Review Article

Constraints on a Fourth Generation of Fermions from Higgs Boson Searches

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We review the past and current status of the extension of the standard model (SM) by a fourth generation of fermions. In particular the new results for Higgs boson searches at the LHC and at Tevatron exclude the possibility of having simply a perturbative fourth generation of fermions with one Higgs doublet (SM4). We also briefly mention more complicated extensions of the SM4, which are not yet excluded, like adding in addition another Higgs doublet to the SM4.

1. Introduction

In the standard model [1, 2] the masses of the W and Z bosons are generated via the so-called Higgs mechanism [3–7]. Also all fermion masses can be created by this mechanism via the Yukawa interaction. Schematically the Lagrangian of the SM reads

$$
\begin{aligned}
\mathscr{L} = &-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\overline{\Psi}\slashed{D}\Psi + \left| D_\mu \Phi \right|^2 \\
&- V(\Phi) + i\overline{\Psi}_i Y_{ij} \Phi \Psi_j + h.c.
\end{aligned}
\tag{1}
$$

The first term of (1) describes the gauge fields of the strong, weak, and electromagnetic interaction, the second term describes the massless fermions and their interaction with the gauge fields. The third and fourth term represent the free scalar field, the Higgs potential, and the interaction of the scalar field with the gauge fields. The special form of the Higgs potential will result in masses for some of the gauge bosons. The last term describes the interaction between fermions and the scalar field, the so-called Yukawa interaction. In the above equation the number of fermion generations is a free parameter. Experimentally three generations have been observed, but a priori there is no reason why there could not be more generations. The Yukawa interaction results in masses for all the fermions and also in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [8, 9], which describes the coupling of the quarks to the charged electroweak gauge bosons W^+ and W^-. In the case of two fermion generations the CKM matrix consists of one real parameter (the so-called Cabibbo angle), in the case of three generations of three real parameters and one complex phase and in the case of four generations there are six real mixing angles and three complex phases. A complex coupling in the theory will give rise to CP-violation and the CKM sector is the only part of the SM, where CP-violation has been experimentally detected. CP-violation is in particular interesting because it is one of the three Sakharov criteria [10–12] that allow the dynamical creation of the observed baryon asymmetry in the universe. In that sense, having three generations of fermions is a minimal requirement in order to have CP-violation in the fundamental laws of nature. It turns out however, that the amount of CP-violation in the CKM matrix with three generations is not sufficient to explain the baryon asymmetry, while the amount of CP-violation with four generations seems to be sufficient [13]. This clearly seems to be a nice motivation to study an extension of the SM with additional fermion generations.

Besides giving masses to the gauge bosons of the weak interaction and the fermions the Higgs mechanism predicts also in its simplest form the existence of one massive neutral scalar particle, the Higgs boson. The search for the Higgs boson was one of the primary goals of the LHC, which has
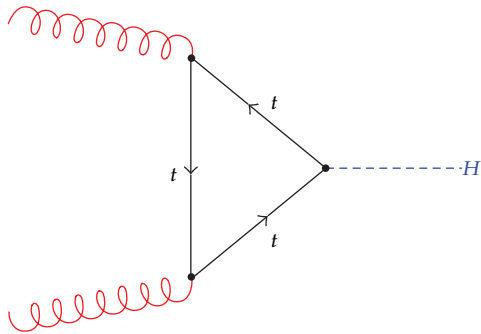
FIGURE 1: Gluon fusion with an internal top loop turns out to be the dominant Higgs production mechanism at the LHC.

probably been achieved in July 2012, when a new boson with a mass of about 125 GeV was observed by ATLAS and CMS [14]. The properties of this new boson seem to be in accordance with the properties of SM Higgs boson, but to draw definite conclusions more data are needed.

At the LHC the dominant production mechanism of the Higgs boson is gluon fusion [19], where two gluons couple to a top triangle, which again couples to a Higgs boson, see Figure 1 (taken from [20])—for a review of Higgs boson production and decay, see [21]. This process has been studied in detail in the standard model and many corrections to it have been determined. Leading QCD corrections have been calculated already in 1991 [22–24] and they turned out to be huge. Depending on the Higgs mass, they can be up to 100%. Hence, it was necessary to calculate also NNLO QCD corrections [25–37]. Also NLO-electroweak and mixed QCD-electroweak corrections were determined for the gluon fusion [38–44].

At the LHC one is, however, also sensitive to subdominant production processes like associated vector boson-Higgs production/Higgs-Strahlung ($pp \rightarrow VH$) [45, 46], vector boson fusion ($pp \rightarrow qqH$) [47], and top-Higgs production ($pp \rightarrow tH$).

End of 2011 some hints for the existence of a Higgs-like boson at a mass of about 125 GeV have been presented by ATLAS [48–56] and CMS [57–65]. The strongest signal were found in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ channel, but also $H \rightarrow WW$, $H \rightarrow \tau^+\tau^-$ and $H \rightarrow b\bar{b}$ was investigated. In March 2012 Tevatron presented also small hints for a Higgs boson via the reaction $p + \bar{p} \rightarrow VH \rightarrow Vb\bar{b}$ in the same mass region [66]. On July 2, 2012 Tevatron updated their result and they found an even stronger indication for $H \rightarrow b\bar{b}$ [67]. Compared to March 2012 the statistical significance increased from 2.6 standard deviations to 2.9 standard deviations. Finally ATLAS and CMS announced on July 4, 2012 the observation of a new Higgs-like boson [14]. ATLAS presented results for the decay channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$, (Recently ATLAS made also some data for the channel $H \rightarrow WW$ public in ATLAS-CONF-2012-098.) obtaining a statistical significance of 5.0 standard deviations for a boson with a mass of 126.5 GeV. CMS included in addition $H \rightarrow WW$, $H \rightarrow \tau^+\tau^-$, and $H \rightarrow b\bar{b}$, obtaining a

statistical significance of 4.9 standard deviations for a boson with a mass of 125.3 ± 0.6 GeV. The couplings agree within errors with the SM expectations, although the signal strength for the $H \rightarrow \gamma\gamma$ channel is enhanced in both ATLAS (1.9 ± 0.5) and CMS (1.56 ± 0.43). Here more data are needed to investigate whether this is a statistical fluctuation or a first glimpse of physics beyond the SM. These results have profound implications on the physics of a fourth generation of fermions, which will be discussed below.

2. Higgs Production and Decay within the SM4

2.1. The Model. We define the SM4 as the extension of the usual standard model simply by an additional chiral family of fermions. Its fermionic contents reads

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \begin{pmatrix} \nu_4 \\ l_4^- \end{pmatrix}. \quad (2)$$

In addition one assumes Dirac masses for the heavy neutrinos, only one Higgs doublet, and the perturbativity of the Yukawa couplings. The strong conclusions we will make about the exclusion of the SM4 rely on all these assumptions, so it is important to keep them in mind. For some reviews of this model see, for example, [68, 69].

Extending the SM by an additional fermion generation might change many observables directly, but also indirectly via loop processes. Thus, the SM4 is subjected to a number of constraints:

(1) direct searches for the production of heavy quarks and leptons of the fourth generation at the LHC and at Tevatron;

(2) flavor observables are affected by a fourth generation via a change of the values of the CKM elements and via loop processes;

(3) electroweak precision observables are affected by a fourth generation via loop processes;

(4) higgs production and decay are affected by a fourth generation via loop processes.

The first three classes of constraints will be discussed briefly and the last class in detail below.

2.2. The Numerous Deaths of the SM4. The SM4 was already killed many times in the literature, however, until very recently the arguments for the exclusion of the SM4 relied always on some additional unjustified assumptions, which will be elaborated below. In the 1980s the idea of a fourth generation was relatively popular, see, for example, [70–81]. Later on this possibility was widely considered not to be attractive, see, for example, [82] for an early reference, where arguments like "*Rather than being nice the presence of a 4th family is likely to be an hindrance for our understanding of the patterns in flavor physics.*", were given against the existence of the fourth generation. The scientific content of such statements is clearly questionable.

After LEP measured the number of light neutrinos to be very close to three, $N_\nu = 2.9840 \pm 0.0084$ [83], this was

considered to be a further argument against the fourth generation, because it was implicitly assumed that the neutrino of the fourth generation is massless as well. The actual bound from LEPI was, however, only valid for light neutrinos, with $m_\nu < M_Z/2$. After the observation that neutrinos have mass ($m_\nu \neq 0$), see, for example, [84, 85], it was still considered to be *unnatural* that the fourth neutrino should be heavy $m_\nu > M_Z/2$, while the first three ones are very light. We would like to stress here, however, that it is not excluded by any principle that nature itself is *unnatural* in the above sense!

Electroweak precision observables are also very sensitive to loop effects of the new heavy fermions. In the PDG article from Langacker and Erler [83] the effects of the SM4 to the Peskin and Takeuchi parameters [86, 87] S and T were investigated. Concretely, these were the 1-loop contributions to the W- and Z-boson and the γ self-energies with virtual t'-, b'-quarks or virtual ν_4 and l_4. For a long time the PDG article from Langacker and Erler (see, e.g., the archive of [83]) gave the wrong impression that a fourth generation is excluded by electroweak constraints. We list here some statements of previous PDG versions.

   (i) 1994: one heavy generation of ordinary fermions is allowed at 95% CL.

   (ii) 1998: an extra generation of ordinary fermions is now excluded at the 99.2% CL.

   (iii) 2002: an extra generation of ordinary fermions is excluded at the 99.8% CL on the basis of the S parameter alone [...]. This result assumes [...] that any new families are degenerate. This restriction can be relaxed [...] to 95%.

   (iv) 2010: An extra generation of SM fermions is excluded at the 6 σ level on the basis of the S parameter alone [...]. This result assumes that [...] any new families are degenerate [...]. Thus, a fourth family is disfavored, but not excluded by current data.

Concerning some of the above statements one should keep in mind that there is no reason at all to consider the S parameter alone and there is also no reason to consider only a degenerate fourth family. Thus, we consider the statements, which were made under these assumptions, to be misleading.

So for quite some time it was an established prejudice; that the SM4 is excluded. This situation changed quite significantly with the paper of Kribs et al. from 2007 [88]. This paper marked somehow the resurrection of the SM4. Till July 2012 it was cited more than 300 times, showing the renewed interest in the physics of a fourth family. The authors showed in their paper that the SM4 is phenomenologically not excluded, in particular it is not in conflict with electroweak precision observables. In more details they noticed that a change of the Peskin and Takeuchi [86, 87] parameter S can be compensated to a large extent by a similar change in the parameter T, that is, $\Delta S \approx \Delta T$ is in agreement with data for not too large values of ΔS. This shows clearly that it can be misleading to make statements based on the S parameter alone. Moreover the new contribution to S can be decreased by taking into account a mass splitting of the fourth generation. Finally the SM4 can also compensate effects of

a high mass of the Higgs boson. The authors of [88] state "*the fit to electroweak data is in agreement with the existence of a fourth generation and a light Higgs about as well as the fit to the standard model alone with $m_H = 115 \, GeV$.*" So now the SM4 is not only not excluded, it is also not disfavored by the electroweak data. (This statement is not in agreement with, for example, the 2012 version of [83, 89], where it is still claimed that the SM4 is disfavoured compared to the SM. We do not try to settle this issue here.)

Similar arguments as the ones in [88] have actually been made previously from a Russian group [90–92] and also in [93, 94]. But none of these papers managed to trigger so much interest in the community as [88].

There were, however, still some missing points in the investigation of the electroweak precision observables. First, treating the fourth generation lepton masses as free parameters allows, for example, easily also a degenerate fourth quark generation, see, for example, [15, 95]. In Figure 2 (taken from [15]) the allowed mass splitting of fourth generation fermions according to the constraints from the Peskin and Takeuchi parameters is shown. One clearly sees that mass degenerate quarks of the fourth family are not ruled out. Similar results were obtained, for example, in [95, 96]. Second, also the full CKM dependence of the T and U parameters has to be included. This was first done in [95] and leads to the interesting result that even for fixed lepton masses now a degenerate fourth quark generation is possible. (The dominant CKM effects in the electroweak precision observables were investigated in [97, 98].) In Figure 3 a comparison of the electroweak fit without CKM mixing, that is setting by hand $V_{tb} = 1 = V_{t'b'}$, with the fit with the full CKM dependence is shown. For both cases the lepton masses are fixed. In the case of no CKM mixing (a commonly used assumption, which is, however, not justified by any principle!) one finds that degenerate quark masses are more or less excluded, while degeneracy is perfectly consistent with data, if CKM mixing is included. Allowing for both free lepton masses and CKM mixing one obtains the result from Figure 4. Hence, the degeneracy of the fourth generation is clearly not ruled out by electroweak precision observables. Similar results, like in Figure 4, were obtained in [96]. Third, instead of the Peskin and Takeuchi parameter it is of course desirable to use the full electroweak observables. An effective way to implement them was developed in [99]. This approach was applied in [18, 100] in combination with the data from Higgs searches and will be discussed below. The S, T, U parameters were also investigated in [101, 102] for the case of the SM4.

A fourth generation of fermions can also have sizeable effects on flavor observables. First, the 3 times 3 CKM matrix will in general no longer be unitary—only the 4 times 4 CKM matrix has to fulfill unitarity. Thus, the current strong constraints on, for example, V_{td}, V_{ts} and V_{tb} are no longer valid and their values can differ sizeably from the SM values, obtained in CKM fits, see, for example, [103–105]. Second, the new heavy fermions contribute via loops in flavor changing neutral current processes like $b \rightarrow s\gamma$ or B mixing. Since there were for quite some time several deviations between SM predictions and measurements of certain flavor observables, see, for example, [106], there were justified hopes that this
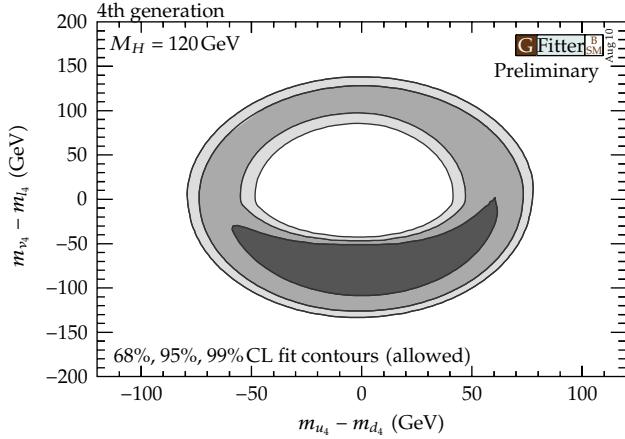
FIGURE 2: Allowed mass splitting of fourth generation fermions according to the constraints from electroweak precision observables. One clearly sees that mass degenerate quarks of the fourth family are not ruled out. Note, that for this result CKM mixing was neglected. Figure from [15].

might be the first hints for physics beyond the SM and this triggered a lot of interest in the literature, see, for example, the list of citations for [107]. Flavor observables within the SM4 were recently investigated in, for example, [108–119]. Because of the success of the CKM paradigm [120], one might expect that the CKM mixing between the first three generations and the fourth one is strongly constrained to tiny values. It was quite unexpected that flavor constraints alone allow still for huge effects in FCNC processes. In [109] it is explained in detail how for example, a t'-contribution to the box diagram for the mass difference in the neutral B-meson system, which is larger than the SM value, can be compensated by the modified values of the CKM elements V_{td}, V_{ts}, and to a lesser extent V_{tb}. Also quite unexpected was the fact that stronger bounds on the CKM mixing with a fourth generation of quarks are actually obtained from electroweak precision observables [95, 97, 98]. Nevertheless there is a lot room for new effects in the CKM sector of the SM4, which might explain the above-mentioned discrepancies in the flavor sector. Unfortunately now many of these discrepancies have disappeared because of new data, in particular from LHCb see, for example, [121, 122]. Also a long standing discrepancy concerning the leptonic decay $B \rightarrow \tau \nu$ seems to have been resolved experimentally by the Belle Collaboration [123].

To summarize the results of this section we make the following statement: the SM4 can easily accommodate all flavor and electroweak data and the previous claims on the exclusion of the SM4 relied on unjustified additional assumptions. One thing to keep in mind is the fact that currently two-loop electroweak corrections for the electroweak precision observables are still missing and these corrections might be sizeable.

Currently there are also stringent limits on the masses of the fourth generation quarks from direct searches [124–129], which push the values of the masses close to the non-perturbative regime. Here we only would like to mention

that many of these analyses rely on some additional, non-general assumptions, for example, about the CKM mixing of the fourth generation [130]. Giving up these additional assumptions one gets typically considerably weaker bounds on the masses.

Till now we found that the SM4 is resistant against all experimental attacks. In the next section we will, however, show that the SM4 cannot comply with the recent data from Higgs searches.

2.3. Common Folklore. Concerning Higgs production and Higgs decay the common folklore reads as follows: gluon fusion is enhanced by a factor of nine (e.g., [131]) due to the additional running of the t'- and b'- quark in the loop of Figure 1 and therefore the SM4 can easily be killed, if no huge Higgs signals are observed. On the other hand in the SM4 severe cancellations arise in the decay $H \rightarrow \gamma\gamma$ [132–135]. In (13) of [88] the situation for a light Higgs mass (i.e., below 200 GeV) was roughly summarized as

$$
\begin{aligned}
&\sigma\left(gg \longrightarrow H\right) \cdot \operatorname{Br}\left(H \longrightarrow \gamma\gamma\right)\big|_{\mathrm{SM4}} \\
&\quad \approx \sigma\left(gg \longrightarrow H\right) \cdot \operatorname{Br}\left(H \longrightarrow \gamma\gamma\right)\big|_{\mathrm{SM}},
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
&\sigma\left(gg \longrightarrow H\right) \cdot \operatorname{Br}\left(H \longrightarrow ZZ\right)\big|_{\mathrm{SM4}} \\
&\quad \approx (5 \ldots 8)\,\sigma\left(gg \longrightarrow H\right) \cdot \operatorname{Br}\left(H \longrightarrow ZZ\right)\big|_{\mathrm{SM}},
\end{aligned}
\tag{4}
$$

$$
\begin{aligned}
&\sigma\left(gg \longrightarrow H\right) \cdot \operatorname{Br}\left(H \longrightarrow f\overline{f}\right)\big|_{\mathrm{SM4}} \\
&\quad \approx 5\,\sigma\left(gg \longrightarrow H\right) \cdot \operatorname{Br}\left(H \longrightarrow f\overline{f}\right)\big|_{\mathrm{SM}}.
\end{aligned}
\tag{5}
$$

References [136, 137] obtain higher values for $gg \rightarrow H \rightarrow \gamma\gamma$—there the SM4 value is enhanced by a factor of up to 4 compared to the SM value. Reference [138] gives only values for M_H between 115 GeV and 130 GeV and there the enhancement factor for $gg \rightarrow H \rightarrow \gamma\gamma$ is between 1.4 and 2.6.

Despite these minor differences there is a common result: in the SM4 one expects more or at least as much Higgs events (depending on the channel) as in the SM. Hence, seeing nothing above the SM expectation rules out the SM4. These line of arguments can, for example, be found in the interpretation of the LHC Higgs searches presented at Lepton-Photon 2011, see also [139].

There are, however, two possible flaws in this argumentation, which have to be taken into account and which might actually revert the conclusions.

2.4. Loop Hole No.1: Invisible Higgs Decays. First, there is still the possibility that the heavy fourth neutrino is lighter than half of the Higgs mass. Current experimental bounds do not exclude a fourth neutrino with a mass larger than half of the Z mass (depending on the lifetime of the fourth neutrino). Having a neutrino with $m_{\nu_4} < m_H/2$ would open up a new invisible decay channel, which can suppress all other Higgs branching ratios and therefore compensate for the enhancement factor of the gluon fusion process within the SM4. This idea was first presented in [140] and later on further
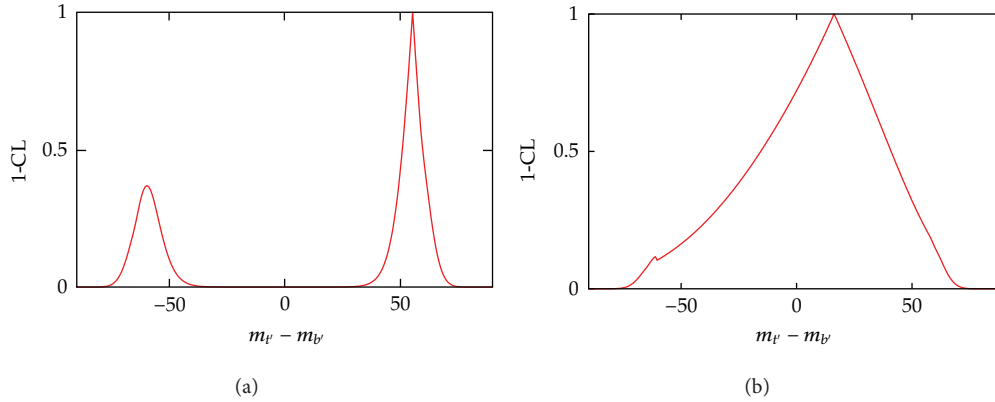
(a)

(b)

FIGURE 3: Allowed mass splitting of fourth generation quarks according to the constraints from electroweak precision observables. (a) CKM mixing is forced to be zero, (b) it is allowed to an extent that does not violate any bound from flavor physics. For both pictures the lepton masses were fixed.
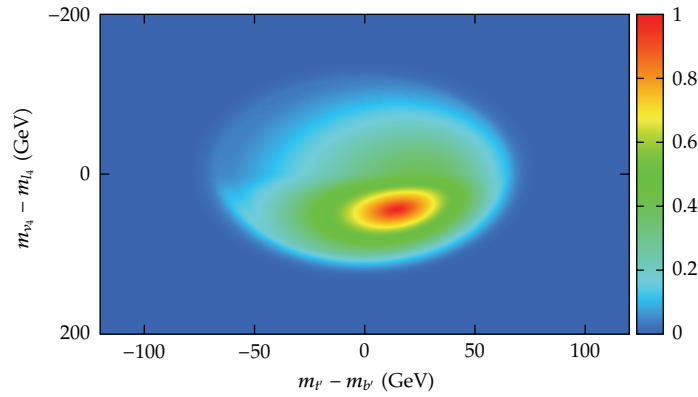

FIGURE 4: Allowed mass splitting of fourth generation fermions according to the constraints from electroweak precision observables, allowing for CKM mixing and free lepton masses.

investigated in, for example, [141–145]. A more general lepton sector, where the neutrino can also have a Majorana character, was discussed, for example, in [146–149].

2.5. Loop Hole No.2: Huge NLO Electroweak Corrections.
NLO-electroweak corrections to the Higgs production have already been determined in the midnineties [38–40]. In these works the dominant contributions proportional to $G_F m_t^2$ were determined. The full dependence on the mass of the heavy fermions was calculated recently in [16, 150]. As a result it turned out that the corrections can be huge. The corrections to the gluon fusion process are shown in **Figure 5**. For low Higgs masses (100 GeV–200 GeV) the NLO-electroweak corrections are sizeable—of the order of +10%. For large Higgs masses (>900 GeV) they are huge, that is, larger than −50% and the perturbative approach probably breaks down.

Also the decay rates of the Higgs boson are sizeably affected by NLO-electroweak corrections. In **Figure 6** a comparison of the different Higgs branching ratios within the SM4 and the standard model is shown. The invisible decay of the Higgs boson is not yet taken into account here.

With the results from Figures 5 and 6 one obtains the following expectations for Higgs searches:

$$\sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow \gamma\gamma\right)\big|_{\mathrm{SM4}}$$
$$< 0.27\,\sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow \gamma\gamma\right)\big|_{\mathrm{SM}},$$
$$(\approx 1)$$

$$\sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow ZZ\right)\big|_{\mathrm{SM4}}$$
$$\approx (1.35\ldots 9)\,\sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow ZZ\right)\big|_{\mathrm{SM}}, \quad (6)$$
$$\approx (5\ldots 8)$$

$$\sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow b\bar{b}\right)\big|_{\mathrm{SM4}}$$
$$\approx (6.3\ldots 27)\,\sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow b\bar{b}\right)\big|_{\mathrm{SM}},$$
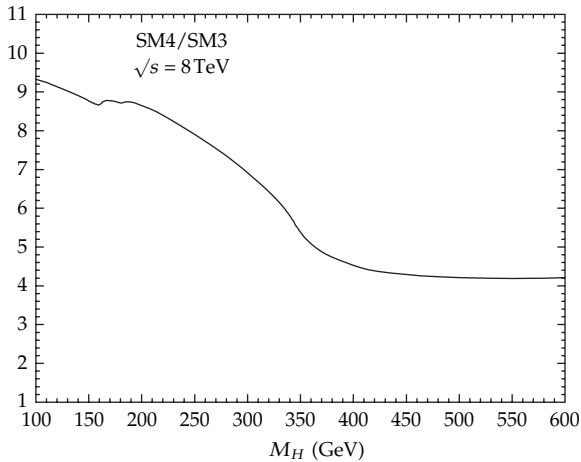$$(\approx 5).$$

FIGURE 5: Comparison of gluon fusion cross-section within the SM4 and the standard model. Depending on the value of the Higgs mass sizeable deviations of the naive expectation for ratio to be nine is possible. For Higgs masses in the region of 125 GeV this expectation works, however, very well. Figure from [16].
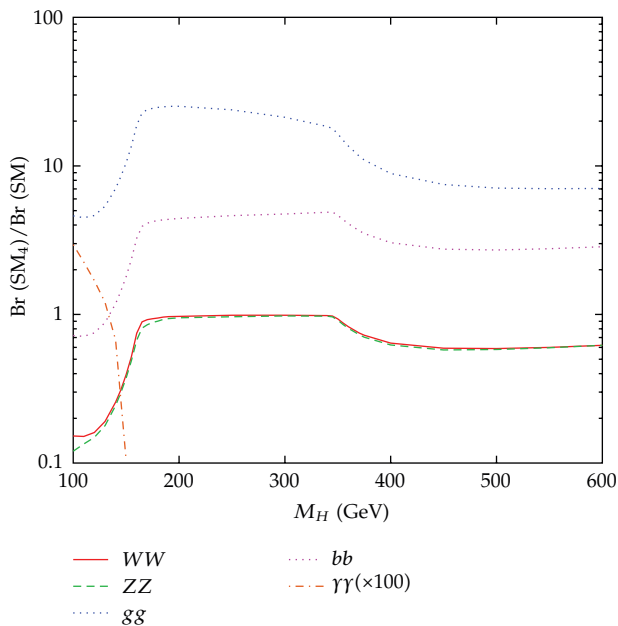

FIGURE 6: Comparison of Higgs decay rates within the SM4 and the standard model including NLO-electroweak corrections. In particular interesting is the strong reduction of the $H \rightarrow \gamma\gamma$ channel. Figure from [16].

For a comparison we have also shown the results from [88] (see (5)) in brackets below the new values. To summarize, NLO-electroweak corrections turned out to be huge and therefore any analysis without these corrections, that is, any analysis before 2012, cannot provide reliable results. The most stringent new result is now the predicted underproduction in the channel $H \rightarrow \gamma\gamma$.

There are however still some minor drawbacks, which should be kept in mind. First in the calculation of the

NLO-electroweak corrections [16, 150] CKM mixing was neglected. Second the results of [16, 150] are not given for the general parameter space of the SM4. The parameter range was considerably extended from v1 (only one parameter point) of [16] to v2, but still, for example, the interesting region with a neutrino mass of about 60 GeV and a corresponding lepton mass, which is consistent with electroweak precision observables, is not available. Approximate formulas for this mass region are, however, included in the latest version (4.45) of the programme HDECAY [151, 152], which became publically available on March 13, 2012.

2.6. Closing the Loop Holes. The complete NLO-electroweak corrections to Higgs production and decay and the possibility of an invisible Higgs decay were taken into account for the first time in [17] and later on in [18, 100, 153, 154]. To the best of my knowledge in experimental investigations at ATLAS [155] and CMS [156] the NLO-electroweak corrections are now included but the possibility of a fourth neutrino in which the Higgs could decay is still not considered. After Moriond 2012 all theoretical tools, in particular the NLO-electroweak corrections, were publically available and now one was for the first time in a position where definite conclusions can be drawn. Assuming a Higgs mass of 125 GeV one gets an enhancement factor of about nine for gluon fusion and the Higgs branching ratios given in Figure 7 in dependence of the mass of the fourth neutrino. For high neutrino masses one obtains the classic result that the SM4 predicts too many Higgs events and hence, can be excluded if no more Higgs events than expected in the SM are found. For low masses of the fourth neutrinos the SM4 yields, however, less Higgs events than in the SM. In Figure 7 still an approximate NLO expression for $H \rightarrow \gamma\gamma$ was used. The full expression will give a further suppression of the two-photon channel by a factor of about six, see [17]. For neutrino masses between 100 GeV and 600 GeV and for a Higgs mass of 125 GeV one gets now [17]

$$
\begin{aligned}
\sigma\left(gg \longrightarrow H\right) &\cdot \mathrm{Br}\left(H \longrightarrow \gamma\gamma\right)\big|_{\mathrm{SM4}} \\
&\approx (0.09\dots 0.2)\, \sigma\left(gg \longrightarrow H\right) \cdot \mathrm{Br}\left(H \longrightarrow \gamma\gamma\right)\big|_{\mathrm{SM}}.
\end{aligned}
\tag{7}
$$

This clearly means that if a SM-like Higgs signal in the two-photon channel is seen at LHC then the SM4 is ruled out because there at most 20% of the events expected in the SM can be created. Thus, contrary to the common belief, the SM4 might actually be killed because of a predicted underproduction of Higgses and not of an overproduction. Due to the huge cancellations that arise now in the decay $H \rightarrow \gamma\gamma$, one might, however query the reliability of the theory prediction for $\Gamma(H \rightarrow \gamma\gamma)$. In Moriond Tevatron also presented results [66] for $p + \overline{p} \rightarrow H + V \rightarrow b\overline{b} + V$, which were within the statistical uncertainties in agreement with the SM expectations. In the SM4 one expects at most 35% of the number of SM events [17]. The conclusion of [17] was that if the currents hint for Higgs boson production and decay in the channels $H \rightarrow \gamma\gamma$ and $H \rightarrow b\overline{b}$ presented in Moriond 2012 will stay with more data at their current values, then the SM4
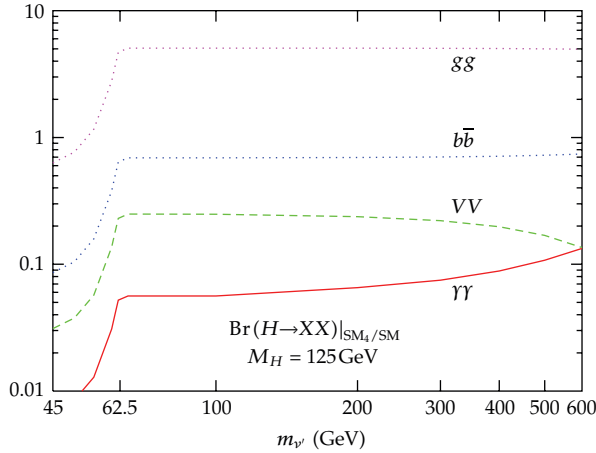
FIGURE 7: Higgs branching ratios in dependence of the mass of the fourth neutrino for a Higgs mass of 125 GeV. Below $m'_\nu = 62.5$ GeV the new invisible decay channel $H \rightarrow \nu_4\nu_4$ opens and all other branching ratios will be strongly suppressed. This plot was, however, created with an approximate NLO expression for $H \rightarrow \gamma\gamma$. The full expression will give a further suppression of the two-photon channel by a factor of about six. Figure taken from [17].

will be excluded, because it predicts considerably less events in these two channels.

A combined fit of electroweak precision observables and data for Higgs boson production and decay was presented in [100]. Later on this was updated, in particular with data for the channel $H \rightarrow \tau^+\tau^-$ in [18]. In Figure 8 the pulls of the Higgs signal strengths are shown for the channels $H \rightarrow \gamma\gamma, WW, ZZ, b\bar{b}$, and $\tau^+\tau^-$, comparing the SM3 and the SM4 predictions. It turns out that the biggest effect is seen in the channel $H \rightarrow \tau^+\tau^-$. Here the classic expectations holds: the SM4 predicts a much higher rate than observed. For the channels $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$ the reverse effect arises: the SM4 predicts a much lower rate than observed experimentally. One can see from Figure 8 that also the SM does not describe the data perfectly: the data for $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$ are higher than expected, while the data for $H \rightarrow WW$ and $H \rightarrow \tau^+\tau^-$ are lower than expected. But all in all the SM describes the data much better than the SM4. This will be quantified below.

In Figure 9 the best fit results in dependence of the mass of the fourth neutrino are shown. The SM4 has only a small chance to be viable in regions where the Higgs boson can decay invisibly in the two neutrinos. This is strongly triggered by the data for $H \rightarrow \tau^+\tau^-$; in this channel the SM4 predicts a strong enhancement, which can only be compensated by the invisible decay of the Higgs boson. To be more quantitative: before the ICHEP 2012 Conference the SM4 was disfavored compared to the SM by 3.1 standard deviations [18]. (For more information about how the corresponding P value of this exclusion can be determined, see [157].)

2.7. Welcome to the Real World. On July 4, 2012 ATLAS and CMS announced new results for the Higgs boson search [14].

The new data worsens the situation for the SM4 in several points.

(1) Both ATLAS and CMS see a $H \rightarrow \gamma\gamma$—signal with a statistical significance of more than 4 standard deviations. The total observed rate was higher than expected by the SM (a factor of 1.9 ± 0.5 for ATLAS and a factor of 1.56 ± 0.43 for CMS). In the SM4 one would expect instead a reduction of the rate by at least a factor of 5 compared to the standard model, see (7). Thus, both ATLAS and CMS individually see a $H \rightarrow \gamma\gamma$—signal, which is about 4 standard deviations away from the expectation of the SM4, which rules out the SM4. As discussed above, the theory prediction for $H \rightarrow \gamma\gamma$ in the SM4 suffers from severe cancellations, so one might not want to rely on this decay channel alone.

(2) On July, 2012 also CDF and D0 updated their Higgs search [67] in the Higgs-strahlung channel, discussed above. There the statistical significance increased from 2.6 standard deviations in [66] to 2.9 standard deviations in [67]. At $m_H = 125$ GeV Tevatron finds a signal strength of $1.97^{+0.74}_{-0.68}$, so a little above the SM expectation, while the SM4 predicts values below 0.35 [17]. Again a stronger indication against the SM4 compared to the status of Moriond 2012.

(3) In the SM4 one would expect a sizeable enhancement of the $H \rightarrow \tau\tau$ channel, see for example, [18], which is not observed [14] in the new data. A further argument against the SM4 at the 4σ level.

In v2 of [17] the following conclusion was drawn from these new results: "...*we conclude that the standard model with a perturbative 4th generation and one Higgs doublet is ruled out by this new experimental developments.*"

Before these new results the SM4 was excluded by 3.1 standard deviations; with the new data we expect the SM4 to be excluded by about five standard deviations [158].

3. Beyond the Simple Perturbative SM4

The results, which were discussed here, relied strongly on the assumption of perturbativity of the heavy fermions and are also only valid for a minimal Higgs sector, that is, for only one Higgs doublet.

3.1. NonPerturbative SM4. Investigations of a non-perturbative fourth generation can be found, for example, in [159].

3.2. Extended Higgs Sectors. The easiest way to avoid the above-discussed bounds on an additional fermion generation is to extend also the sector. A fourth generation in combination with a second Higgs doublet has been discussed in [93, 160–166].
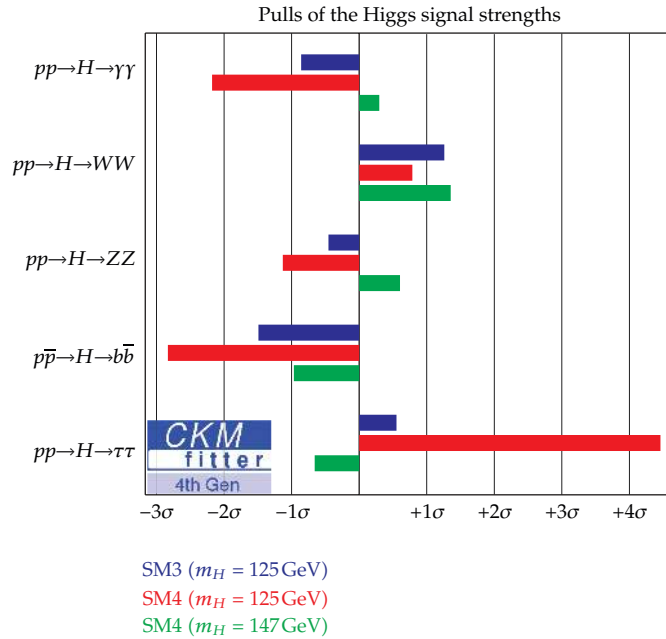
FIGURE 8: Pulls of the Higgs signal strengths with the data before ICHEP 2012. Figure from [18].
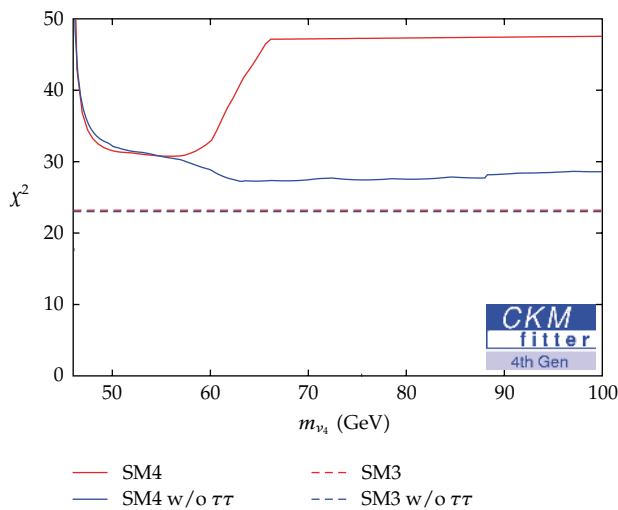

FIGURE 9: Best fit results in dependence of the mass of the fourth neutrino. As soon as $H \rightarrow \tau^+\tau^-$ is included, the only remaining possibility for the SM4 is to open up the decay channel $H \rightarrow \nu_4\nu_4$. Figure from [18].

4. Discussions and Conclusions

We reviewed the past and current status of the extension of the SM by an additional chiral generation of fermions. An amusing aspect thereby was the fact that the SM4 was declared dead many times. But all these declarations relied on some unjustified assumptions—giving them up the model was still viable. This clearly would be an interesting topic for a sociological study: why were there so many prejudices against the existence of this simple model? Nevertheless, it turned finally out that the SM4 is ruled out by experimental data (So unfortunately we did not learn the lesson that prejudices should be avoided in physics.): The SM4 cannot accommodate the new data for Higgs searches presented by LHC and Tevatron and thus, it is excluded.

There are still some missing ingredients like that the 2-loop corrections to the electroweak precision observables within the SM4 are still missing. Moreover the NLO-electroweak corrections to Higgs production and decay were calculated by neglecting CKM mixing.

Finally we commented very briefly that extending in addition the Higgs sector, for example, by an additional Higgs doublet might circumvent many of the above-discussed bounds.

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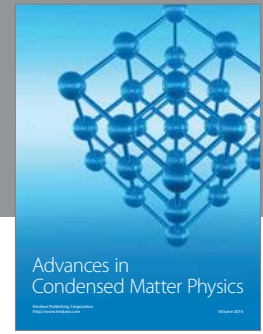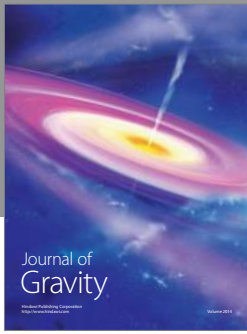
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