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Search for a Light Pseudoscalar Higgs Boson in the Dimuon Decay Channel in pp Collisions at $\sqrt{s} = 7$ TeV

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The dimuon invariant mass spectrum is searched in the range between 5.5 and 14 GeV for a light pseudoscalar Higgs boson a, predicted in a number of new physics models, including the next-to-minimal supersymmetric standard model. The data sample used in the search corresponds to an integrated luminosity of 1.3 fb^{-1} collected in pp collisions at $\sqrt{s} = 7$ TeV with the CMS detector at the LHC. No excess is observed above the background predictions and upper limits are set on the cross section times branching fraction $\sigma \times \mathcal{B}(pp \to a \to \mu^+\mu^-)$ in the range of 1.5–7.5 pb. These results improve on existing bounds on the $ab\bar{b}$ coupling for $m_a < m_{\Upsilon(1S)}$ and are the first significant limits for $m_a > m_{\Upsilon(3S)}$. Constraints on the supersymmetric parameter space are presented in the context of the next-to-minimal model.

Low energy supersymmetry is an elegant solution to the hierarchy problem that arises in the standard model, provides a candidate for dark matter, and allows for the unification of gauge couplings at the grand-unified-theory scale [1–5]. However, the minimal supersymmetric model (MSSM) has an *ad hoc* Higgs superfield mixing parameter (μ) and requires very large masses for the supersymmetric partner of the top quark (stop) in order for the lightest *CP*-even Higgs boson to be heavier than 122 GeV without large stop mixing [6]. Both problems are solved in the next-to MSSM (NMSSM) (a review can be found in Ref. [7]), which extends the MSSM by introducing a complex singlet superfield which necessarily contains a scalar field component. Associated super- and scalar-potential terms generate an effective μ parameter and easily raise the mass of the light Higgs boson without requiring a heavy stop [8,9]. The added scalar field expands the Higgs sector to three *CP*-even scalars (h_1, h_2, h_3), two *CP*-odd scalars (a_1, a_2), and two charged scalars (H^+, H^-). The a_1 is a superposition of the MSSM doublet pseudoscalar (a_{MSSM}) and the additional singlet pseudoscalar of the NMSSM (a_S): $a_1 = \cos\theta_A a_{\mathrm{MSSM}} + \sin\theta_A a_S$, where θ_A is the mixing angle. The NMSSM has two symmetries that, if imposed (e.g., at the grand-unified-theory scale), imply that small m_{a_1}, even $m_{a_1} < 2m_B$ (where m_B is the B meson mass), and $|\cos\theta_A| \ll 1$ are very natural possibilities [10]. However, the reduced couplings $C_{a_1 b\bar{b}} = C_{a_1 \mu^+\mu^-} = C_{a_1 \tau^+\tau^-} = \tan\beta\cos\theta_A$ can be sizeable for large values of $\tan\beta$, the ratio of neutral Higgs field vacuum

expectation values, even if $\cos\theta_A$ is small. More generally, superstring modeling suggests the possibility of many light a particles, at least some of which couple to $\mu^+\mu^-$, $\tau^+\tau^-$, and $b\bar{b}$ [11]. In the following, a (a_1) denotes a general (NMSSM) light pseudoscalar Higgs boson.

Searches for a light a are mainly sensitive to $C_{ab\bar{b}}$ [12,13]. For $m_a < m_{\Upsilon(3S)}$, the strongest constraints on $C_{ab\bar{b}}$ are those from *BABAR* [14,15]. For $m_a > m_{\Upsilon(3S)}$, only the Tevatron and Large Hadron Collider (LHC) have sensitivity [16], using production via $gg \to a$, where the coupling $C_{ab\bar{b}}$ derives from quark (especially bottom and top) triangle loops. This process, plus higher-order corrections, leads to a large cross section due to the large gg parton luminosity at small gluon momentum fractions, provided the $C_{ab\bar{b}}$ ($q = t, b$ in particular) couplings are not too suppressed. This large cross section will typically lead to a significant number of $gg \to a \to \mu^+\mu^-$ events even though $\mathcal{B}(a \to \mu^+\mu^-)$ is small.

In the NMSSM context, where $C_{a_1 b\bar{b}} = \tan\beta\cos\theta_A$, the existing limits [17,18] translate to rather modest limits on $|\cos\theta_A|$. Such bounds do not strongly constrain NMSSM models of interest for possibly hiding a light Higgs boson because of $h \to aa$ decays (with $a \to 2\tau, 2g, 2c, 2s$ decays being dominant [19]) that are not excluded by large electron-positron (LEP) collider experiments [20,21].

At tree level, the branching fraction for $a \to \mu^+\mu^-$ depends on m_a and on $\tan\beta$, but not on $\cos\theta_A$ [16]. It is nearly constant for $m_a > 5$ GeV and ranges from 10^{-3} to 4×10^{-3} for $\tan\beta = 1$ to $\tan\beta = 50$, changing very little once $\tan\beta > 2$. In contrast, $\sigma(gg \to a)$ increases rapidly with $\tan\beta$ due to the fact that $C_{ab\bar{b}} \propto \tan\beta$. However, top-quark loop contributions and higher-order corrections imply a slower $\sigma(gg \to a)$ increase than $\tan^2\beta$. In the context of the NMSSM, all $q\bar{q}$ couplings of the a_1 are proportional to $\cos\theta_A$, implying that $\sigma(gg \to a_1) \propto \cos^2\theta_A$.

This Letter presents the results of a search in pp collisions for a light a with a mass near the Υ resonances decaying into two oppositely charged muons. Data used for this analysis were recorded by the Compact Muon Solenoid (CMS) detector in pp collisions at a center-of-mass energy of 7 TeV, between August and November 2011. The sample corresponds to a total integrated luminosity of 1.3 fb^{-1}, collected with a dedicated trigger. As estimated in Ref. [16] and explicitly demonstrated here, CMS has sensitivity beyond the *BABAR* and CDF limits, for the latter due to the higher production yield $[\sigma_{\mathrm{LHC}}(pp \to a) \sim 4.5\sigma_{\mathrm{Tevatron}}(p\bar{p} \to a)]$ and the higher acceptance and efficiency of the muon detector. Furthermore, the CMS analysis can extend the limits into the $m_a > m_{\Upsilon(3S)}$ mass range.

The central feature of the CMS detector is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass-scintillator hadron calorimeter. Muons are measured by gas-ionization detectors embedded in the steel return yoke in the pseudorapidity range $|\eta| < 2.4$, ($\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the polar angle of the trajectory of a particle with respect to the direction of the counterclockwise proton beam) using three detector technologies: drift tubes (DT) (for the range $|\eta| < 1.2$), resistive plate chambers (RPC) (for $|\eta| < 1.6$) and cathode strip chambers (CSC) (for $0.9 < |\eta| < 2.4$). The DT and RPC are indicated as the central ''barrel'' while the CSC comprises the ''end caps.'' A more detailed description of the CMS detector can be found in [22].

We search the dimuon invariant mass distribution between 5.5 and 8.8 GeV (defined as ''mass range 1'') and between 11.5 and 14 GeV (''mass range 2'') for a narrow resonance a, with a decay width $\sim$MeV, which is natural in the NMSSM context. We avoid the range between 9 and 11 GeV because the abundant contributions of the bottomonium resonances to the mass spectrum makes this search unfeasible. Selection criteria are applied to reduce backgrounds from the QCD continuum, and we perform a mass scan in mass ranges 1 and 2 to determine a potential contribution from an a signal. Given the better mass resolution in the barrel part of the detector than in the end caps, we also separate the mass scan into two acceptance regions, based on the dimuon η, in order to improve the sensitivity.

We analyze events collected with an online selection that requires the detection of two opposite-sign muons with transverse momenta $p_T > 3.5$ GeV and additional requirements imposed at the high level trigger (HLT). All three muon systems, DT, CSC, and RPC, take part in the trigger decision. A good primary vertex is also required, as defined in Ref. [23]. The additional HLT requirements include $p_T(\mu^+\mu^-) > 6$ GeV, $5.5 < m_{\mu^+\mu^-} < 14$ GeV, and a distance of the closest approach of the muon tracks to the

beam axis compatible with that expected for prompt decays. A prescale factor of 2 was imposed on the trigger to maintain a reasonable trigger rate.

The main backgrounds arise from QCD processes and, in the lower invariant mass range, from a residual tail of the $\Upsilon(1S)$ resonance. We determine the background shape in the invariant mass directly from data, and use simulated events as a cross check. Signal samples, QCD, and Υ resonances are simulated with PYTHIA 6.4.24, Tune D6T [24], and CTEQ6 parton distribution functions [25]. Tune Z2 gives compatible results. As the NMSSM is not fully implemented in PYTHIA, we generate the MSSM pseudoscalar A boson in the mass range of 5.5 to 14 GeV and require dimuon decays. These samples also contain a simulation of the effects on the number of primary vertices from overlapping pp interactions in the same bunch crossing.

To select the best dimuon candidate in each event, quality criteria are applied to the tracks which reject misidentified muons and muons from kaon and pion decays. Muons are required to be within the geometrical acceptance ($|\eta| \le 2.4$) and to be in the plateau of the trigger efficiency, with $p_T > 5.5$ GeV. Muon tracks are required to have at least 11 hits in the silicon tracker, at least one of which must be in the pixel detector, and a track fit $\chi^2/\mathrm{dof} < 1.8$. This value is chosen to maximize the signal significance with respect to the QCD continuum, which is extracted directly from data.

Isolation requirements suppress misidentified leptons from jets and nonprompt muons from hadron decays. Muons are required to be isolated within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon direction, where ϕ is the azimuthal angle. The muon isolation, I_{rel}, is defined as the sum of the p_T (as measured in the silicon tracker) and transverse energy (as measured in the calorimeters) of all objects within this cone (excluding the muon itself), divided by the muon as measured by the tracker. We require $I_{\mathrm{rel}} < 0.2$. This requirement is optimized by comparing the simulated a signal with opposite-sign dimuons from data, and we verify that this value is appropriate for both the barrel and end cap dimuon pairs. This isolation requirement rejects a large fraction of the background arising from the QCD production of jets.

Dimuon candidates consist of two opposite-sign muons [26] with an invariant mass between 5.5 and 14 GeV. If more than one dimuon candidate is present, that with the highest χ^2 probability associated to the kinematic fit of the dimuon vertex is retained.

The invariant mass spectrum in the search range has two main contributions: the QCD continuum and the bottomonium resonances. To characterize these shapes for use in the mass scan, we perform a binned maximum likelihood fit to the total invariant mass distribution. For the QCD continuum, we use a first-order polynomial probability density function (PDF). Each Υ resonance is parametrized
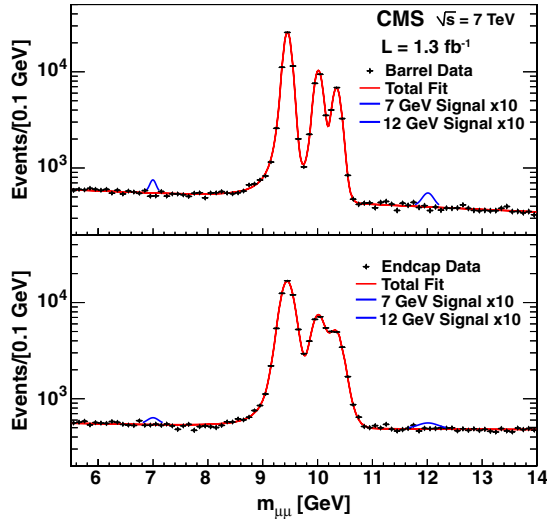
FIG. 1 (color online).   Dimuon invariant mass distribution for
the barrel (upper) and end caps (lower) after the event selection.
The invariant mass distributions are fitted accounting for the
three Υ resonances and QCD continuum. Hypothetical signals
from pseudoscalar Higgs bosons a at 7 and 12 GeV are shown.

via a double Crystal Ball (CB) function [27,28]. The
resolution of one of the CB functions is left free in the fit
but is constrained to be the same for all the three reso-
nances. The resolution of the second CB function is deter-
mined from the fit of the $\Upsilon(1S)$ peak, and forced to scale
with the mass of the other two resonances. As the reso-
nances overlap, we fit for the presence of all three Υ states
simultaneously using three double CB functions. The mean
of the CB of the $\Upsilon(1S)$ is left free in the fit to accommodate
a possible bias in the momentum scale calibration. The
number of free parameters is reduced by fixing the $\Upsilon(2S)$
and $\Upsilon(3S)$ mass differences, relative to $\Upsilon(1S)$, to their
world average values [6].

The fits to the Υ shape and continuum background are
performed in the barrel and end cap regions separately, and
are shown in Fig. 1. The fitted numbers of events are given
in Table I; the barrel-end caps ratio for the Υ peaks is
consistent with Monte Carlo (MC) predictions. Outside the
Υ peak range, corresponding to the signal search mass
ranges, the data are well described by a first-order poly-
nomial. Figure 1 also shows hypothetical signals from
pseudoscalar Higgs bosons a with masses 7 and 12 GeV,
and 2 pb cross sections, scaled by a factor of 10 for
visibility. We perform mass scans of the invariant mass
spectra, dividing mass range 1 into 110 steps and mass

TABLE I.   Fitted numbers of Υ and continuum background
events in the invariant mass range 5.5–14 GeV. The Υ contribu-
tions are summed over the three resonances.

Contribution	events (barrel)	events (end caps)
Υ	93 753 ± 396	95 876 ± 454
Continuum	41 210 ± 320	45 792 ± 385

range 2 into 100 steps of 30 MeV each, and treating the
barrel and end cap spectra separately. At each step, we
build a signal Gaussian PDF with a mean fixed to the center
of the step and a width determined by the mass resolution,
use a first-order polynomial to characterize the back-
ground, and perform an unbinned maximum likelihood fit
to search for a possible contribution from the a. For each
signal mass point, we determine the resolution by fitting
the a invariant mass spectrum with two CB functions (as
for the Υ, the sum of two CB functions better describes
the resolution) and the mass resolution is calculated as the
weighted average of the widths of the two functions. The
resulting dimuon invariant mass resolution ranges from 50
to 120 MeV (90 to 190 MeV) in the barrel (end caps) for
the mass range 5.5 to 14 GeV. These agree well with the
resolution obtained from the Υ resonances in data and MC
simulation. We fit the resolution as a function of mass
using the simulated signal samples, and use this to extract
the values of the dimuon mass resolution for each mass bin
needed in the scan to determine the upper limit.

In mass range 1, we take into account the radiative tail of
the $\Upsilon(1S)$ by including its shape determined from the full
invariant mass spectrum fit. No significant discrepancy
with SM background predictions is observed, and we
proceed to set cross section limits, as described below.

The efficiency for the selection is factorized into three
contributions, $\epsilon = \epsilon_{acc} \times \epsilon_{trig} \times \epsilon_{sel}$, where ϵ_{acc} is the kin-
ematic acceptance for the a, ϵ_{trig} is the efficiency of the
muon trigger, and ϵ_{sel} is the efficiency of the selection
applied to the dimuon candidates. We use PYTHIA 6 to
simulate the a signal and to determine ϵ_{acc}. The trigger
and selection efficiencies (ϵ_{trig} and ϵ_{sel}) are measured with
J/ψ events in data using the tag-and-probe technique [28].
We perform this study in bins of η and p_T of the probe
muon. The efficiency values extracted from data are com-
pared with those obtained from the simulation of prompt
$J/\psi \to \mu^+\mu^-$. The difference between the efficiency in
data and MC simulation is evaluated in bins of p_T and η
and used as a correction to weight the MC events in order
to accommodate possible discrepancies. These corrections
are typically on the order of a few percent. For each
dimuon candidate, the weight is the product of the correc-
tions for the two muons.

The isolation requirement efficiency that contributes to
ϵ_{sel} cannot be measured using the J/ψ data set as one of
the main production mechanisms for J/ψ is through
B-meson decays, resulting in nonisolated muons. This is
not well accounted for in simulation, and would result in
biased data or MC efficiency corrections. In order to
estimate this correction, we use $Z \to \mu^+\mu^-$ events and
consider the lower p_T spectrum of the probe muon.

The total efficiency ϵ is defined for each a mass sample
as the fraction of generated signal events, weighted by
the appropriate data-MC corrections, that satisfy all the
selection requirements. This ranges from 1%–3.5% for the

a mass range of 5.5–14 GeV, and we fit the ϵ distributions with second (third) order polynomial functions in the barrel (end caps) to use in the mass scan. The increase in the efficiency as a function of the invariant mass is mainly due to the p_T requirements on the muons at the HLT level.

Several sources of systematic uncertainty affect these results, including a 2.2% uncertainty on the integrated luminosity [29]. The efficiency corrections are determined using the tag-and-probe results described above. We determine, event-by-event, the uncertainty on the total efficiency corrections by propagating the uncertainties on the single muon corrections. This total event efficiency uncertainty is largely independent of mass, with a maximum value of 12%. We apply this value as a systematic uncertainty for every bin in the scan.

The isolation efficiency is uncertain at the 5% level, corresponding to the largest discrepancy between data and MC simulation in the entire relevant p_T range. We evaluate the systematic uncertainty on the resolution of the *a* as the quadrature sum of the difference between the mass resolution of the *a* with a mass of 10 GeV and the resolution of the $\Upsilon(2S)$ (which has the same mass) in MC simulation, and the difference between the latter and the mass resolution obtained for the $\Upsilon(2S)$ from data. Additionally, the finite statistics for the determination of the mass resolution as a function of the dimuon mass contributes a source of uncertainty. We consider the mass ranges separately and include these systematic uncertainties in the calculation of the upper limit on the cross section times branching fraction. Overall, this adds an 11% (4%) effect for the barrel (end caps).

Systematic uncertainties on the background description include the shape uncertainty of the first-order polynomial fit of the background PDF. We fit the background with alternative functions (a second-order polynomial and an exponential function), generate MC pseudoexperiments using these functions, and fit the distributions using the first-order polynomial. The resulting systematic uncertainties, from the distribution of the fitted parameters, is of the order of a few percent.

No significant signal is observed, and we determine 95% confidence level (C.L.) upper limits on $\sigma \times \mathcal{B}(pp \rightarrow a \rightarrow \mu^+ \mu^-)$ as a function of the dimuon mass using the CL_s approach [30–32]. A few steps at the edges of the mass scans, where the fitting procedure has no predictive power on the signal shape, are not used. Figure 2 shows the upper limit results for the two mass ranges including the systematic uncertainties discussed above. These limits are significant in the context of the NMSSM, and can be presented in terms of upper limits on $|\cos\theta_A|$. The larger the value of $\tan\beta$, the stronger is the constraint. Figure 3 presents upper limits, $|\cos\theta_A|^{\mathrm{max}}$ as a function of m_{a_1} for $\beta = 1, 2, 3, 10, 30, 50$. Our upper limits are compared to an earlier analysis of the *BABAR* $\Upsilon(1S)$ and $\Upsilon(3S)$ data [33], and are superior for $m_{a_1} \gtrsim 7.5$ GeV for $\tan\beta = 50$,
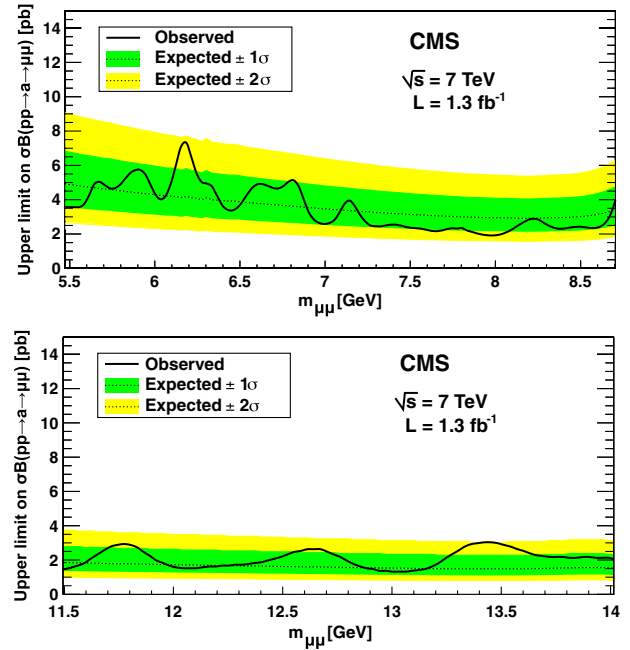
FIG. 2 (color online). Upper limits at 95% C.L. on $\sigma \times \mathcal{B}(pp \rightarrow a \rightarrow \mu^+\mu^-)$ in mass range 1 (upper panel) and mass range 2 (lower panel) including systematic uncertainties. The dotted lines correspond to the expected limits, and the bands correspond to 1- and 2-σ level uncertainties on the expected limits.

decreasing to $m_{a_1} \gtrsim 6$ GeV for $\tan\beta = 2$, and are superior for all masses at $\tan\beta = 1$. Further, these are the first significant limits for $m_a > m_{\Upsilon(3S)}$.

In conclusion, we performed a search for a narrow, low mass pseudoscalar *a*, which is produced by $gg \rightarrow a$ and decays via $a \rightarrow \mu^+ \mu^-$ in the mass ranges 5.5–8.8 GeV and
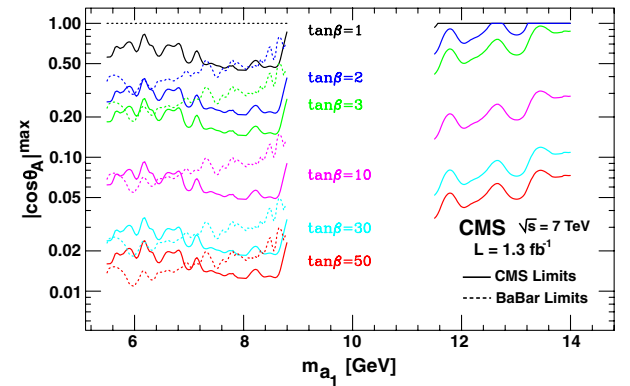

FIG. 3 (color online). Upper limits on the NMSSM parameter $|\cos\theta_A|$ as a function of m_{a_1} in the two mass ranges. The solid curves correspond to different $\tan\beta$ values: from top to bottom, $\tan\beta = 1$, $\tan\beta = 2$, $\tan\beta = 3$, $\tan\beta = 10$, $\tan\beta = 30$, and $\tan\beta = 50$. For each $\tan\beta$ value in mass range 1, the second, dotted curve shows the limits from the *BABAR* Υ analysis. There are no *BABAR* limits for $\tan\beta = 1$ in mass range 1, or for any $\tan\beta$ in mass range 2. The line at $|\cos\theta_A|^{\mathrm{max}} = 1$ is equivalent to no limit. Results from CDF are not shown as they are less stringent than the *BABAR* limits.

11.5–14 GeV, using a data sample corresponding to an integrated luminosity of 1.3 fb^{-1} collected with the CMS detector. No significant signal is observed, and we set upper limits on $\sigma \times \mathcal{B}(pp \rightarrow a \rightarrow \mu^+\mu^-)$. These upper limits are applied in the context of the light pseudoscalar a_1 of the NMSSM to yield upper limits on the NMSSM parameter $|\cos\theta_A|$. These limits are superior to existing constraints for a significant portion of the $m_{a_1} < m_{\Upsilon(1S)}$ mass range, and are the first significant limits available in the $m_{a_1} > m_{\Upsilon(3S)}$ mass range.

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