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Searches for Higgs bosons in pp collisions at $\sqrt{s} = 7$ and 8 TeV in the context of four-generation and fermiophobic models

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ABSTRACT

Searches are reported for Higgs bosons in the context of either the standard model extended to include a fourth generation of fermions (SM4) with masses of up to 600 GeV or fermiophobic models. For the former, results from three decay modes ($\tau\tau$, WW, and ZZ) are combined, whilst for the latter the diphoton decay is exploited. The analysed proton–proton collision data correspond to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and up to 5.3 fb^{-1} at 8 TeV. The observed results exclude the SM4 Higgs boson in the mass range 110–600 GeV at 99% confidence level (CL), and in the mass range 110–560 GeV at 99.9% CL. A fermiophobic Higgs boson is excluded in the mass range 110–147 GeV at 95% CL, and in the range 110–133 GeV at 99% CL. The recently observed boson with a mass near 125 GeV is not consistent with either an SM4 or a fermiophobic Higgs boson.

1. Introduction

In the standard model (SM) [1–3], electroweak symmetry breaking is achieved by introducing a complex scalar doublet, leading to the prediction of the Higgs boson (H) [4–9]. Precision electroweak measurements indirectly constrain the SM Higgs boson mass m_{H} to be less than 158 GeV [10]. The direct experimental searches exclude at 95% confidence level (CL) the SM Higgs boson in the mass range up to 600 GeV, except for the mass window 122–128 GeV [11–14], where a new particle with a mass near 125 GeV was recently observed in a combination of searches targeting SM Higgs boson decay modes [13,14].

Various extensions of the standard model have been proposed, such as the inclusion of a fourth generation of fermions (the SM4 model) [15–19] or models with multiple Higgs bosons and modified couplings such that one of the Higgs bosons couples only to vector bosons at tree level (the fermiophobic, FP, benchmark model) [20–25]. Both types of model have a major impact on Higgs phenomenology. In the SM4 context for example, constraints from electroweak data become less restrictive, allowing the mass range 115–750 GeV at 95% CL, as long as the mass splitting in the fourth generation is $\mathcal{O}(50)$ GeV [17]. Likewise Higgs boson production cross sections and decay branching fractions are strongly affected in both scenarios. Therefore, the conclusions regarding the existence (or not) of a Higgs boson based on direct searches that assume the SM are not valid in SM4 or FP scenarios without a proper re-interpretation. Given that the nature of the new boson near 125 GeV has yet to be determined definitively, it is appropriate to test alternative interpretations beyond the standard model.

To date, the direct searches for the SM4 Higgs boson have excluded at 95% CL the mass range 121–232 GeV [26–28]. Previous searches using the diphoton decay at the LEP collider [29], the Tevatron collider [26], and the Large Hadron Collider (LHC) [30] exclude a fermiophobic Higgs boson lighter than 121 GeV at 95% CL. Using a combination of decay modes, searches at the LHC [31] have ruled out a fermiophobic Higgs boson in the mass range 110–194 GeV at 95% CL; the range 110–188 GeV is excluded at 99% CL, with the exception of two gaps from 124.5–127 GeV and from 147.5–155 GeV.

In this Letter, we re-interpret and combine the SM Higgs boson searches [13,32–34], carried out by the Compact Muon Solenoid (CMS) experiment [35] at the LHC, in the SM4 context. The search is performed in the mass range 110–600 GeV. We also report on a search for a fermiophobic Higgs boson in the mass range 110–150 GeV, in the $\gamma\gamma$ decay mode. The analysed proton–proton collision data correspond to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and up to 5.3 fb^{-1} at 8 TeV.

2. The SM4 and FP models

The presence of fourth-generation fermions would have a significant impact on the effective couplings of the Higgs boson to the SM particles and, thus, directly affect the Higgs boson production cross sections and decay branching fractions. Since the couplings of the Higgs boson to fermions are proportional to their masses,

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the electroweak loop corrections with fourth-generation fermions have a non-vanishing effect even for arbitrarily heavy fermions, although perturbative calculations become unreliable for fermion masses larger than 600 GeV.

In this analysis, we use the SM4 benchmark recommended by the LHC Higgs cross section group in Ref. [36]: $m_{\ell_4} = m_{\nu_4} = m_{\mathrm{d}_4} =$ 600 GeV and $m_{\mathrm{u}_4} - m_{\mathrm{d}_4} = (50 + 10 \cdot \ln(m_{\mathrm{H}}/115))$ GeV. Here m_{ℓ_4} and m_{ν_4} are the masses of the 4th generation charged lepton and neutrino, while m_{u_4} and m_{d_4} are the masses of the 4th generation "up" and "down" quarks. These masses are not excluded by the direct searches for heavy fermions [37–40] and still allow for perturbative calculations. The SM4 Higgs boson cross sections and decay branching fractions used in this analysis include electroweak next-to-leading order (NLO) corrections [41,42]. The next-to-NLO order QCD corrections are taken from Ref. [43]. Below we summarise the effect of the fourth generation fermions, with the specified masses, on the production and decay of an SM4 Higgs boson compared with the SM Higgs boson of the same mass.

The square of the effective coupling of an SM4 Higgs boson to gluons (g) is increased by a factor $K_{\mathrm{gg}}(m_{\mathrm{H}})$ that ranges between nine and four for a Higgs boson mass that ranges from 110 to 600 GeV. This enhancement results from the inclusion of u_4 and d_4 quarks in the quark loop diagrams associated with the $\mathrm{H} \to \mathrm{gg}$ and $\mathrm{gg} \to \mathrm{H}$ processes. The square of the effective coupling of an SM4 Higgs boson to W and Z vector bosons (henceforth referred to collectively as V bosons) becomes about three times smaller, $K_{VV}(m_{\mathrm{H}}) \sim 0.3$, as the amplitudes of the NLO and leading order (LO) contributions are of opposite signs in this case. A coincidental cancellation of the contributions from W bosons and heavy fermions (top, u_4, d_4, ℓ_4) to the loop diagrams responsible for the $\mathrm{H} \to \gamma\gamma$ decay suppresses the square of the effective coupling to photons by $\mathcal{O}(100)$. The squares of the fermionic (f) couplings are enhanced by a factor $K_{ff}(m_{\mathrm{H}}) \sim 1.6$.

The enhancement in the effective couplings to gluons and the suppression of couplings to vector bosons causes gluon fusion production to dominate over the vector boson fusion (VBF) and associated (VH) production mechanisms. Hence, the last two processes can be neglected in searches for SM4 Higgs bosons, and are ignored in the search presented in this Letter. The contribution from gluon fusion is rescaled by the SM4/SM m_{H}-dependent factor $K_{\mathrm{gg}}(m_{\mathrm{H}})$ mentioned above. The $\mathrm{H} \to \mathrm{bb}$ search channel that fully relies on associated production is not included in this combination. For simplicity, $\mathrm{H} \to \mathrm{b\bar{b}}$ is denoted as $\mathrm{H} \to \mathrm{bb}$, $\mathrm{H} \to \tau^+\tau^-$ as $\mathrm{H} \to \tau\tau$, etc. Following Ref. [36], the uncertainties on the gluon fusion cross section for the SM4 model are assumed to be the same as for the SM Higgs boson and are taken from Ref. [44]. The change in the Higgs boson decay partial widths modifies the decay branching fractions as follows. The branching fraction $\mathcal{B}(\mathrm{H} \to \gamma\gamma)$ is suppressed by $\mathcal{O}(100)$ with respect to the standard model. The branching fractions $\mathcal{B}(\mathrm{H} \to \mathrm{WW})$ and $\mathcal{B}(\mathrm{H} \to \mathrm{ZZ})$ are suppressed by approximately a factor of five for low Higgs boson masses for which the WW and ZZ partial widths are not dominant. They remain almost unchanged in the mid-range around $m_{\mathrm{H}} \sim 200$ GeV, where vector boson partial widths are the main contributors to the total width Γ_{tot}, and are about 60% of the SM Higgs boson values above $m_{\mathrm{H}} \sim 350$ GeV after the $\mathrm{H} \to \mathrm{tt}$ decay channel opens up. The branching fraction $\mathcal{B}(\mathrm{H} \to \tau\tau)$ is affected only slightly, $\mathcal{O}(20\%)$, in the mass range where this decay mode is used. The total width of the SM4 Higgs boson at high masses, where it is relevant for the $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ (where ℓ denotes an electron or a muon) search, is about 30–50% of the SM Higgs width, depending on the Higgs boson mass.

Since the $\mathrm{H} \to \gamma\gamma$ channel is so strongly suppressed, it has nearly no sensitivity for the SM4 Higgs boson and is therefore not included in the combination. We explicitly checked that including or omitting this channel has no effect on the combined SM4 Higgs boson search results even in the presence of the significant excess near 125 GeV observed in the standalone search for $\mathrm{H} \to \gamma\gamma$ [13].

The theoretical uncertainties on the SM4 Higgs boson decay branching fractions are derived from three independent sources of relative uncertainty on the partial widths, which amount to approximately 50%, 10%, and 5% for Γ_{VV}, Γ_{ff}, and Γ_{gg}, respectively [36]. Any given decay channel $\mathrm{H} \to xx$ is affected by each of these three uncertainties. Using the equation $\mathcal{B}_{xx} = \Gamma_{xx}/\Gamma_{\mathrm{tot}}$ and standard error propagation, we translate the uncertainties on the partial widths into uncertainties on the branching fractions of the decay modes ($\tau\tau$, WW, ZZ) used in this combination. The signal acceptance for each exclusive final state is assumed to be the same as reported in previous SM Higgs boson searches [13,32–34].

As a fermiophobic Higgs boson does not couple to fermions, gluon fusion production becomes negligible, while the VBF and VH production cross sections remain unchanged. Direct decays to fermion pairs become impossible, which significantly increases the branching fractions $\mathcal{B}(\mathrm{H} \to \gamma\gamma)$, $\mathcal{B}(\mathrm{H} \to \mathrm{WW})$ and $\mathcal{B}(\mathrm{H} \to \mathrm{ZZ})$. The diphoton decays are enhanced further as the negative interference between the W and top loops responsible for this decay in the SM is no longer present. For a low mass FP Higgs boson ($m_{\mathrm{H}} \approx 125$ GeV) the decay to two photons is enhanced by an order of magnitude with respect to the SM [23–25], and this compensates for the reduced production cross section, keeping the overall diphoton signal rate very similar to that in the SM. Production cross sections and decay branching fractions, together with their uncertainties, are taken from Ref. [44] and are derived from Refs. [45–50].

3. The CMS detector and event reconstruction

The CMS apparatus [35] consists of a barrel assembly and two endcaps, comprising, in successive layers outwards from the collision region, the silicon pixel and strip tracker, the lead tungstate crystal electromagnetic calorimeter (ECAL), the brass/scintillator hadron calorimeter, the superconducting solenoid, and gas-ionization chambers embedded in the steel flux return yoke for the detection of muons. The polar coordinate system (θ, ϕ) is used to describe the direction of particles and jets emerging from the pp collisions, where θ is the polar angle measured from the positive z axis (along the anticlockwise beam direction) and ϕ is the azimuthal angle. The pseudorapidity, defined as $\eta = -\ln[\tan(\theta/2)]$, is commonly used in place of θ.

Particles are reconstructed with the CMS "particle-flow" event description [51,52] using an optimised combination of all subdetector information to form "particle-flow objects": electrons, muons, photons, charged and neutral hadrons. Jets are formed by clustering these objects with the anti-k_{T} algorithm [53] using a distance parameter $\Delta R = 0.5$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle differences between the jet axis and the particle direction. The missing transverse energy vector, $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, is taken as the negative vector sum of all particle transverse momenta, and its magnitude is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$.

4. Search channels

4.1. The SM4 search channels

The SM4 results presented are obtained by combining searches in the individual Higgs boson decay channels listed in Table 1. The table summarises the main characteristics of these searches, namely: the mass range of the search, the integrated luminosity

Table 1
Summary of the analyses included in the SM4 combination.

Channel	m_H range (GeV)	Int. lumi. (fb^{-1})		Sub-channels	m_H resolution	Ref.
		7 TeV	8 TeV			
$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu/\mu\mu$	110–145	4.9	5.1	16	20%	[13]
$H \to WW \to 2\ell 2\nu$	110–600	4.9	5.1	4	20%	[13,32]
$H \to ZZ \to 4\ell$	110–600	5.0	5.3	3	1–2%	[13]
$H \to ZZ \to 2\ell 2\nu$	250–600	4.9	–	2	7%	[33]
$H \to ZZ \to 2\ell 2q$	130–164 200–600	4.9	–	6	3% 3%	[34]

used, the number of exclusive sub-channels, and the approximate instrumental mass resolution.

Below we give a brief summary of the individual searches. More detailed descriptions of all analyses can be found in Refs. [13, 32–34]. In the combination presented here, Higgs boson production via VBF is neglected, and thus sub-channels in the $H \to \tau\tau$ and $H \to WW$ decay channels that explicitly target VBF production are also dropped.

The $H \to \tau\tau$ search [13] is performed using the final-state signatures $e\mu$, $\mu\mu$, $e\tau_h$, and $\mu\tau_h$, where electrons and muons arise from leptonic τ decays and τ_h denotes hadronic τ decays. Each of these categories is further divided into 4 exclusive sub-categories based on the jet multiplicity and transverse momentum (p_T) of the visible tau lepton decay. In each category, we search for a broad excess in the reconstructed $\tau\tau$ mass distribution. The main irreducible background, $Z \to \tau\tau$ production, and the largest reducible backgrounds ($W+\text{jets}$, multijet production, $Z \to ee$) are evaluated from various control samples in data.

The $H \to WW \to 2\ell 2\nu$ analysis [13,32] searches for an excess of events with two leptons of opposite charge, large missing transverse energy E_T^{miss}, and less than two jets. Events are divided into four categories, with different background compositions and signal-to-background ratios, according to the number of jets and whether the leptons are of the same or different flavour. For events with no jets, the main background stems from non-resonant WW production; for events with one jet, the dominant backgrounds are from WW and top-quark production. The events are split into same-flavour and different-flavour dilepton sub-channels, since the background from Drell–Yan production is much larger for the same-flavour dilepton events. To improve the separation of signal from background in the 7 TeV analysis, multivariate analysis classifiers are trained for a number of Higgs boson masses, and a search is made for an excess of events in the output distributions of the classifiers. All background rates, except for small expected contributions from WZ, ZZ, and $W\gamma$, are evaluated from data.

In the $H \to ZZ \to 4\ell$ channel [13], we search for a four-lepton mass peak over a small continuum background. To separate signal and background, we use a discriminant calculated for each event as the ratio of the respective probability densities for signal and background to form an event with the observed kinematic configuration of four leptons. The 4e, 4μ, and $2e2\mu$ sub-channels are analysed separately since there are differences in the four-lepton mass resolutions and the background rates arising from jets misidentified as leptons. The dominant irreducible background in this channel is from non-resonant ZZ production with both Z bosons decaying to either 2e, 2μ, or 2τ (with the tau leptons decaying leptonically) and is estimated from simulation. The smaller reducible backgrounds with jets misidentified as leptons, e.g. $Z+\text{jets}$, are estimated from data.

In the $H \to ZZ \to 2\ell 2\nu$ search [33], we select events with a lepton pair (e^+e^- or $\mu^+\mu^-$), with invariant mass consistent with that of an on-shell Z boson, and a large missing transverse energy. We then define a transverse invariant mass m_T from the dilepton momenta and $\vec{E}_T^{\text{miss}}$, which is assumed to originate from neutrinos in the $Z \to \nu\nu$ decays, and search for a broad excess of events in the m_T distribution. The ZZ and WZ backgrounds are taken from simulation, while all other backgrounds, $Z+\text{jets}$ and a cumulative sum of the rest, are evaluated from control samples in data.

In the $H \to ZZ \to 2\ell 2q$ search [34], we select events with two oppositely-charged leptons (e^+e^- or $\mu^+\mu^-$), and two jets. The two leptons and the two jets are required to have invariant masses consistent with that of on-shell Z bosons. The events are categorised by the lepton flavour and the number of jets identified as coming from the decay of a b-quark, thus defining six exclusive final states. We search for a peak in the invariant mass distribution of the dilepton–dijet system, with the background rate and shape estimated using control regions in data.

4.2. The FP search channels

In this section, we describe the FP Higgs boson search with the 8 TeV dataset. We use the $H \to \gamma\gamma$ decay mode and exploit the characteristic signatures associated with the VBF and VH processes: namely, the two forward jets produced by the scattered quarks in VBF production and charged leptons (electrons or muons) or large missing transverse energy induced by neutrinos, both coming from vector boson decays in VH production. The FP Higgs boson search in the diphoton decay mode with the 7 TeV dataset is described elsewhere [31].

The simulated VBF signal samples are generated with POWHEG [54]. The difference in the event selection acceptance for samples generated with POWHEG at NLO and with PYTHIA [55] at LO is taken as a systematic uncertainty, which is found to have a negligible impact on the final results. The simulated VH samples are generated with PYTHIA.

Nine exclusive classes are defined. All require two, isolated, high p_T photons. Five of the nine require an additional tag: either a pair of jets (subdivided into two sub-classes with low and high dijet invariant masses, m_{jj}), or an isolated lepton (subdivided into e and μ sub-classes), or a large missing transverse energy. The remaining diphoton events failing to pass VBF and VH production tags form an untagged category, which is divided into four sub-classes according to the photon shower shape and position in the detector [13]. The selection criteria for the photon candidates are the same as in the SM search [13] except for the modifications noted below. A Higgs boson produced via the VBF or VH mechanisms typically has a larger p_T than a Higgs boson produced via gluon fusion (which dominates SM Higgs production) and hence the photon p_T thresholds are increased. Furthermore, such photons also have a harder transverse momentum spectrum than those of photons produced by background processes [56] and thus significant separation of signal and background can be achieved. The transverse momentum of the photon pair ($p_T^{\gamma\gamma}$) together with their invariant mass ($m_{\gamma\gamma}$) are included in a two-dimensional unbinned maximum likelihood. The signal and background models, which are used to extract limits on the signal cross section, are described in detail in Ref. [31]. The dijet-tagged class has the greatest sensitivity; here the background model is derived from

Table 2
Number of selected events in the $\gamma\gamma$ event classes, for data in the mass range 100–180 GeV and for a fermiophobic Higgs boson signal ($m_H = 125$ GeV). The expected number of background events in the signal region 120–130 GeV obtained from the fit of the data in the full mass range 100–180 GeV and the mass resolution for the 125 GeV FP Higgs boson signal in each event class are also given. All numbers are for the 8 TeV dataset.

	E_T^{miss} tag	Dijet high m_{jj}	Dijet low m_{jj}	Lepton tag (e, μ)	Untagged			
					(a)	(b)	(c)	(d)
Data	41	84	271	30	4992	9546	5105	8574
Signal ($m_H = 125$ GeV)	2.3	14	10	3.5	18	23	12	14
Expected background	5.8	17	40	4.1	740	1400	760	1300
σ_{eff} (GeV)	2.0	2.1	2.2	2.1	1.5	2.0	3.8	3.9

data, by fitting the diphoton mass distributions over the range $100 < m_{\gamma\gamma} < 180$ GeV.

In the dijet-tagged classes the photon p_T thresholds are raised (compared with the SM search [13]) to $p_T^\gamma(1) > m_{\gamma\gamma}/2$, and $p_T^\gamma(2) > 25$ GeV, where $p_T^\gamma(1)$ and $p_T^\gamma(2)$ are the transverse momenta of the leading and sub-leading photons respectively. The p_T thresholds for the two jets are 30 GeV and 20 GeV, and their separation in η must be greater than 3.0. The dijet mass is required to be greater than 250 GeV. The selected events are subdivided into two regions $250 < m_{jj} < 500$ GeV and $m_{jj} > 500$ GeV, based on the amount of background contamination as a function of dijet mass. In addition, for events with $m_{jj} > 500$ GeV, the p_T threshold for the subleading jet is raised to 30 GeV. Two additional selection criteria, relating the dijet and diphoton systems, are applied to all selected events. The difference between the average η of the two jets and the η of the diphoton system is required to be less than 2.5 [57]. The difference in ϕ between the diphoton and dijet systems is required to be greater than 2.6 radians.

In the lepton-tagged channel, which targets VH production, the p_T thresholds are again altered; values of $p_T^\gamma(1) > 3 \times m_{\gamma\gamma}/8$, and $p_T^\gamma(2) > 25$ GeV are set. Separate muon and electron sub-classes are defined, with at least one muon (electron) with $p_T > 20$ GeV and within $|\eta| < 2.4$ ($|\eta| < 2.5$) required. The leptons must be isolated, using isolation criteria similar to those used for photons, and separated from the photons by $\Delta R > 1$. To protect against background events that arise from an electron misidentified as a photon in the $Z \to ee$ process, the mass of the photon–electron system must differ from the Z boson mass by at least 5 GeV.

A significant fraction of events from VH production contains large missing transverse energy due to the neutrinos from $Z \to \nu\nu$ decays. Events that passed the requirements of the lepton-tag channel are excluded to form a statistically independent E_T^{miss}-tag class. The E_T^{miss} is required to be larger than 70 GeV. The photon p_T threshold requirements are the same as for the lepton-tag class. Due to the negligible contribution of photons at large pseudorapidity to the expected exclusion limit, only photons falling within the ECAL barrel are kept ($|\eta| < 1.48$).

A substantial fraction of the FP signal events are not expected to pass any of the previous tags, and so the remaining untagged events are also exploited. Photon p_T requirements of $p_T^\gamma(1) > m_{\gamma\gamma}/3$, $p_T^\gamma(2) > m_{\gamma\gamma}/4$ and $p_T^{\gamma\gamma}/m_{\gamma\gamma} > 0.1$ are applied. The selected events are divided into four classes according to the expected mass resolution and amount of background contamination [13]. Two classifiers are used: the minimum R_9 of the two photons, R_9^{min}, and the maximum absolute pseudorapidity of the two photons. The quantity R_9 is defined as the sum of the energy in the 3×3 crystal array centred on the crystal with the maximum energy deposit divided by the total clustered energy, and is designed to identify photons undergoing a conversion. The untagged diphoton event classes are: (a) both photons in the barrel and $R_9^{\text{min}} > 0.94$, (b) both photons in the barrel and $R_9^{\text{min}} < 0.94$, (c) one or both photons in the endcaps and $R_9^{\text{min}} > 0.94$, and (d) one or both photons in the endcaps and $R_9^{\text{min}} < 0.94$.

The numbers of events in the $\gamma\gamma$ event classes are shown in Table 2, for simulated signal events and for data. A Higgs boson with $m_H = 125$ GeV is chosen for the signal, and the data are counted in the mass range 100–180 GeV. The table also shows the mass resolution, σ_{eff}, defined as half the width of the narrowest window containing 68.3% of the distribution.

5. Combination method

The combination of the Higgs boson searches, be it across different sub-channels within a given decay mode or across different decay modes, requires simultaneous analysis of the data selected by all individual analyses, accounting for all statistical and systematic uncertainties and their correlations. The overall statistical methodology used in this combination was developed by the ATLAS and CMS Collaborations in the context of the LHC Higgs Combination Group. The description of the general methodology can be found in Refs. [58,59]. Below we give concise definitions of statistical quantities we use for characterising the outcome of the search. Results presented in this Letter are obtained using asymptotic formulae [60], including a few updates recently introduced in the RooStats package [61].

For calculations of exclusion limits, we adopt the modified frequentist criterion CL_s [62,63]. The chosen test statistic, q_μ, used to determine how signal- or background-like the data are, is based on the profile likelihood ratio. Systematic uncertainties are incorporated in the analysis via nuisance parameters and are treated according to the frequentist paradigm. The profile likelihood ratio is defined as

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{obs} \mid \mu \cdot s + b, \hat{\theta}_\mu)}{\mathcal{L}(\text{obs} \mid \hat{\mu} \cdot s + b, \hat{\theta})}, \qquad (1)$$

where s stands for the expected number of signal events under the SM4/FP Higgs boson hypothesis, μ is a signal strength modifier introduced to accommodate deviations from SM4/FP Higgs boson predictions, b stands for backgrounds, and θ are nuisance parameters describing systematic uncertainties The likelihood in the numerator reaches its maximum, for a given μ, at $\hat{\theta}_\mu$; while $\hat{\mu}$ and $\hat{\theta}$ define the point at which the likelihood reaches its global maximum. The quantity $\hat{\mu}$ is constrained to be between 0 and μ.

The ratio of probabilities to observe a value of the test statistic at least as large as the one observed in data, q_μ^{obs}, under the signal + background (s + b) and background-only (b) hypotheses,

$$\text{CL}_s = \frac{\text{P}(q_\mu \geqslant q_\mu^{\text{obs}} \mid \mu \cdot s + b)}{\text{P}(q_\mu \geqslant q_\mu^{\text{obs}} \mid b)} \leqslant \alpha, \qquad (2)$$

is used as the criterion for excluding the signal at the $1 - \alpha$ confidence level.

To quantify the presence of an excess of events over what is expected for the background, we use another test statistic where the

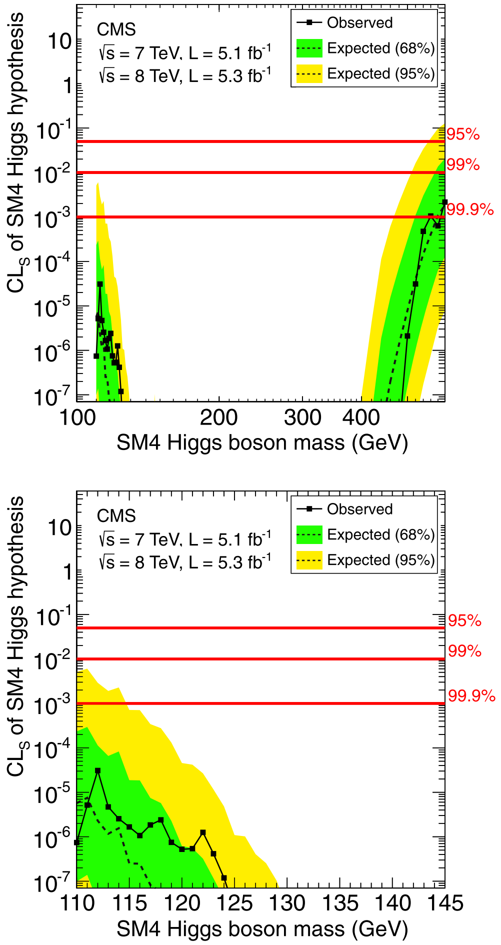

Fig. 1. The observed and expected $\mathrm{CL_s}$ values for the SM4 Higgs boson hypothesis as a function of the Higgs boson mass in the range 110–600 GeV (top) and 110–145 GeV (bottom). The three horizontal lines show confidence levels of 95%, 99%, and 99.9%, defined as $(1-\mathrm{CL_s})$.

likelihood appearing in the numerator is for the background-only hypothesis:

$$q_0 = -2\ln\frac{\mathcal{L}(\mathrm{obs}\mid b, \hat{\theta}_0)}{\mathcal{L}(\mathrm{obs}\mid \hat{\mu}\cdot s + b, \hat{\theta})}. \tag{3}$$

The statistical significance Z of a signal-like excess is computed from the probability p_0

$$p_0 = \mathrm{P}\big(q_0 \geqslant q_0^{obs} \mid \mathrm{b}\big), \tag{4}$$

henceforth referred to as the p-value, using the one-sided Gaussian tail convention:

$$p_0 = \int_{Z}^{+\infty} \frac{1}{\sqrt{2\pi}} \exp\big(-x^2/2\big)\,\mathrm{d}x. \tag{5}$$

In the Higgs boson search, we scan over Higgs boson mass hypotheses and look for the one giving the minimum local p-value $p_{\mathrm{local}}^{\mathrm{min}}$, which describes the probability of a background fluctuation for that particular Higgs boson mass hypothesis. The probability to find a fluctuation with a local p-value lower or equal to the observed $p_{\mathrm{local}}^{\mathrm{min}}$ anywhere in the explored mass range is referred to as the global p-value, p_{global}.

The fact that p_{global} can be significantly larger than $p_{\mathrm{local}}^{\mathrm{min}}$ is often referred to as the look-elsewhere effect. The global significance (and global p-value) of the observed excess can be evaluated in this case by generating pseudo-datasets, which, however, becomes too computationally intensive and not practical for very small p-values. Therefore, we use the method suggested in Ref. [64]. The relationship between global and local p-values is given by:

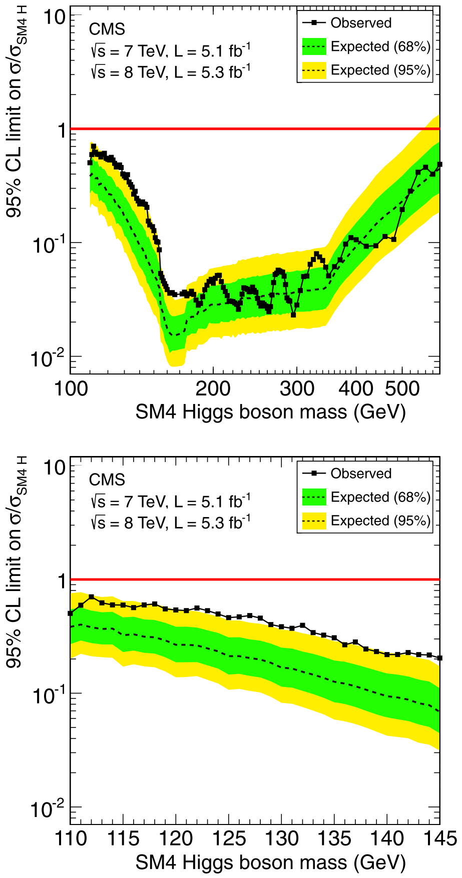

Fig. 2. The observed and expected 95% CL upper limits on the signal strength modifier, $\mu = \sigma/\sigma_{\mathrm{SM4\,H}}$, for the SM4 Higgs boson hypothesis as a function of the Higgs boson mass in the range 110–600 GeV (top) and 110–145 GeV (bottom).

$$p_{\mathrm{global}} = p_{\mathrm{local}}^{\mathrm{min}} + C\cdot \mathrm{e}^{-Z_{\mathrm{local}}^2/2}. \tag{6}$$

When the look-elsewhere effect is very large, as in this search, the constant C can be evaluated directly from data [58] by counting upcrossings N_{up} of $\hat{\mu}(m_{\mathrm{H}})$ with the line $\mu = 0$ and setting $C = N_{\mathrm{up}}$. The best-fit signal strength $\hat{\mu}$ in this case is obtained from maximising the likelihood $\mathcal{L}(\mathrm{obs}\mid \hat{\mu}\cdot s + b, \hat{\theta})$ with no constraints on $\hat{\mu}$.

6. Results

The following conventions are used. The observed values are shown in the plots by a solid line. A dashed line is used to indicate the median of the expected results for the background-only hypothesis. The green (dark) and yellow (light) bands show the ranges in which the measured values are expected to reside in at least 68% and 95% of all experiments under the background-only hypothesis.

6.1. *The SM4 results*

The $\mathrm{CL_s}$ value for the SM4 Higgs boson hypothesis as a function of its mass is shown in Fig. 1. $\mathrm{CL_s}$ values of 0.05, 0.01, and 0.001 are indicated by horizontal thick red lines. The mass regions where the observed $\mathrm{CL_s}$ values are below these lines are

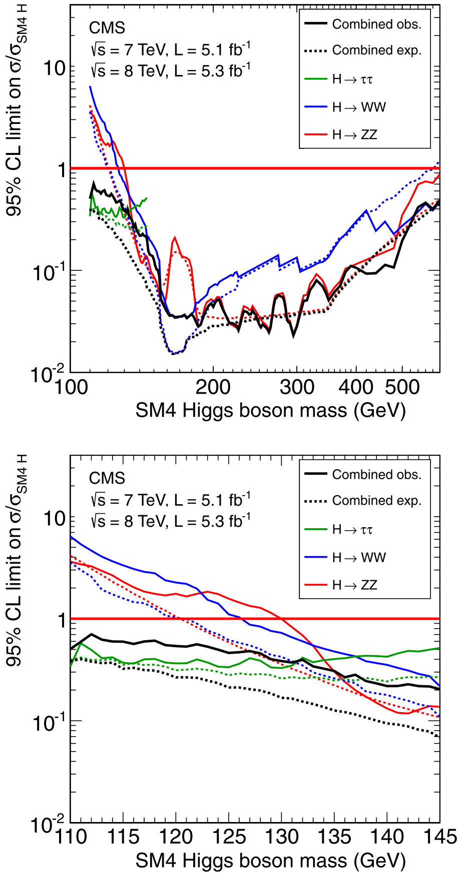

Fig. 3. The observed (solid lines) and expected (dashed lines) 95% CL upper limits on the signal strength modifier, $\mu = \sigma/\sigma_{\mathrm{SM4\,H}}$, as a function of the SM4 Higgs boson mass in the range 110–600 GeV (top) and 110–145 GeV (bottom) for the four explored Higgs boson decay modes and their combination.

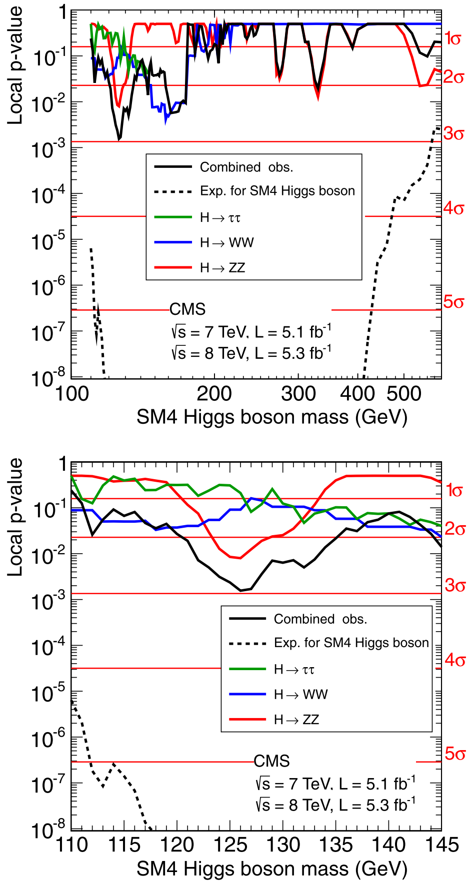

Fig. 4. The observed local p-value p_0 as a function of the SM4 Higgs boson mass in the range 110–600 GeV (top) and 110–145 GeV (bottom). The dashed line shows the expected local p-values should an SM4 Higgs boson with a mass m_{H} exist. The expected p-value is obtained with nuisance parameters constrained by the data, giving it some dependence on the observed data, and hence the small modulations on top of the overall smooth trend as a function of m_{H}.

excluded with the corresponding $(1 - \mathrm{CL_s})$ confidence levels of 95%, 99%, and 99.9%. We exclude an SM4 Higgs boson in the range 110–600 GeV at 99% CL, and in the range 110–560 GeV at 99.9% CL. Fig. 2 shows the 95% CL upper limits on the signal strength modifier, $\mu = \sigma/\sigma_{\mathrm{SM4\,H}}$, as a function of m_{H}. The ordinate on this plot shows the Higgs boson cross section that is excluded at 95% CL, expressed as a multiple of the SM4 Higgs boson cross section.

Fig. 3 shows the observed and expected limits for the three individual decay channels that have been considered, and their combination. The $\mathrm{H} \to \tau\tau$ search is the most sensitive channel in the mass range below 135 GeV. In the mass range 135–150 GeV, the best sensitivity is shared between $\mathrm{H} \to \mathrm{ZZ}$ and $\mathrm{H} \to \mathrm{WW}$. In the mass range 150–190 GeV, the $\mathrm{H} \to \mathrm{WW}$ channel has the best sensitivity. For masses above 190 GeV, the sensitivity is driven mostly by the $\mathrm{H} \to \mathrm{ZZ}$ decay channels.

To quantify the consistency of the observed excesses with the background-only hypothesis, we show in Fig. 4 a scan of the combined local p-value p_0, together with the results observed in the individual Higgs boson decay channels. The minimum combined local p-value $p_{\mathrm{local}}^{\mathrm{min}} = 1.5 \times 10^{-3}$ at $m_{\mathrm{H}} \simeq 126$ GeV corresponds to a local significance Z_{local} of 3σ. The global probability of observing at least as large an excess somewhere in the entire search range 110–600 GeV is estimated directly from the data using Eq. (6). The best-fit value $\hat{\mu}(m_{\mathrm{H}})$, shown in Fig. 5, has four upcrossings with $\hat{\mu} = 0$. This can be better seen as upcrossings of the solid line above the dashed line in Fig. 2. Taking into account the number of observed upcrossings, the global p-value of observing a local 3σ excess anywhere in the search region for the background-only hypothesis is 0.05.

Fig. 5 also illustrates why the SM4 Higgs boson is excluded even though a 3σ excess is observed at a mass near 126 GeV. The band shown in Fig. 5 corresponds to the ±1 standard deviation uncertainty (statistical + systematic) on the $\hat{\mu}$ value. Given these uncertainties, the best-fit values of signal strength $\hat{\mu}(m_{\mathrm{H}})$ are significantly smaller than expected for the SM4 Higgs boson ($\hat{\mu} = 1$) in the entire explored mass range.

Although the SM4 combination is not optimal for searching for the SM Higgs boson, the presence of such a boson would still produce an excess in the SM4 combination. The expected significance for a SM Higgs boson with a mass near 125 GeV is 3.5σ, which is very close to the observed value of 3σ. For reference, the expected significance at 125 GeV with the dedicated SM Higgs boson combination is 5.8σ [13].

6.2. The FP results

The $\mathrm{CL_s}$ value for the FP Higgs boson hypothesis as a function of its mass is shown in Fig. 6 (top). The $\mathrm{CL_s}$ values of 0.05, 0.01, and 0.001 are indicated by thick red horizontal lines. The mass regions where the observed $\mathrm{CL_s}$ values are below these lines are excluded with the corresponding $(1 - \mathrm{CL_s})$ confidence levels of 95%, 99%, and 99.9%. The fermiophobic Higgs boson is excluded at 95% CL in the mass range 110–147 GeV and at 99% CL in the range 110–133 GeV.

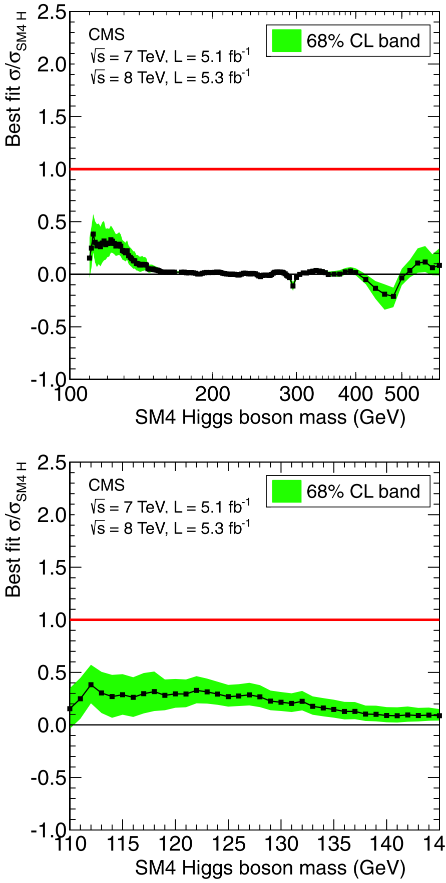

Fig. 5. The best-fit $\hat{\mu} = \sigma/\sigma_{\mathrm{SM4\,H}}$ as a function of the SM4 Higgs boson mass in the range 110–600 GeV (top) and 110–145 GeV (bottom). The band corresponds to the ±1 standard deviation uncertainty on the $\hat{\mu}$ values.

Fig. 6 (bottom) shows the 95% CL upper limits on the signal strength modifier, $\mu = \sigma/\sigma_{\mathrm{FP\,H}}$, as a function of m_{H}. The ordinate on this plot shows the Higgs boson cross section that is excluded at 95% CL, expressed as a multiple of the FP Higgs boson cross section.

Fig. 7 (top) shows the local p-value as a function of the FP Higgs boson mass for each run period and for their combination. The largest upwards fluctuation of events over the expected background is observed at 125.5 GeV, and is computed to have a local significance of 3.2σ. This deviation from the expected limit is too weak to be consistent with the fermiophobic Higgs boson signal, as can be seen in Fig. 7 (bottom), which shows that the observed signal strength for a fermiophobic Higgs boson at 125.5 GeV is 0.49 ± 0.18, as obtained from the fit of signal + background on data. The excess of events at 125.5 GeV is present in the SM Higgs boson search reported in Ref. [13] and corresponds to the discovery of the new boson around 125 GeV. This recently observed boson is not consistent with a fermiophobic Higgs boson at 99% confidence level.

As in the SM4 case, the FP analysis is not optimal for searching for the SM Higgs boson, but still has some sensitivity. The expected sensitivity to a SM Higgs boson with a mass of 125 GeV is 1.3σ; we observe 3.2σ. For reference, in the dedicated SM Higgs boson diphoton analysis, using the same dataset as the FP combination here, the observed significance of the excess near 125 GeV is 4.1σ, with an expected sensitivity of 2.8σ [13]. In both the SM and FP diphoton analyses the observed significances for the SM Higgs boson are greater than the expected, but statistically compatible at the $\mathcal{O}(10\%)$ level.

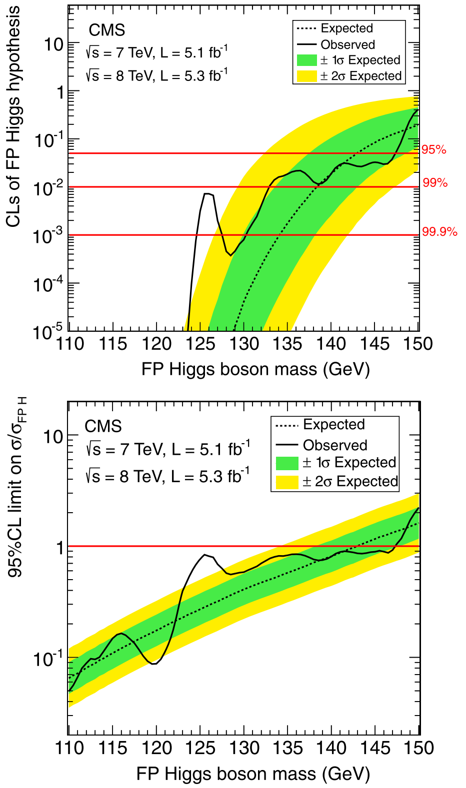

Fig. 6. (Top) The observed and expected $\mathrm{CL_s}$ values for the FP Higgs boson hypothesis as a function of the Higgs boson mass in the range 110–150 GeV. (Bottom) The observed and expected 95% CL upper limits on the signal strength modifier, $\mu = \sigma/\sigma_{\mathrm{FP\,H}}$, as a function of the FP Higgs boson mass in the range 110–150 GeV.

7. Summary

Searches are reported for Higgs bosons in the context of either the standard model extended to include a fourth generation of fermions with masses of up to 600 GeV or fermiophobic models. For the former, results from three decay modes ($\tau\tau$, WW, and ZZ) are combined, whilst for the latter the diphoton decay is exploited. The analysed proton–proton collision data correspond to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and up to 5.3 fb^{-1} at 8 TeV. The observed results exclude the SM4 Higgs boson in the mass range 110–600 GeV at 99% CL, and in the mass range 110–560 GeV at 99.9% CL. A fermiophobic Higgs boson is excluded in the mass range 110–147 GeV at 95% CL, and in the range 110–133 GeV at 99% CL. The recently observed boson with a mass near 125 GeV is not consistent with either an SM4 or a fermiophobic Higgs boson.

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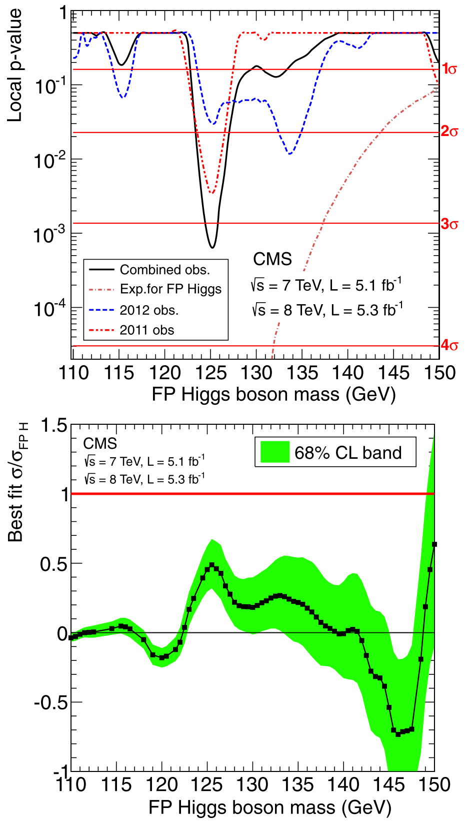

Fig. 7. (Top) The observed local p-value p_0 as a function of the FP Higgs boson mass in the range 110–150 GeV. The dashed–dotted line shows the expected local p-values should a fermiophobic Higgs boson with a mass m_{H} exist. The contributions to the expected limit for each run period are shown. (Bottom) The best-fit $\hat{\mu} = \sigma/\sigma_{\mathrm{FP\,H}}$ as a function of the FP Higgs boson mass in the range 110–150 GeV. The band corresponds to the ±1 standard deviation uncertainty on the $\hat{\mu}$ values.

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