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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.

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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]: $m_{\ell_4} = m_{\nu_4} = m_{d_4} =$ 600 GeV and $m_{u_4} - m_{d_4} = (50 + 10 \cdot \ln(m_H/115))$ 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 $K_{gg}(m_H)$ 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 $H \to gg$ and $gg \to H$ 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, $K_{VV}(m_H) \sim 0.3$, 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 $H \to \gamma\gamma$ 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 $K_{ff}(m_H) \sim 1.6$.

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 $K_{gg}(m_H)$ mentioned above. The $H \to bb$ search channel that fully relies on associated production is not included in this combination. For simplicity, $H \to b\bar{b}$ is denoted as $H \to bb$, $H \to \tau^+\tau^-$ as $H \to \tau\tau$, 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 $\mathcal{B}(H \to \gamma\gamma)$ is suppressed by $\mathcal{O}(100)$ with respect to the standard model. The branching fractions $\mathcal{B}(H \to WW)$ and $\mathcal{B}(H \to ZZ)$ 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 $m_H \sim 200$ 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 $m_H \sim 350$ GeV after the $H \to tt$ decay channel opens up. The branching fraction $\mathcal{B}(H \to \tau\tau)$ 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 $H \to ZZ \to 4\ell$ (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 $H \to \gamma\gamma$ 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 $H \to \gamma\gamma$ [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 $H \to xx$ is affected by each of these three uncertainties. Using the equation $\mathcal{B}_{xx} = \Gamma_{xx}/\Gamma_{tot}$ 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 $\mathcal{B}(H \to \gamma\gamma)$, $\mathcal{B}(H \to WW)$ and $\mathcal{B}(H \to ZZ)$. 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 ($m_H \approx 125$ 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, $\vec{E}_T^{miss}$, is taken as the negative vector sum of all particle transverse momenta, and its magnitude is referred to as E_T^{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

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