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Search for the Higgs Boson Decaying to Two Muons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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A search for the Higgs boson decaying to two oppositely charged muons is presented using data recorded by the CMS experiment at the CERN LHC in 2016 at a center-of-mass energy $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. Data are found to be compatible with the predicted background. For a Higgs boson with a mass of 125.09 GeV, the 95% confidence level observed (background-only expected) upper limit on the production cross section times the branching fraction to a pair of muons is found to be 3.0 (2.5) times the standard model expectation. In combination with data recorded at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV, the background-only expected upper limit improves to 2.2 times the standard model value with a standard model expected significance of 1.0 standard deviation. The corresponding observed upper limit is 2.9 with an observed significance of 0.9 standard deviation. This corresponds to an observed upper limit on the standard model Higgs boson branching fraction to muons of 6.4×10^{-4} and to an observed signal strength of $1.0 \pm 1.0(\mathrm{stat}) \pm 0.1(\mathrm{syst})$.

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In the standard model (SM), the masses of fermions are generated by their Yukawa coupling to the Higgs field [1–4], whose existence was confirmed by the Higgs boson (H) discovery [5–7]. Measurements at CMS and ATLAS provided evidence that the Higgs boson couples to bottom quarks [8,9] and established that it couples with tau leptons [10,11] and top quarks [12,13]. The Higgs boson mass has been measured and is found to be $m_{\mathrm{H}} = 125.09 \pm 0.24$ GeV in a combination of ATLAS and CMS data samples [14]. The study of the Higgs boson decays to muons is of particular importance, because it extends the investigation to its couplings to fermions of the second generation. For a Higgs boson with a mass of 125.09 GeV, the expected branching fraction ($\mathcal{B}$) to muons is 2.17×10^{-4} [15], and the narrow decay width of the Higgs boson [16,17] is several orders of magnitude smaller than the $O(\mathrm{GeV})$ experimental dimuon mass resolution. The signal would appear as a narrow resonance over a smoothly falling mass spectrum from the SM background processes, primarily Drell-Yan (DY) and leptonic $t\bar{t}$ decays.

The CMS and ATLAS Collaborations placed upper limits on the product of the Higgs boson production cross section and branching fraction $\mathcal{B}(H \to \mu^+\mu^-)$ of approximately 7 times the SM value at 95% confidence level (C.L.) with LHC run 1 data [18,19], collected at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV. The ATLAS Collaboration improved its expected limit to 2.9 times the SM expectation by adding 36.1 fb^{-1} of data collected at 13 TeV [20] and measured an observed limit of 2.8 times the SM expectation. This Letter presents a search for $H \to \mu^+\mu^-$ events with the CMS detector using 35.9 fb^{-1} of proton-proton (pp) collision data collected in 2016 at $\sqrt{s} = 13$ TeV and its combination with the data collected at $\sqrt{s} = 7$ and 8 TeV corresponding to integrated luminosities of 5.0 and 19.7 fb^{-1}, respectively.

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 solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [21].

The Monte Carlo (MC) simulated events used to model the signal include the four leading Higgs boson production processes: gluon-gluon fusion (ggH), vector boson fusion (VBF), and associated production with a vector boson ($\mathrm{V}H$, $\mathrm{V} = W$ or Z) or top quarks ($t\bar{t}H$). The Higgs boson MC samples are generated at next-to-leading order (NLO) for masses of 120, 125, and 130 GeV with POWHEG2.0 [22],

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using the parton distribution function sets of NNPDF3.0 [23]. The ggH acceptance in each analysis category is found to be in agreement with that calculated at NLO with the MadGraph5_aMC@NLO2.2.2 [24] generator. The SM background processes considered are DY, single and pair production of top quarks (st and $t\bar{t}$, respectively), and di- and triboson production (VV and VVV, respectively). Simulated background processes are used only to optimize the event selection and not for the final background estimate, which is obtained from the data. Background samples are generated using MadGraph5_aMC@NLO and powheg. Spin correlations in multiboson processes generated using MadGraph 5_aMC@NLO are simulated using MadSpin [25]. The parton shower and hadronization processes are modeled by the pythia8.212 [26] generator with the CUETP8M1 [27] underlying event tune. The detector response is based on a detailed description of the CMS detector and is simulated with the Geant4 package [28]. Simultaneous pp interactions overlapping the event of interest (pileup) are included in the simulated samples. The distribution of the number of additional interactions per bunch crossing in the simulation corresponds to that observed in the 13 TeV data collected in 2016, with an average of 23 interactions. The SM Higgs boson cross section and branching fractions are taken from the LHC Higgs boson cross section working group recommendations [15], while cross sections for the background processes are taken from fewz3.1 [29], Top++2.0 [30], hathor [31,32], and mcfm [33].

The particle-flow (PF) algorithm [34] is used to reconstruct observable particles in each event. It combines all subdetector information to reconstruct individual particles and identify them as charged or neutral hadrons, photons, or leptons. Electron and muon candidates are formed by associating a track in the silicon detectors with a cluster of energy in the electromagnetic calorimeter [35] or a track in the muon system. The relative transverse momentum (p_T) resolution of muon candidates with $p_T < 100$ GeV is $\lesssim$1.6% in the barrel [36]. Jets are reconstructed using the anti-k_T clustering algorithm [37] with a distance parameter of 0.4, as implemented in the FastJet package [38]. Jets are required to have a minimum p_T of 30 GeV and a maximum $|\eta|$ of 4.7. Further identification criteria are applied in order to reject jets from pileup or noise present in the detector [39]. For jets with $|\eta| < 2.4$, multivariate algorithms discriminate jets arising from the hadronization of b quarks [40]. The missing transverse momentum $p_T^{\rm miss}$ is defined as the magnitude of the negative vector $\vec{p}_T$ sum of all reconstructed particles (charged and neutral) in the event and is modified by corrections to the energy scale of reconstructed jets. The reconstructed vertex with the largest value of summed physics object ${p_T}^2$ is taken to be the primary pp interaction vertex.

Events are selected by the trigger system requiring the presence of at least one isolated muon with $p_T > 24$ GeV [41]. The offline selection, optimized to maximize the sensitivity of the analysis, requires at least two oppositely charged muons with $p_T > 26$ GeV ($p_T > 20$ GeV) for the leading (subleading) muon and $|\eta| < 2.4$. To reject events with muons from nonprompt decays, muons must be isolated, with a relative isolation sum <25%. The relative isolation sum is calculated as the scalar p_T sum of PF objects, excluding the muon, within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ centered on the direction of the muon, and divided by the muon p_T. Charged particles not associated with the event vertex are not considered in this sum, and a correction is applied in order to account for the neutral particle contamination arising from pileup [42]. The invariant mass of the Higgs boson candidate ($m_{\mu\mu}$) is constructed from the two highest p_T oppositely charged muons, and the event is retained for further analysis if $110 < m_{\mu\mu} < 150$ GeV. The overall trigger efficiency for these events is 98.5%.

Events are classified into categories using variables that are largely uncorrelated with $m_{\mu\mu}$ in order to enhance the sensitivity to the Higgs boson signal. The primary Higgs boson production mechanisms targeted by this analysis are VBF and ggH. The p_T and η of the dimuon system, and the $|\Delta\eta|$ and $|\Delta\phi|$ between the muons, distinguish between ggH signal events and the DY background. The $|\eta|$ of each of the two highest p_T jets, the mass and $|\Delta\eta|$ between the jets in each of the two highest mass dijet pairs, and the number of jets with $|\eta| < 2.4$ (central jets) and $|\eta| > 2.4$ (forward jets) identify VBF signal events. Finally, the number of b-tagged jets and $p_T^{\rm miss}$ identify events with $t\bar{t}$ decays. These variables are used as input to a boosted decision tree (BDT) [43], which was trained with simulated signal and background events normalized to their respective SM cross sections. The dimuon mass and its resolution are not used as input to the BDT in order to avoid biasing the background shape but are used in the signal extraction as discussed later. Simulated signal events used in the training steps are not used later in the analysis. Figure 1 shows the BDT output distributions for data and for simulated events. The output of the classifier was transformed such that the sum of all signal events has a uniform distribution. A large fraction of the VBF signal events can be distinguished from background processes and corresponds to events with the highest BDT score.

The event categories are defined using the BDT score and the expected dimuon mass resolution, gauged by the largest $|\eta|$ of the two muons. The best mass resolution is obtained when both muons are located in the central part of the detector $|\eta| < 0.9$, where the muon momentum resolution is approximately constant, and degrades when one of the muons is more forward, especially in the region $|\eta| > 1.9$, where there are reduced lever arm and increased multiple scattering within the tracking volume.

The number of categories and the values of the BDT and $|\eta|$ boundaries of the categories were optimized according

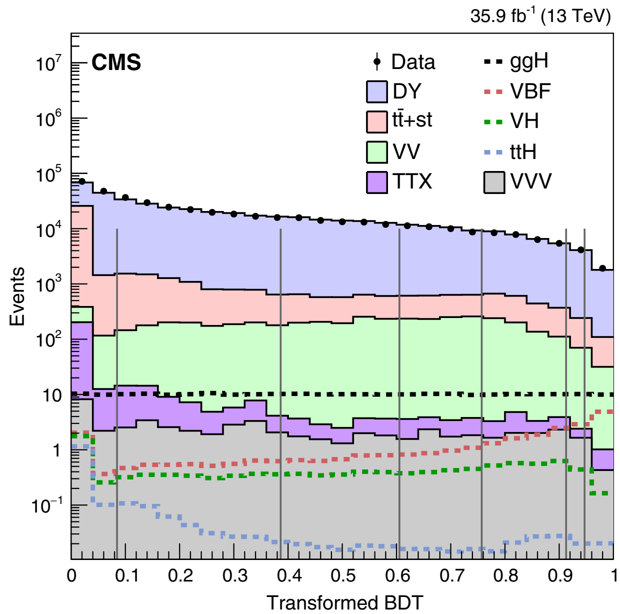

FIG. 1. The transformed BDT output distributions in data (solid points) and MC simulation (histograms). The stacked solid histograms represent the background processes, while the stacked dashed histograms represent the signal. In the legend, V denotes the vector bosons W and Z, and TTX indicates the top quark pair production in association with a vector boson V or another top quark pair. The vertical lines denote the BDT response intervals indicated in Table I.

to an iterative process using $\sum_i S_i^2/B_i$ as a figure of merit, where S_i and B_i are the number of expected signal and background events, respectively, in each category in the ith mass bin from 120 to 130 GeV with 0.5 GeV spacing. A first category boundary is created by optimizing the figure of merit against all possible boundaries in $|\eta|$ and in the BDT score separately and then choosing the one with the larger gain. The process is then repeated recursively within each of the two newly created categories to create additional category boundaries within them until a set number of categories is achieved. Some rounding of the values of the boundaries was made afterward, checking that the simplification does not significantly worsen the expected limit.

This procedure incorporates the dimuon mass resolution into the definition of the categories, optimizing the sensitivity of the analysis. This optimization results in 15 categories shown in Table I. Simulated events are used to optimize the event categories and to estimate the selection efficiency for signal events. In each category, the shape and the normalization of the dimuon mass distribution of the background contributions are obtained from a parametric fit to the data using a set of empirical functions. The product of signal acceptance and efficiency for the $H \to \mu^+\mu^-$ signal varies depending on the production process. This product is shown in Table I for each category for a Higgs boson mass of 125 GeV, together with the functional form used to derive the background from the data and the $S/\sqrt{B}$ ratio within the full width at half maximum (FWHM) of the expected signal distribution.

The reconstructed invariant mass of the signal is modeled with a sum of up to three Gaussian functions, which provides a satisfactory description of the low-mass tail of the distribution, and each model is separately fit to the

TABLE I. The optimized event categories, the product of acceptance and selection efficiency in percent for the different production processes, the total expected number of SM signal events ($m_H = 125$ GeV), the estimated number of background events per GeV at 125 GeV, the FWHM of the signal peak, the background functional fit form, and the $S/\sqrt{B}$ ratio within the FWHM of the expected signal distribution.

BDT response quantile (%)	Maximum muon $\lvert\eta\rvert$	ggH (%)	VBF (%)	WH (%)	ZH (%)	$t\bar{t}H$ (%)	Signal	Bkg/GeV @125 GeV	FWHM (GeV)	Bkg fit function	$S/\sqrt{B}$ @ FWHM
0–8	$\lvert\eta\rvert < 2.4$	4.9	1.3	3.3	6.3	32	21.2	3.13×10^3	4.2	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.12
8–39	$1.9 < \lvert\eta\rvert < 2.4$	5.6	1.7	3.9	3.5	1.3	22.3	1.34×10^3	7.2	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.16
8–39	$0.9 < \lvert\eta\rvert < 1.9$	10	2.8	6.5	6.4	5.2	41.1	2.24×10^3	4.1	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.29
8–39	$\lvert\eta\rvert < 0.9$	3.2	0.8	1.9	2.1	3.5	12.7	7.83×10^2	2.9	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.18
39–61	$1.9 < \lvert\eta\rvert < 2.4$	2.9	1.7	2.7	2.7	0.3	11.8	4.37×10^2	7.0	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.14
39–61	$0.9 < \lvert\eta\rvert < 1.9$	7.2	3.3	6.1	5.2	1.3	29.2	9.70×10^2	4.0	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.31
39–61	$\lvert\eta\rvert < 0.9$	3.6	1.1	2.6	2.2	0.9	14.5	4.81×10^2	2.8	$\mathcal{D}_{\rm MBW}$	0.26
61–76	$1.9 < \lvert\eta\rvert < 2.4$	1.2	1.5	1.8	1.7	0.2	5.2	1.48×10^2	7.6	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.11
61–76	$0.9 < \lvert\eta\rvert < 1.9$	4.8	3.6	4.5	4.4	0.7	20.3	5.12×10^2	4.2	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.29
61–76	$\lvert\eta\rvert < 0.9$	3.2	1.6	2.3	2.1	0.6	13.1	3.22×10^2	3.0	$\mathcal{D}_{\rm MBW}$	0.28
76–91	$1.9 < \lvert\eta\rvert < 2.4$	1.2	3.1	2.2	2.1	0.2	5.8	1.04×10^2	7.1	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.14
76–91	$0.9 < \lvert\eta\rvert < 1.9$	4.4	8.7	6.2	6.0	1.1	20.3	3.60×10^2	4.2	$\mathcal{D}_{\rm MBW}$ $B_{\rm deg\ 4}$	0.35
76–91	$\lvert\eta\rvert < 0.9$	3.1	4.0	3.8	3.6	0.9	13.7	2.36×10^2	3.2	$\mathcal{D}_{\rm MBW}$	0.34
91–95	$\lvert\eta\rvert < 2.4$	1.7	6.4	2.5	2.6	0.5	8.6	96.0	4.0	$\mathcal{D}_{\rm MBW}$	0.28
95–100	$\lvert\eta\rvert < 2.4$	2.0	19	1.5	1.4	0.7	13.7	83.4	4.1	$\mathcal{D}_{\rm MBW}$	0.48
Total	$\lvert\eta\rvert < 2.4$	59	61	51	52	49	253	1.30×10^4	3.9		

simulated dimuon invariant mass distribution for each production process in each category for $m_H = 120$, 125, and 130 GeV. The fit parameters are interpolated for masses within that range. The invariant mass distribution of the background primarily follows the smoothly falling spectrum of the high-mass DY background. Secondary contributions come from the single and pair production of top quarks. In each category, the background distribution is modeled by fitting the data with a single analytic function, chosen from a set of alternative options. These include a sum of exponential functions, Bernstein polynomials ($B_{\deg n}$), and a modified version of the Breit-Wigner Z boson line shape $\mathcal{D}_{\mathrm{MBW}}$ derived and validated by fitting FEWZ predictions of the DY invariant mass distribution at next-to-NLO [44,45]:

$$\mathcal{D}_{\mathrm{MBW}}(x) = \frac{\mathrm{e}^{a_2 x + a_3 x^2}}{(x - m_{\mathrm{Z}})^{a_1} + (\frac{\Gamma_{\mathrm{Z}}}{2})^{a_1}}, \qquad (1)$$

where m_{Z} and Γ_{Z} are the mass and the width, respectively, of the Z boson fixed to known values [46]. In addition, FEWZ spectra templates multiplied by polynomial functions are considered, as well as a modified Breit-Wigner distribution multiplied by a Bernstein polynomial of up to degree 4 ($B_{\deg 4}$). The chosen function maximizes the expected sensitivity while introducing only a negligible bias in the measured signal yield, which is determined as follows. In each category, background-only fits to the data are performed with every function. From each of these fits, thousands of pseudodata sets are generated, taking into account the uncertainties in the fit parameters and their correlations, and simulated signal events are added according to their expected SM yields. Each of the background functions is then used to fit the pseudodata sets generated from every other function, with the total signal yield floating freely in the fit. The bias is estimated as the median excess or deficit in the measured signal yield relative to the SM expectation. Accepted functions in each category have a maximum possible bias of less than 20% of the statistical uncertainties for $m_H = 120$, 125, and 130 GeV. Including these deviations as spurious signals leads to an overall uncertainty in the calculated limit of less than 1%, which is neglected. Correlation between bias terms is also found to be negligible.

The systematic uncertainties considered in the analysis account for possible mismodeling in the signal shape or rate. The shape of the reconstructed Higgs boson invariant mass is affected by the muon momentum scale and resolution. Uncertainties in the calibration of these values are propagated to the shape of the invariant mass distribution of the Higgs boson, assuming a Gaussian prior, yielding variations of up to 0.05% in the position of the peak and up to 10% in its width. Jet energy uncertainties in scale and resolution affect the analysis through migrations between categories. The largest variation of this kind amounts to 6% of the relative yield. Uncertainty in the simulation of additional pileup events is modeled by varying the total inelastic cross section [47,48] by $\pm 5\%$, which translates to $\approx 1\%$ variations in the yields. The systematic uncertainty in the b tagging or light-quark and gluon jet mistagging efficiencies results in event migration across categories of $\approx 1\%$. Lepton efficiency mismodeling is accounted for with trigger and isolated muon identification uncertainties ($\approx 2\%$). The factorization and renormalization scales used in the MC simulations are varied up and down separately by a factor of 2, translating to changes of up to 6% in the signal acceptance per category. The parton distribution functions used in the signal MC simulations are varied using the NNPDF3.0 replicas, which yield differences of $\approx 2\%$. In the comparison of measured signal yields with expectation, additional uncertainties in the calculated signal cross sections are considered. They are due to the choice of factorization and renormalization scale (3.9, 0.4, 3.8, 1.9, and $\lesssim 10\%$, for ggH, VBF, ZH, WH, and $t\bar{t}H$, respectively) and parton distribution functions (3.2, 2.1, 1.6, 1.9, and 3.7%), as well as the 1.7% uncertainty in the $H \to \mu^+\mu^-$ branching fraction [15]. Finally, a 2.5% uncertainty is associated with the integrated luminosity measurement [49].

A maximum likelihood signal-plus-background fit to the dimuon invariant mass spectrum is performed across all categories to measure the signal strength modifier μ, defined as $(\sigma\mathcal{B})_{\mathrm{obs}}/(\sigma\mathcal{B})_{\mathrm{SM}}$ where σ indicates the Higgs boson production cross section. The best fit signal strength for a Higgs boson mass hypothesis of 125.09 GeV ($\hat{\mu}_{125}$) and 68% C.L. interval is extracted with a profile likelihood ratio, according to the procedure described in Ref. [50], yielding $\hat{\mu}_{125} = 0.7 \pm 1.0(\mathrm{stat})^{+0.2}_{-0.1}(\mathrm{syst})$ for $m_H = 125.09$ GeV [51]. Figure 2 shows the background component and the signal-plus-background fits to the data in all categories combined, weighted by the expected ratio of signal to signal plus background in each category. The 95% C.L. upper limit on the signal strength modifier computed with the asymptotic $\mathrm{CL_s}$ method [52–54] and the compatibility of the dimuon yield with the background-only hypothesis for the 2016 data set (13 TeV) are also derived. The observed (expected for $\mu = 0$) upper limit at 95% C.L. for $m_H = 125.09$ GeV is 3.0 (2.5), with an observed (expected for $\mu = 1$) significance of the incompatibility with the background-only hypothesis of 0.6 (0.9) standard deviation (s.d.).

The 95% C.L. upper limit on the signal strength as a function of m_H in the region around the Higgs boson mass for a combination of data recorded at center-of-mass energies of 7, 8, and 13 TeV is shown in Fig. 3 and yields an observed (expected for $\mu = 0$) limit on the production rate of 2.9 (2.2) times the SM value at $m_H = 125.09$GeV. The observed limit generally agrees well with the expected limit curve for $\mu = 1$ that is also shown and corresponds to an upper limit on the $H \to \mu^+\mu^-$ branching fraction of

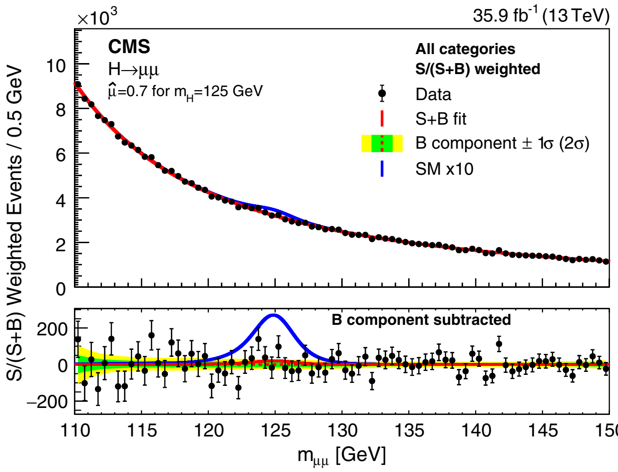

FIG. 2. Data and weighted sum of signal-plus-background fits to each category. Events are weighted according to the expected ratio of signal to signal plus background in the category to which they belong. The solid blue line represents the expectation from the SM Higgs boson multiplied by a factor of 10. The lower panel shows the difference between the data and the background component of the fit.

6.4×10^{-4}, assuming the SM production cross sections. The best fit signal strength for $m_H = 125.09$ GeV is $\hat{\mu}_{125}^{\text{comb}} = 1.0 \pm 1.0(\text{stat})^{+0.1}_{-0.1}(\text{syst})$, and the observed combined significance is 0.9 s.d. The expected value for $\mu = 1.0$ is $\hat{\mu}_{125}^{\text{comb}} = 1.0^{+1.1}_{-1.0}$, and the combined expected significance is 1.0 s.d. Theoretical uncertainties are considered correlated across the data sets, while the main experimental uncertainties are considered uncorrelated.

In summary, we present a search for the Higgs boson decaying to two muons using data recorded by the CMS experiment at the LHC in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. No significant evidence for this decay is observed. Limits are set on the cross section times the branching fraction of the Higgs boson decaying to two muons. The combination with data recorded at center-of-mass energies of 7 and 8 TeV yields a 95% confidence level observed upper limit of 2.9 times the standard model value for $m_H = 125.09$ GeV. The corresponding expected upper limit in the absence of a SM decay in this channel is 2.2, which is the most sensitive to date. This corresponds to an observed (standard model expected) significance of the Higgs boson decaying into two muons of 0.9 (1.0) standard deviation and an observed signal strength of $1.0 \pm 1.0(\text{stat}) \pm 0.1(\text{syst})$. Assuming standard model production cross sections for the Higgs boson, the observed limit corresponds to an upper limit of 6.4×10^{-4} on the Higgs boson branching fraction to two muons.

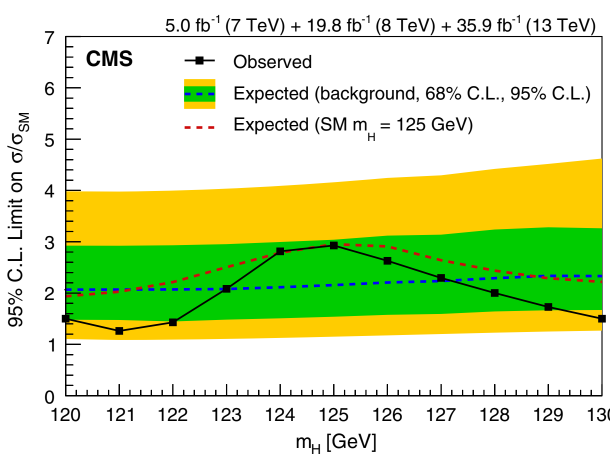

FIG. 3. The 95% C.L. upper limit on the signal strength modifier μ in the region around the Higgs boson mass for the combination of the 7, 8, and 13 TeV data sets together with the expected limit obtained in the background-only hypothesis (dashed black line) and in the signal-plus-background hypothesis (dashed red line) for the SM Higgs boson with $m_H = 125$ GeV.

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