Joint analysis of Higgs decays and electroweak precision observables in the Standard Model with a sequential fourth generation

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We analyse the impact of LHC and Tevatron Higgs data on the viability of the Standard Model with a sequential fourth generation (SM4), assuming Dirac neutrinos and a Higgs mass of 125 GeV. To this end we perform a combined fit to the signal cross sections of $pp \to H \to \gamma\gamma, ZZ^*, WW^*$ at the LHC, to $p\bar{p} \to VH \to Vb\bar{b}$ $(V = W, Z)$ at the Tevatron and to the electroweak precision observables. Fixing the mass of the fourth generation down-type quark b' to 600 GeV we find best-fit values of $m_{t'} = 634$ GeV, $m_{l_4} = 107.6$ GeV and $m_{\nu_4} = 57.8$ GeV for the other fourth-generation fermion masses. We compare the χ^2 values and pulls of the different observables in the three and four-generation case and show that the data is better described by the three-generation Standard Model. We also investigate the effects of mixing between the third and fourth-generation quarks and of a future increased lower bound on the fourth-generation charged lepton mass of 250 GeV.

INTRODUCTION

While the Standard Model (SM) possesses a minimal boson field content, it indulges itself in the luxury of replicated fermion generations. It is difficult to predict the number of generations from fundamental theoretical principles; the determination of the correct number of fermion families is ultimately an experimental task. A sequential fourth generation is non-decoupling, meaning that its effect on certain observables does not vanish in the limit of infinitely heavy fourth-generation fermions. Among these observables are the gluon-fusion Higgs production cross section and the decay rate of $H \to \gamma\gamma$. This feature makes the SM with four generations, SM4, prone to be the first popular model of new physics on which the LHC will speak a final verdict.

Within the three generation SM (SM3) the production cross section $\sigma(gg \to H)$, which governs $pp \to H$ studied at the LHC, is dominated by a triangle diagram with a top quark. While the loop diagram decreases as $1/m_t$ for $m_t \to \infty$, this decrease is compensated by the linear growth of the top Yukawa coupling $y_t \propto m_t$. Consequently, in the SM4 the new contributions from the heavy t' and b' quarks will modify $\sigma(gg \to H)$ by a term which is independent of $m_{t'}$ and $m_{b'}$ at the one-loop level. One finds an increase by roughly a factor of 9, which seemingly entails a corresponding increase in the LHC signal cross section of Higgs decays into (virtual) gauge bosons, given by the product $\sigma(pp \to H)\,\mathcal{B}(H \to WW^*, ZZ^*, \gamma\gamma)$. However, higher-order corrections to the Higgs production cross sections and branching ratios due to the fourth-generation fermions can be substantial because of their large Yukawa couplings. In [1, 2] it was shown that, for light Higgs bosons, the $H \to WW^*$ and $H \to ZZ^*$ branching ratios in the SM4 can be suppressed by a factor of 0.2 or less as compared to their SM3 values. In the photonic Higgs decay rate $\Gamma(H \to \gamma\gamma)$ the destructive interference between fermion and gauge boson mediated contributions even leads to an accidental cancellation which would render the $H \to \gamma\gamma$ decay unobservable. As pointed out in [3], this leads to tensions with the observed excesses in $H \to \gamma\gamma$ searches at LHC and the searches for $H \to b\bar{b}$ in HW, HZ associated production at the Tevatron.

In [4–11] it was discussed that the SM4 may permit the decay mode $H \to \nu_4\bar{\nu}_4$, where ν_4 denotes the neutrino of the fourth generation. If the ν_4 is sufficiently long-lived, LHC triggers will not associate the ν_4 decay with the primary Higgs production and decay event, such that $H \to \nu_4\bar{\nu}_4$ will stay undetected. That is, with present experimental techniques the mere effect of an open $H \to \nu_4\bar{\nu}_4$ channel will be an increase of the total Higgs width and thus a decrease of all other branching fractions. In this paper we will only consider the case of Dirac neutrinos. The fourth-generation neutrino must therefore be heavier than $M_Z/2$ to comply with the invisible Z width measured at LEP1. While a nonzero $H \to \nu_4\bar{\nu}_4$ decay rate can reconcile the LHC data on $\sigma(pp \to H)\,\mathcal{B}(H \to WW^*, ZZ^*)$ with the SM4, it will only increase the tensions with the excesses in $H \to \gamma\gamma$ at the LHC and $H \to b\bar{b}$ at the Tevatron.

As long as the observed excesses are inconclusive one must resort to a global fit to all relevant observables to assess the viability of the SM4. The non-decoupling property of the SM4 implies that the SM3 can not be considered as a special case of the SM4 where some parameters are fixed. This actually represents a conceptual problem for a standard frequentist analysis as the choice of a suitable test statistic for the definition of p-values is no longer straightforward. We do not attempt to solve this issue here. Instead we simply compare the χ^2 values of the two models and the pulls of the individual observables. In all our fits we assume that the observed excesses in $H \to \gamma\gamma$ and $H \to b\bar{b}$ searches are not statistical fluctuations and we therefore fix the Higgs mass at $m_H = 125$ GeV.

Stringent constraints on the SM4 are also found from analyses of the electroweak precision observables [12], because the extra fermions induce non-decoupling contributions to the W mass, partial Z decay widths and asymmetries which are very sensitive to the mass splittings within the fermionic isospin doublets. It has been shown in Ref. [13–17] that the SM4 is compatible with the experimental constraints from LEP if the $m_{t'}$–$m_{b'}$ and/or m_{l_4}–m_{ν_4} mass splittings are chosen properly. Here l_4 denotes the charged lepton of the fourth generation. In this letter we perform a global fit to the parameters of the SM4, using the LHC data on the abovementioned Higgs decays, Tevatron data on $H \to b\bar{b}$ and electroweak precision data. We also discuss the impact of mixing between the third and fourth-generation quarks as well as the impact of an increased lower bound on the fourth generation charged lepton mass. For our fits we use the CKMfitter package, which implements the Rfit procedure [18], a frequentist statistical method.

METHODOLOGY

The main topic of this letter is a combined fit of the following (pseudo-)observables, which defines our analysis A1:

i) the signal strengths $\hat{\mu}(pp \to H \to WW^*)$ measured by CMS [19] (defined below) and $\hat{\mu}(pp \to H \to ZZ^*)$ measured by CMS [19] and ATLAS [20],

ii) the signal strengths $\hat{\mu}(VV \to H \to \gamma\gamma)$ and $\hat{\mu}(gg \to H \to \gamma\gamma)$ for Higgs production via vector boson fusion and gluon fusion, respectively, and subsequent decay into two photons as measured by CMS [21],

iii) the signal strength $\hat{\mu}(p\bar{p} \to HV \to Vb\bar{b})$ for Higgs production in association with a vector boson and subsequent decay into a $b\bar{b}$ pair, as measured by CDF and D0 [22],

iv) the electroweak precision observables (EWPOs) M_Z, Γ_Z, $\sigma_{\rm had}$, $A^l_{\rm FB}$, $A^c_{\rm FB}$, $A^b_{\rm FB}$, A_l, A_c, A_b, $R_l = \Gamma_{l^+l^-}/\Gamma_{\rm had}$, R_c, R_b, $\sin^2\theta_l^{\rm eff}$ measured at LEP and SLC [23] as well as m_t, M_W, Γ_W and $\Delta\alpha^{(5)}_{\rm had}$ [12].

v) the lower bounds $m_{t',b'} \gtrsim 600$ GeV(from the LHC) [24–27] and $m_{l_4} > 101$ GeV (from LEP2) [12].

Here and in the following, the term “signal strength” refers to the ratio of SM4 and SM3 signal cross sections evaluated with the same Higgs mass

$$\hat{\mu}(X \to H \to Y) = \frac{\sigma(X \to H)\mathcal{B}(H \to Y)|_{\rm SM4}}{\sigma(X \to H)\mathcal{B}(H \to Y)|_{\rm SM3}} \quad . \quad (1)$$

where a signal cross section is given by the product of the Higgs production cross section and a branching fraction into a certain final state.

When confronting the SM4 with electroweak precision data, the usual method is to compute the oblique electroweak parameters S and T [28], and compare the results to the best-fit values for S and T provided by the LEP Electroweak Working Group [23]. For the SM4, such studies were done, for example, in Refs. [12, 16, 17, 29]. However, it is well-known that the parametrisation of the EWPOs (iv) by S and T becomes inaccurate when some of the fourth-generation fermion masses are close to M_Z or when the fourth-generation fermions mix with the fermions of the first three generations. Since here, we are interested in a scenario where $m_{\nu_4} < M_Z$ we do not use the oblique electroweak parameters in our analysis, but fit the EWPOs directly. To this end, we use ZFitter [30–32] to compute accurate predictions for the EWPOs in the SM3. (More precisely, we use the DIZET subroutine of the ZFitter package.) Then we follow the procedure of [33] and add corrections due to the fourth-generation fermions to the EWPOs. The differences between EWPOs in the SM4 and SM3 are calculated at one-loop order, but no further approximations are made for the EWPOs. As experimental inputs we use $M_W = 80.390 \pm 0.016$ GeV [34] and otherwise the same inputs as the GFitter collaboration [35]. With our program we reproduce the best-fit parameters and observables for the SM3 within less than 10% of the (fit) error quoted in [35] for each parameter or observable. Our electroweak fit differs from the one in [35] in two points: we neglect the bottom and charm mass in the calculation of the EWPOs and we do not include theoretical errors. For the present analysis we also fix the Higgs mass to 125 GeV.

The current limit on the b' mass according to [26] is approximately 600 GeV. However, this and other limits on fourth generation quark masses by CMS and ATLAS rely on certain assumptions about the decay pattern of the quarks. These limits can be severely weakened if CKM mixing and ‘cascade decays’ such as $t' \to b'W$ are taken into account [36]. In this letter we avoid the bounds on fourth-generation quark masses by fixing the b' mass to $m_{b'} = 600$ GeV. The splitting between the fourth-generation quark masses is strongly constrained by the EWPOs, so that the bound on $m_{t'}$ will automatically be satisfied.

In close correspondence to SM3 electroweak fits such as [12, 35], we let the following parameters float in our fit:

$$\Delta\alpha^{(5)}_{\rm had},\ \alpha_s,\ M_Z,\ m_t,\ m_{t'},\ m_{\nu_4},\ m_{l_4}\ \text{and}\ \theta_{34}, \qquad (2)$$

where $\Delta\alpha^{(5)}_{\rm had}$ is the hadronic contribution to the running of the fine-structure constant in the 5-flavour scheme and θ_{34} denotes the mixing angle between the third and fourth generation, defined analogously to the Cabibbo angle. The importance of the mixing angle θ_{34} in the SM4 electroweak fit was pointed out in [37]. Mixing of the fourth generation with the first two generations and additional CP violating phases can be relevant if flavour observables are included in the fit. However, the constraints on these parameters from flavour physics are so strong that the allowed variations do not have a big effect on the observables studied in this letter. We therefore set these additional phases and mixing angles to zero. Note that we fix the Higgs mass to 125 GeV, which is the value favoured by the hints seen in 2011 LHC data. The choice of a fixed value for $m_{b'}$ does not lead to a significant loss of generality, as the experimental lower bound $m_{b'} \gtrsim 600$ GeV [26] is already rather close to the scale where the Yukawa interactions become non-perturbative [38]. Also, the non-decoupling property of the most relevant quantities implies a rather mild dependence on $m_{b'}$.

We include the two-loop electroweak corrections to Higgs production and decay in our evaluation of the Higgs signal cross sections in the SM4 by means of the program HDECAY v. 4.45 [39]. This is mandatory, because the flat dependence of these decay amplitudes on m_{t',b',l_4} is broken by the leading two-loop corrections [2]. To avoid the complicated procedure of interfacing the HDECAY code with our program we set — for the evaluation of the Higgs signal cross sections — $m_{t'} = 650$ GeV, $\theta_{34} = 0$ and the SM parameters α, α_s, M_Z and m_t to the default values of HDECAY. The dependence of the cross sections on m_{ν_4} and m_{l_4} is then accounted for by linear interpolation of two-dimensional lookup-tables with a granularity of 0.5 GeV for m_{ν_4} and 50 GeV for m_{l_4}. As the experimental errors on the Higgs signal cross sections are still rather large this simplification has no noticable impact on our fit.

Table I summarises our experimental inputs for the Higgs signal strengths in the different search channels: The signal strength for Higgs production via vector boson fusion (VBF) and subsequent decay into $\gamma\gamma$ ($VV \to H \to \gamma\gamma$) corresponds to the signal strength for the dijet class in [21]. We assume that the events in this category stem entirely from vector boson fusion processes. This is, of course, a somewhat crude approximation. There will also be a certain contamination from gluon fusion events in that sample, but lacking more detailed information on this contamination we are forced to ignore it. The signal strength for Higgs production via gluon fusion and subsequent decay into $\gamma\gamma$ ($gg \to H \to \gamma\gamma$) was obtained by removing the dijet contribution from the combined result for the signal strength in [21]. In doing this, we implicitly neglect all Higgs production mechanisms except gluon fusion and vector boson fusion. The signal strength for $pp \to H \to ZZ^*$ is a combination of the results presented in [19] and [20]. The signal strength for $pp \to H \to WW^*$ was taken from [19]. The input for the $p\bar{p} \to HV \to Vb\bar{b}$ process is taken from the latest Tevatron search [22] for Higgs bosons produced in association with a W or Z boson and subsequently decaying into a $b\bar{b}$ pair.

process	signal strength	reference
$VV \to H \to \gamma\gamma$	$3.7^{+2.0}_{-1.7}$	[21]
$gg \to H \to \gamma\gamma$	1.10 ± 0.65	[21]
$pp \to H \to WW^*$	$0.39^{+0.61}_{-0.56}$	[19]
$pp \to H \to ZZ^*$	$0.69^{+0.93}_{-0.52}$	[19], [20]
$p\bar{p} \to HV \to Vb\bar{b}$	$2.03^{+0.73}_{-0.71}$	[22]

TABLE I. Experimental inputs for Higgs signal strengths at $m_H = 125$ GeV.

For the computation of signal cross sections in the SM4 we use an effective coupling approximation along the lines of [40, 41]. Specifically, we calculate the SM4 signal cross sections by taking SM3 production cross sections for the different production mechanisms from [42] (LHC) and [43] (Tevatron), scaling them with corresponding SM4/SM3 ratios of related partial Higgs decay widths and multiplying with the SM4 branching fractions calculated by HDECAY. For instance, the SM4 signal cross section for $gg \to H \to \gamma\gamma$ is calculated as

$$\sigma(gg \to H \to \gamma\gamma)_{\rm SM4} = \sigma(gg \to H)_{\rm SM3} \times \frac{\Gamma(H \to gg)_{\rm SM4}}{\Gamma(H \to gg)_{\rm SM3}} \mathcal{B}(H \to \gamma\gamma)_{\rm SM4}\ , \qquad (3)$$

with $\sigma(gg \to H)_{\rm SM3}$ taken from [42] and the remaining quantities on the right-hand side calculated by HDECAY. The factor $\Gamma(H \to gg)_{\rm SM4}/\Gamma(H \to gg)_{\rm SM3}$ accounts for the modified Hgg effective coupling in the SM4. For the VBF process $VV \to H \to \gamma\gamma$ the Higgs can come from a HWW or HZZ vertex. We assume that 75% of the production cross section comes from WW fusion and 25% from ZZ fusion. These ratios were obtained from [44], which implements the NLO results from [45]. Equations analogous to (3) are then used separately for the $WW \to H$ and $ZZ \to H$ production modes. For the $pp \to H \to WW^*$ and $pp \to H \to ZZ^*$ signal cross sections all production mechanisms were taken into account. For the (Tevatron) $p\bar{p} \to HV \to Vb\bar{b}$ process only the HW and HZ associated production mechanisms contribute. The corresponding SM3 production cross sections were taken from [43]. Like the LHC cross sections these were scaled with the SM4/SM3 ratios of $H \to WW$ and $H \to ZZ$ partial widths, respectively, and multiplied with the SM4 $H \to b\bar{b}$ branching fraction.