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# Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states ☆

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ABSTRACT

Results are reported from a search for non-standard-model Higgs boson decays to pairs of new light bosons, each of which decays into the $\mu^+\mu^-$ final state. The new bosons may be produced either promptly or via a decay chain. The data set corresponds to an integrated luminosity of 5.3 $\text{fb}^{-1}$ of proton–proton collisions at $\sqrt{s} = 7$ TeV, recorded by the CMS experiment at the LHC in 2011. Such Higgs boson decays are predicted in several scenarios of new physics, including supersymmetric models with extended Higgs sectors or hidden valleys. Thus, the results of the search are relevant for establishing whether the new particle observed in Higgs boson searches at the LHC has the properties expected for a standard model Higgs boson. No excess of events is observed with respect to the yields expected from standard model processes. A model-independent upper limit of $0.86 \pm 0.06$ fb on the product of the cross section times branching fraction times acceptance is obtained. The results, which are applicable to a broad spectrum of new physics scenarios, are compared with the predictions of two benchmark models as functions of a Higgs boson mass larger than 86 GeV/$c^2$ and of a new light boson mass within the range 0.25–3.55 GeV/$c^2$.



## 1. Introduction

The observation of a new particle [1,2] with a mass near 125 GeV/$c^2$ in searches for the standard model (SM) Higgs boson [3–5] at the Large Hadron Collider (LHC) raises the critical question of whether the new particle is in fact the SM Higgs boson. The precision of the comparisons of the new particle's production and decay properties with the final states predicted by the SM will improve with additional data. However, distinguishing a true SM Higgs boson from a non-SM Higgs bosons with couplings moderately different from the SM values will remain a challenge. Searches for non-SM Higgs boson production and decay modes are therefore particularly timely as they provide a complementary path, which in many cases can allow a discovery or rule out broad ranges of new physics scenarios with existing data.

This Letter presents a search for the production of a non-SM Higgs boson (h) decaying into a pair of new light bosons (a) of the same mass, which subsequently decay to pairs of oppositely charged muons (*dimuons*) isolated from the rest of the event activity: $\mathrm{h} \to 2\mathrm{a} + \mathrm{X} \to 4\mu + \mathrm{X}$, where X denotes possible additional particles from cascade decays of a Higgs boson. This sequence of decays is predicted in several classes of models beyond the SM. One example is the next-to-minimal supersymmetric standard model (NMSSM) [6–14], which extends the minimal supersymmetric standard model (MSSM) [15–17] by an additional gauge singlet field under new $U(1)_{\mathrm{PQ}}$ symmetry in the Higgs sector of the superpotential. Compared to the MSSM, the NMSSM naturally generates the mass parameter $\mu$ in the Higgs superpotential at the electroweak scale [18] and significantly reduces the amount of fine tuning required [19–21]. The Higgs sector of the NMSSM consists of 3 CP-even Higgs bosons $\mathrm{h}_{1,2,3}$ and 2 CP-odd Higgs bosons $\mathrm{a}_{1,2}$.

In the NMSSM, the CP-even Higgs bosons $\mathrm{h}_1$ and $\mathrm{h}_2$ can decay via $\mathrm{h}_{1,2} \to 2\mathrm{a}_1$, where one of the $\mathrm{h}_1$ or $\mathrm{h}_2$ is a SM-like Higgs boson that could correspond to the newly observed state at the LHC with a mass near 125 GeV/$c^2$ [1,2] and $\mathrm{a}_1$ is a new CP-odd light Higgs boson [22–26]. The Higgs boson production cross section may differ substantially from that of the SM, depending on the parameters of a specific model. The new light boson $\mathrm{a}_1$ couples weakly to SM particles, with the coupling to fermions proportional to the fermion mass, and can have a substantial branching fraction $\mathcal{B}(\mathrm{a}_1 \to \mu^+\mu^-)$ if its mass is within the range $2m_\mu < m_{\mathrm{a}_1} < 2m_\tau$ [27,28].

Pair production of light bosons can also occur in supersymmetric models with additional hidden (or *dark*) valleys [29–31], which are motivated by the excesses in positron spectra observed by satellite experiments [32,33]. These dark-SUSY models predict cold dark matter with a mass scale of ∼1 TeV/$c^2$, which can provide

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the right amount of relic density due to the Sommerfeld enhancement in the annihilation cross section arising from a new $U(1)_D$ symmetry [34,35]. In these models, $U(1)_D$ is broken, giving rise to light but massive dark photons $\gamma_D$ that weakly couple to the SM particles via a small kinetic mixing [36–38] with photons. The lightest neutralino $n_1$ in the *visible* (as opposed to *hidden*) part of the SUSY spectrum is no longer stable and can decay via e.g. $n_1 \to n_D + \gamma_D$, where $n_D$ is a light dark fermion (dark neutralino) that escapes detection. The SM-like Higgs boson can decay via $h \to 2n_1$, if $m_h > 2m_{n_1}$. The branching fraction $\mathcal{B}(h \to 2n_1)$ can vary from very small to large, bounded by the LHC measurements in the context of Higgs searches, since the bounds obtained at LEP can be circumvented [31]. The lack of an anti-proton excess in the measurements of the cosmic ray spectrum constrains the mass of $\gamma_D$ to be $\leqslant \mathcal{O}(1)$ GeV/$c^2$ [39]. Assuming that $\gamma_D$ can only decay to SM particles, the branching fraction $\mathcal{B}(\gamma_D \to \mu^+\mu^-)$ can be as large as 45%, depending on $m_{\gamma_D}$ [31]. The Higgs boson production cross section may or may not be enhanced compared to the SM, depending on the specific parameters of the model. The search described in this Letter was designed to be independent of the details of specific models, and the results can be interpreted in the context of other models predicting the production of the same final states.

Previous searches for the pair production of new light bosons decaying into dimuons were performed at the Tevatron with a 4.2 fb$^{-1}$ data sample [40] and more recently at the LHC with a 35 pb$^{-1}$ [41] and a 1.9 fb$^{-1}$ [42] data samples. Associated production of the light CP-odd scalar bosons has been searched for at $e^+e^-$ colliders [43,44] and the Tevatron [45]. Direct production of the $a_1$ has been studied at the LHC [46], but in the framework of NMSSM the sensitivity of these searches is limited by the typically very weak coupling of the $a_1$ to SM particles. The most stringent limits on the Higgs sector of the NMSSM are provided by the WMAP data [47] and LEP searches [48–50] ($m_{h_1} > 86$ GeV/$c^2$). In the framework of dark SUSY, experimental searches for $\gamma_D$ have focused on the production of dark photons at the end of SUSY cascades at the Tevatron [51–53] and the LHC [41]. Furthermore, if the newly observed particle at the LHC [1,2] is indeed a Higgs boson, the studies of its SM decays will provide additional constraints on the allowed branching fractions for the non-SM decays.

## 2. The CMS detector

The analysis presented in this Letter uses experimental data collected by the Compact Muon Solenoid (CMS) experiment at the LHC in 2011. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and $\theta$ is the polar angle with respect to the direction of the counterclockwise proton beam that is the $z$-axis of the CMS reference frame. The tracker provides an impact parameter resolution of ∼15 μm and a transverse momentum ($p_T$) resolution of about 1.5% for 100 GeV/$c$ particles. Muons are measured in gas-ionization detectors embedded in the steel return yoke. The muon detectors are made using the following technologies: drift tubes ($|\eta| < 1.2$), cathode strip chambers ($0.9 < |\eta| < 2.4$), and resistive-plate chambers ($|\eta| < 1.6$). Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1 and 5% for $p_T$ values up to 1 TeV/$c$. A more detailed description can be found in Ref. [54].

## 3. Data selection

The search is performed as a "blind" analysis, i.e. data in the signal region were not used to define the reconstruction and selection procedures. The analysis is based on a data sample corresponding to an integrated luminosity of 5.3 fb$^{-1}$ of proton–proton collisions at $\sqrt{s} = 7$ TeV, obtained in 2011. The data were collected with a trigger selecting events containing at least two muons, one with $p_T > 17$ GeV/$c$ and one with $p_T > 8$ GeV/$c$. In the offline analysis, events are selected by requiring at least one primary vertex reconstructed with at least four tracks and with its $z$ coordinate within 24 cm of the nominal collision point. Offline muon candidates are built using tracks reconstructed in the inner tracker matched to track segments in the muon system, using an arbitration algorithm [55]. The candidates are further required to have at least eight hits in the tracker, with the $\chi^2$/Ndof $< 4$ for the track fit in the inner tracker (where Ndof is the number of degrees of freedom), and at least two matched segments in the muon system. The data are further selected by requiring at least four offline muon candidates with $p_T > 8$ GeV/$c$ and $|\eta| < 2.4$; at least one of the candidates must have $p_T > 17$ GeV/$c$ and be reconstructed in the central region, $|\eta| < 0.9$. Application of the selection requirements described above yields 1,745 events in the data. The trigger efficiency for the selected events is high (96–97%) and is nearly independent of the $p_T$ and $\eta$ of any of the four muons. The $|\eta| < 0.9$ requirement is tighter than that imposed by the trigger, but eliminates significant model dependence attributable to the reduced trigger performance in the forward region in the presence of multiple spatially close muons. This $\eta$ requirement causes an overall reduction in the analysis acceptance of about 20%, as obtained in a simulation study with one of the NMSSM benchmark samples used in the analysis.

Next, oppositely charged muons are grouped into dimuons (a muon may be shared between several dimuons) if their pairwise invariant mass satisfies $m_{\mu\mu} < 5$ GeV/$c^2$ and if either the fit of the two muon tracks for a common vertex has a $\chi^2$ fit probability greater than 1% or the two muon tracks satisfy the cone size requirement $\Delta R(\mu^+, \mu^-) = \sqrt{(\eta_{\mu^+} - \eta_{\mu^-})^2 + (\phi_{\mu^+} - \phi_{\mu^-})^2} < 0.01$, where $\phi$ is the azimuthal angle in radians. The $\Delta R$ requirement compensates for the reduced efficiency of the vertex probability requirement for dimuons with very low mass ($m_{\mu\mu} \gtrsim 2m_\mu$), in which the two muon tracks are nearly parallel to each other at the point of closest approach.

Once all dimuons are constructed, only events with exactly two dimuons not sharing common muons are selected for further analysis. There is no restriction on the number of ungrouped (*orphan*) muons. Assuming that each dimuon is a decay product of a new light boson, we require that the two dimuons have invariant masses in the range 0.25–3.55 GeV/$c^2$. We reconstruct $z_{\mu\mu}$, the projected $z$ coordinate of the dimuon system at the point of the closest approach to the beam line, using the dimuon momentum measured at the common vertex and the vertex position. We ensure that the two dimuons originate from the same pp interaction by requiring $|z_{\mu\mu_1} - z_{\mu\mu_2}| < 1$ mm. This selection yields 139 events in data and it is fully efficient for signal events while reducing the probability of selecting rare events with dimuons from two separate primary interactions.

To suppress backgrounds with dimuons coming from jets, we require that the dimuons be isolated from other activity in the event, using the criterion $I_{\text{sum}} < 3$ GeV/$c$, where the isolation parameter of the dimuon system $I_{\text{sum}}$ is defined as the scalar sum of the transverse momenta of all additional charged tracks with $p_T > 0.5$ GeV/$c$ within a cone of size $\Delta R = 0.4$ centered on the momentum vector of the dimuon system. Tracks used in the