection are listed below, and summarized in Table 2. The events are selected using a single-muon trigger, which requires at least one isolated muon with $p_T > 24$ GeV in the pseudorapidity range $|\eta| < 2.1$. The distance of the primary vertex along the z axis from the nominal centre of the detector must be $|z_{PV}| < 24$ cm. Muon candidates are reconstructed and identified using both the inner tracker and the muon detector information. The selected events must have at least two oppositely-charged muon candidates, each with $p_T > 25$ GeV. In events with more than two muon candidates, the two with opposite charges and the highest $p_T$ are retained. The $\eta$ of both muon candidates is chosen to match the trigger acceptance. Each muon track must have at least one hit in the pixel detector, more than five or eight layers with hits in the tracker, respectively, for the 8 and 7 TeV data and a directional matching to hits in at least two different muon detector planes. In addition the global fit to the hits of the muon candidate must include at least one hit in the muon detector. The $\chi^2$/dof of the global fit of the muon track must be smaller than 10. These requirements ensure a good measurement of the momentum, and significantly reduce the amount of hadronic punch-through background [38]. To reject cosmic ray muons, the transverse and longitudinal impact parameters of each muon track must satisfy the requirements $|d_{xy}| < 0.02$ cm and $|d_z| < 0.1$ cm, respectively. Both parameters are defined relative to the primary vertex. To ensure that the trigger muon candidate is well-matched to the reconstructed muon track, at least one of the two muon tracks is required to match the direction of the trigger candidate within a cone $\Delta R = 0.2$, where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ is the distance between the muon track and the trigger candidate direction in the $\eta-\phi$ plane, with $\phi$ being the azimuthal angle measured in radians. Both reconstructed muon candidates must fulfill isolation criteria. A muon isolation variable is constructed using the scalar sum of the $p_T$ of all PF particles, except the muon, reconstructed within a cone $\Delta R = 0.4$ around the muon direction. A correction is applied to account for the possible contamination from neutral particles arising from pileup interactions. A muon is accepted if the value of the corrected isolation variable is less than 12% of the muon $p_T$.

A selection based on $E_T^{\text{miss}}$ provides good separation between signal events and $t\bar{t}$ background, in the case of leptonic decay of
the W boson from top decay. The $E^{\text{miss}}_T$ distributions for events collected at $\sqrt{s} = 7$ and 8 TeV are shown in Fig. 2 for events with a reconstructed muon pair with invariant mass $m_{\mu^+\mu^-} > 60$ GeV. The background contributions from SM processes are superimposed. For illustration, the expected distribution for signal processes is also shown for $m_A = 150$ GeV and $\tan \beta = 30$. Studies performed using the simulation show that the $E^{\text{miss}}_T$ distribution for signal events does not vary significantly for different $m_A$ and $\tan \beta$ assumptions, and indicate that the selection $E^{\text{miss}}_T < 35$ GeV provides highest sensitivity for signal at both centre-of-mass energies.

The reconstructed jets are required to have transverse momenta $p_T^{\text{jet}} > 20$ GeV within the range $|\eta| < 2.4$. A multivariate analysis technique is used to remove jets from pileup interactions [51]. Tagging of b quarks in jets relies on the combined secondary-vertex discriminator [52], based on the reconstruction of the secondary vertex from weakly decaying b hadrons. The discriminant $b_{\text{disc}}$ is constructed from tracks and secondary vertex information, and helps to distinguish jets containing b, c, or light-flavour hadrons. Jets with an associated $b_{\text{disc}} > 0.679$ are considered to be b tagged. This value represents a good compromise between efficiency to tag b jets in signal events from AP ($\approx 80\%$) and mistagging probability for light-quark jets ($\approx 1\%$). Fig. 3 shows the distribution of $b_{\text{disc}}$ in events that satisfy the selection $E^{\text{miss}}_T < 35$ GeV, for the data collected in the two beam energies. For each event, the largest value of $b_{\text{disc}}$ is selected. The distribution of signal events from the AP process for $m_A = 150$ GeV and $\tan \beta = 30$ is superimposed. Jets originated from b quark fragmentation tend to be emitted more forward in signal events than for tt, thus resulting in a lower observed b-jet multiplicity. For this reason the tt background is further suppressed by rejecting events with more than two b-tagged jets, without significantly affecting the selection efficiency for signal.

The events are split into two mutually-exclusive categories. The first category (C1) contains events with at least one jet identified as originated from b-quark fragmentation (b tagged), and provides highest sensitivity to AP production channel. Events that do not contain b-tagged jets are assigned to category 2 (C2), and provide sensitivity to GF production. The dimuon invariant mass distributions for the C1 and C2 categories are shown in Fig. 4 for data and simulated events for both centre-of-mass energies. The distributions expected for MSSM Higgs bosons with $m_A = 150$ GeV and $\tan \beta = 30$, derived from the $m_{\text{mod}}^+ \rightarrow \mu^+\mu^-$ scenario are also given for comparison. A double peak structure around 125 and 150 GeV appears in the C2 category, due to the h boson and A + H bosons, respectively. The lower peak is not visible in C1, as the h production is suppressed in the AP mechanism relative to the GF process.
Fig. 4. The dimuon invariant mass distribution for events that belong to C1 (upper left) and C2 category (upper right), for data and simulated events at $\sqrt{s} = 7$ TeV. The corresponding quantities are shown for $\sqrt{s} = 8$ TeV (lower left and lower right). The expected contributions to signal assuming the $m_{\text{SUSY}} = 150$ GeV and $\tan\beta = 30$ are displayed for comparison.

5. Signal selection efficiency

While the calculations for the MSSM cross sections performed in the narrow-width approximation refer to the on-shell Higgs boson production, at large values of $m_A$ and $\tan\beta$ the convolution of the larger intrinsic signal widths with the parton distribution functions (PDF) results in a non-negligible fraction of signal events produced significantly off-shell. Events with invariant mass significantly smaller than its nominal value have a lower reconstruction efficiency than those produced near the mass peak. For consistency, we define signal efficiency as the probability for a signal event with the generated invariant mass close to its nominal value to be reconstructed and pass all selection requirements of this analysis. The closeness is defined using a window of size equal to 3 times the intrinsic signal width (an uncertainty associated with this definition is evaluated using a window of 5 times its width, as discussed in Section 7). With this definition, the product of the MSSM Higgs boson production cross section, luminosity and signal efficiency provides the normalization for the Higgs boson produced near on-shell. The full predicted rate of signal events also contains an additional off-shell contribution, which varies with $m_A$ and $\tan\beta$ and is less than 5% for $m_A < 250$ GeV and $\tan\beta < 15$, and can be as large as 15% for $m_A = 300$ GeV and $\tan\beta = 30$.

Additional corrections are applied to the signal efficiency to take into account differences between data and simulation in the muon trigger, reconstruction, and isolation efficiencies. A correction is also applied to account for known data-simulation discrepancies in the b tagging efficiency and mistagging probability. The corrections are summarized by a weight factor, which is assigned to each signal event. The average of the weight factors computed over all the events is very close to one, reflecting the fact that the simulation describes the data with good accuracy.

Fig. 5 shows the signal efficiency at $\sqrt{s} = 8$ TeV for AP (top) and GF (bottom) process after combining the two event categories C1 and C2. The efficiencies at $\sqrt{s} = 7$ TeV are similar. The band in the figure represents the variation of the efficiency due to the limited statistics of the samples used. The relative amount of AP and GF events in the two event categories varies with $m_A$ and $\tan\beta$, since the production cross sections of the two processes depend on these parameters. For example, in the case $m_A = 150$ GeV and $\tan\beta = 30$, more than 90% of the signal events in C1 would be from AP production, and about 60% in C2. For $m_A = 150$ GeV and $\tan\beta = 5$, where the GF contribution becomes more relevant, the content of AP events would be 60% in C1 and only 15% in C2.

6. Fit procedure

The procedure described below is applied separately to C1 and C2 events. The event selection criteria are applied to the simulated samples listed in Table 1. For each sample, and for each of the three $\phi$ bosons, the invariant mass distribution of the events that pass the event selection is approximated with a Breit–Wigner
function convolved with a Gaussian, that accounts for detector resolution. This analytical expression provides a good description of the signal shape for all the $m_A$ and $\tan\beta$ values. The three functions are denoted $F_h$, $F_H$, and $F_A$, and contain the mass and width of the Breit–Wigner and the width of the Gaussian as free parameters. The function $F_{\text{sig}}$ represents the expected signal yield, and it is a linear combination of the three functions described above:

$$F_{\text{sig}} = w_h F_h + w_H F_H + w_A F_A,$$

where $w_h$, $w_H$, and $w_A$, are the number of events containing $h$, $H$, and $A$ bosons, respectively, calculated according to their expected production cross sections. An example of this procedure is shown in Fig. 6 (top) for $m_A = 150$ GeV and $\tan\beta = 30$. The highest peak represents the superposition of the contributions from $H$ and $A$ bosons, that in this case are almost degenerate in mass.

Since the Drell–Yan muon pair production is the dominant background process, it is modeled by a Breit–Wigner function plus a photon-exchange term, which is proportional to $1/m_{\mu^+\mu^-}^2$. Defining $m = m_{\mu^+\mu^-}$, the function $F_{\text{bkg}}$ becomes:

$$F_{\text{bkg}} = e^{i\mu m} \left[ \frac{f_Z}{N_1} \frac{1}{(m-m_Z)^2 + \Gamma_Z^2/4} + \frac{(1-f_Z)}{N_2} \frac{1}{m^2} \right],$$

where $e^{i\mu m}$ describes the effects of the PDF, and the $N_{\text{norm}}$ terms correspond to the integral of the corresponding functions in the chosen mass range. The quantity $f_Z$ represents the contribution of the Breit–Wigner term relative to the photon-exchange term. The quantities $\lambda$ and $f_Z$ are free parameters of the fit. The parameters $\Gamma_Z$ and $m_Z$ are determined separately for the C1 and the C2 events from a fit to the $m_{\mu^+\mu^-}$ distribution in the mass range of the $Z$ boson between 80 and 120 GeV. The fit provides the effective values of such quantities, that include detector and resolution effects for each set of data. Their values are used in $F_{\text{bkg}}$ and are kept constant in the fit.

A linear combination of the two functions for the expected signal and background is then used in an unbinned likelihood fit to the data:

$$F_{\text{fit}} = (1-f_{\text{bkg}}) F_{\text{sig}} + f_{\text{bkg}} F_{\text{bkg}}.$$  

(4)

The parameters that describe the signal are determined in the fit of the simulated signal to Eq. (2), for each pair of $m_A$ and $\tan\beta$ values. Subsequently, they are fixed in $F_{\text{fit}}$, where the free parameters are the quantities $\lambda$, $f_Z$, and $f_{\text{bkg}}$. The fraction of signal events is defined as $f_{\text{sig}} = (1 - f_{\text{bkg}})$. The data are fitted to $F_{\text{fit}}$ in the mass range from 115 to 300 GeV for each point in the $m_A$ and $\tan\beta$ parameter space. As an example, the fit to the data of C2 at $\sqrt{s} = 8$ TeV is illustrated in Fig. 6, (bottom), assuming a signal with $m_A = 150$ GeV and $\tan\beta = 30$.

7. Systematic uncertainties

The following sources of systematic uncertainties are taken into account, and the impact of one standard deviation change is reported in terms of a variation in the nominal signal efficiency defined in Section 5.

The limited number of simulated events introduces an uncertainty in the signal selection efficiency that is at most 2%. The muon trigger, reconstruction, identification, and isolation efficiencies are determined from data using a tag-and-probe technique [38]. The uncertainty in the trigger efficiency correction is
A systematic uncertainty in the pileup multiplicity is evaluated by changing the total cross section for inelastic pp collisions in simulation. The corresponding uncertainty on the signal efficiency is at most 0.8% in both categories.

The event fractions in the two categories depend on the b tagging efficiency and the mistagging probability. The uncertainty in the b tagging efficiency is estimated by comparing data and simulated events with samples of enriched b quark content and different topologies, as described in Ref. [52]. The uncertainty in the efficiency to detect b jets is about 3.0%. Similarly, the uncertainty in the mistagging rate is about 10%. Their overall contribution to the selection efficiency is weighted by the fraction of AP and GF events that are expected in each event category, which depends on \( m_A \) and \( \tan \beta \). The largest overall uncertainty is 3.0% for C1, and 0.4% for C2 events.

The jet energy scale uncertainty is estimated by smearing the jet momentum by a factor depending on \( p_T \) and \( \eta \) of each jet, as described in Ref. [37]. The effect on signal selection efficiency is 4.0% for events that belong to the C1 and 0.5% for the C2 categories, at \( \sqrt{s} = 8 \) TeV. For \( \sqrt{s} = 7 \) TeV the corresponding numbers are 3.8% and 0.6%. The uncertainty in the \( E_T^{\text{miss}} \) scale and resolution is estimated through comparisons between data and simula-
ting the signal + background model (as described in Section 6) to pseudo-data generated for different alternative background models. Such alternative background parametrizations include Bernstein polynomials and combinations of Voigtian and exponential functions. Bias estimates are performed for mass points between \( m_A = 115 \) and 300 GeV. For each \( m_A \) value, the largest bias among the tested functions is taken as the resulting uncertainty. The bias is implemented as a floating additive contribution to the number of signal events, constrained by a Gaussian probability density with mean of zero and width set to the systematic uncertainty. The width of the Gaussian is the largest systematic uncertainty, and the effect is to increase the expected limit on the presence of a signal by 20% in the region near \( m_A = 120 \) GeV and by about 10% at larger mass values.

In the mass range between 115 and 300 GeV, that is relevant for this analysis, the mass resolution is estimated to be between 1.2 and 4 GeV. Uncertainties in the muon momentum determination can affect the invariant mass measurement, and have been carefully studied in data and simulation [38]. The dimuon invariant mass resolution for masses above the Z peak has been previously studied in the search for a SM Higgs decaying to a dimuon pair [58]. The mass resolution determined from data at the Z mass value is 1 GeV, in excellent agreement with the prediction from simulation. This value is consistent with the mass resolution of 1.2 GeV that we estimate from simulation for a mass of 115 GeV, that corresponds to the lower edge of the Higgs mass range considered in this analysis.

The overall capability of the analysis to detect the presence of a signal is verified by introducing a hypothetical simulated signal in the data using the shape parametrization discussed in Section 6. The average measured number of signal events is found to be within 1.3% of the injected signal for the C1 category, and within 4.3% for the C2 category. These differences are assigned as systematic uncertainties.

8. Results

No evidence of MSSM Higgs bosons production is observed in the mass range between 115 and 300 GeV, where the analysis has been performed. Upper limits at 95% confidence level (CL) on the parameter \( \tan \beta \) are computed using the CLs method [59, 60], which is a modified frequentist criterion, and are presented as a function of \( m_A \). Systematic uncertainties are incorporated as nuisance parameters and treated according to the frequentist paradigm [61]. The results are obtained from a combination of both event categories and centre-of-mass energies. For each value of \( m_A \), the value of \( \tan \beta \) at which the CL exceeds 95% is chosen to define the exclusion limit on that \( m_A \). This is performed for all the \( m_A \) values and the results are shown in Fig. 7. These results are obtained within the \( m_{\text{h}}^{\text{mod}} \) scenario. The observed upper limits range from \( \tan \beta \) of about 15 in the low-\( m_A \) region, to above 40 at \( m_A = 300 \) GeV. For larger values of \( m_A \) on the \( \tan \beta \) upper limit becomes large, exceeding \( \tan \beta \approx 50 \), for which the MSSM cross-section predictions are not reliable.

A comparison with the results obtained for the \( m_{\text{h}}^{\text{mod+}}, m_{\text{h}}^{\text{max}} \) light stop and light stau scenarios is also performed. The exclusion limits computed within these other benchmark models are all very similar. For any value of \( m_A \), the quantity \( \Delta \tan \beta = \tan \beta_{\text{mod+}} - \tan \beta_{\text{scenario}} \) represents the difference of the \( \tan \beta \) values at which the 95% CL limit is determined if an alternative scenario is used. Fig. 8 shows the quantity \( \Delta \tan \beta \) as a function of \( m_A \) for all the tested scenarios. For most \( m_A \) values, the 95% CL limits on \( \tan \beta \) computed within a given scenario differ by less than one unit from the results obtained within the \( m_{\text{h}}^{\text{mod+}} \) scenario.

Limits on the production cross section times decay branching fraction \( \sigma B(\phi \rightarrow \mu^+\mu^-) \) for a generic single neutral boson \( \phi \) are determined. In this model independent analysis no assumption is made on the cross section, mass, and width of the \( \phi \) bosons, which is sought as a single resonance with mass \( m_\phi \). The analysis is performed assuming the narrow width approximation, for which the intrinsic width of the signal is smaller than the invariant mass resolution. For this purpose the simulated signal of the \( A \) boson for the case \( \tan \beta = 10 \) is used as a template to compute the detection efficiency for a generic \( \phi \) boson decaying to a muon pair. The single \( \phi \) boson is assumed to be produced entirely either via the AP or the GF process, and the search for a single resonance with mass \( m_\phi \) is performed. The 95% CL exclusion on \( \sigma B(\phi \rightarrow \mu^+\mu^-) \) is determined as a function of \( m_A \), separately for the two production mechanisms. The combination of events belonging to C1 and C2 is shown in Fig. 9, assuming the \( \phi \) boson is produced either via the AP or the GF process. Only data collected at \( \sqrt{s} = 8 \) TeV are used, as they provide a better sensitivity because of the higher luminosity. In addition, since the \( \phi \) production cross section depends on the centre-of-mass energy, a combination with the 7 TeV results would introduce a model
dependence in the description of the cross section evolution with energy.

9. Summary

A search has been performed for neutral MSSM Higgs bosons decaying to $\mu^+\mu^-$ from pp collisions collected with the CMS experiment at $\sqrt{s} = 7$ and 8 TeV, corresponding to integrated luminosities of 5.1 and 19.3 fb$^{-1}$, respectively. The analysis is sensitive to Higgs boson production via gluon fusion, and via association with a bb quark pair. The results of the search, which has been performed in the mass range between 115 and 300 GeV, are presented in the $m_{\phi}$ framework of the MSSM. With no evidence for MSSM Higgs boson production, this analysis excludes at 95% CL values of tan$\beta$ larger than 40 for Higgs boson masses up to 300 GeV. Comparisons with $m_{\phi}$, $m_{\phi}^\text{max}$, light stop, and light stau scenarios are also presented, and offer very similar results relative to the $m_{\phi}^\text{mod-}$ benchmark. Limits are determined on the product of the cross section and branching fraction $\sigma \times B(\phi \rightarrow \mu^+\mu^-)$ for a generic neutral boson $\phi$ at $\sqrt{s} = 8$ TeV, without any assumptions on the MSSM parameters. In this case the $\phi$ boson is assumed to be produced either in association with a bb quark pair or directly through gluon fusion, and sought as a single resonance with mass $m_{\phi}$. Exclusion limits are in the mass region from 115 to 500 GeV. For $m_{\phi} = 500$ GeV, values of $\sigma \times B(\phi \rightarrow \mu^+\mu^-) > 4$ fb are excluded at 95% CL for both production mechanisms. These are the most stringent results in the dimuon channel to date.

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40 Also at University of Athens, Athens, Greece.
41 Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
42 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
43 Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
44 Also at Gaziosmanpasa University, Tokat, Turkey.
45 Also at Mersin University, Mersin, Turkey.
46 Also at Cag University, Mersin, Turkey.
47 Also at Piri Reis University, Istanbul, Turkey.
48 Also at Adiyaman University, Adiyaman, Turkey.
49 Also at Ozyegin University, Istanbul, Turkey.
50 Also at Izmir Institute of Technology, Izmir, Turkey.
51 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
52 Also at Marmara University, Istanbul, Turkey.
53 Also at Kafkas University, Kars, Turkey.
54 Also at Yıldız Technical University, Istanbul, Turkey.
55 Also at Kahramanmaras Sütçü Imam University, Kahramanmaras, Turkey.
56 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
57 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
58 Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
59 Also at Utah Valley University, Orem, USA.
60 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
61 Also at Argonne National Laboratory, Argonne, USA.
62 Also at Erzincan University, Erzincan, Turkey.
63 Also at Hacettepe University, Ankara, Turkey.
64 Also at Texas A&M University at Qatar, Doha, Qatar.
65 Also at Kyungpook National University, Daegu, Republic of Korea.