Impact on the Higgs Production Cross Section and Decay Branching Fractions of Heavy Quarks and Leptons in a Fourth Generation Model

X. Ruan\textsuperscript{a,b}, Z. Zhang\textsuperscript{a,*}

\textsuperscript{a}Laboratoire de l’Accélérateur Linéaire, Université Paris-Sud 11, IN2P3/CNRS, Orsay, France
\textsuperscript{b}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Abstract

In a fourth generation model with heavy quarks, the production cross section of the Higgs boson in the gluon-gluon fusion process is significantly increased due to additional quark loops. In a similar way, the partial decay width of the decay channels $H \rightarrow gg, \gamma\gamma$ and $\gamma Z$ is modified. These changes and their impact on the Higgs search are discussed.

Keywords: Fourth generation, Higgs production, Higgs decays

1. Introduction

The Standard Model (SM) are known to have three families of charged and neutral fermions. There is however no upper limit on the number of fermion families. A fourth family (SM4) \cite{1} could be in fact the key to many unsolved puzzles, such as the hierarchies of the fermion mass spectrum including neutrino masses and mixing, electroweak symmetry breaking, baryogenesis, and a variety of interesting phenomena in CP and flavor physics \cite{2–6}.

Fourth family leptons and quarks have been searched for previously by the LEP and Tevatron experiments and now by the LHC experiments. The most stringent lower mass limits at 95\% CL are \cite{7–9}

\begin{align}
    m_{\nu_4} & > 80.5 - 101.5 \text{ GeV}, \\
    m_{l_4} & > 100.8 \text{ GeV}, \\
    m_{b_4} & > 372 \text{ GeV}, \\
    m_{t_4} & > 335 \text{ GeV}.
\end{align}

The mass bound on the heavy neutrino depends on the type of neutrino (Dirac or Majorana) and whether one considers a coupling of the heavy neutrino to $e^-, \mu^-$ or $\tau^-$. It should also be noted that assumptions about the coupling of the fourth family and the decay mode were made in deriving the quark mass limits. The limits can be weaker without these assumptions. On the other hand, the triviality bound from unitarity of the $t_4t_4$ S-wave scattering \cite{10} indicates a maximum $t_4$ mass of around 500 GeV, although this estimate is based on tree-level expressions.

*Corresponding author

Email address: zhangzq@lal.in2p3.fr (Z. Zhang)

Preprint submitted to Elsevier

January 20, 2013
With the presence of fourth family quarks, the dominant Higgs production process, the gluon-gluon fusion process, is further enhanced (see Sec. 2 and also [11, 12]). Using the large enhancement of $gg \rightarrow H \rightarrow WW$ in SM4, CDF, D0 and CMS have been able to exclude the SM4 Higgs boson at 95% CL for $131 \leq m_H \leq 144$ GeV [13] and $144 \leq m_H \leq 207$ GeV [14].

In [15] (see also [16, 17]), it was pointed out that the mass limit on $m_{\nu_4}$ (Eq. (1)) was derived when the mixing angle between the fourth family neutrino and at least one of the neutrinos in the SM is assumed to be larger than $3 \times 10^{-6}$. For smaller mixing angles, $\nu_4$ is quasistable and the mass of $\nu_4$ is bounded only from the analysis of Z boson decay at $m_{\nu_4} > 46.7$ GeV [18]. In this case, the decay mode $H \rightarrow \nu_4 \nu_4$ becomes the dominant one at low Higgs mass and the Tevatron lower mass limits of 131 GeV would be increased to 155 GeV [15]. In the following, we will not consider this possibility.

### 2. Enhancement of gluon-gluon fusion Higgs production cross section

In the SM, the dominant Higgs production process is the gluon-gluon fusion process where gluons from colliding beams couple to a heavy quark loop from which the Higgs boson is emitted. The cross section at the leading-order (LO) can be written as [19]

$$\sigma(pp \rightarrow HX) = \Gamma(H \rightarrow gg) \frac{\,\pi^2}{8m_H^2} \int_{\tau_H} \frac{1}{x} g(x, m_H^2) g(\tau_H/x, m_H^2) \, dx$$

with

$$\Gamma(H \rightarrow gg) = \frac{G_F m_H^3}{36 \sqrt{2} \pi} \left| \frac{\alpha_s(m_H^2)}{\pi} \right|^2 |I|^2, \quad I = \sum_q I_q$$

and $g(x, Q^2)$ is the gluon distribution evaluated at $x$ and $Q^2$. $G_F$ ($\alpha_s$) is the Fermi (strong) coupling constant. The quantity $I_q$ is given in terms of $\lambda_q = \frac{m_q^2}{m_H^2}$:

$$I_q = 3 \left[ 2 \lambda_q + \lambda_q (4 \lambda_q - 1) f(\lambda_q) \right]$$

where

$$f(\lambda_q) = \begin{cases} -2 \left( \sin^{-1} \frac{1}{2 \sqrt{\lambda_q}} \right)^2, & \text{for } \lambda_q > \frac{1}{4}, \\ \frac{1}{2} \left( \ln \frac{\eta^+}{\eta^-} \right)^2 - \frac{\pi^2}{2} - i \pi \ln \frac{\eta^+}{\eta^-}, & \text{for } \lambda_q < \frac{1}{4}. \end{cases}$$

with $\eta^\pm = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \lambda_q}$. In the heavy quark $m_q$ limit, $\lambda_q \gg 1$, $I_q \rightarrow 1$, whereas in the light quark $m_q$ limit $\lambda_q \ll 1$, $I_q \rightarrow 0$. This is why in the SM, the top quark is by far the dominant contribution.

In a fourth generation with two additional heavier quark $t_4$ and $d_4$, the Higgs production cross section is enhanced with that of the SM by a factor

$$R_{SM4/SM}^{gg \rightarrow H} \equiv \frac{\sigma(gg \rightarrow H)_{SM4}}{\sigma(gg \rightarrow H)_{SM}} = \frac{|I_b + I_t + I_{d_4} + I_{d_4}|^2}{|I_b + I_t|^2}.$$ 

The dependence as a function of the Higgs boson mass $m_H$ is shown in Fig. [1] for two different $m_{d_4}$ values of infinite mass [1] and 400 GeV. The $t_4$ mass is fixed as [11]

$$m_{t_4} = m_{d_4} + 50 + 10 \times \ln \left( \frac{m_H}{115 \text{ [GeV]}} \right),$$

1In practice, a value of 10 TeV is chosen.
Figure 1: The enhancement factor of the Higgs production cross section in a fourth generation over that of the SM as a function of $m_H$ for two scenarios with $m_{d_4} = 10$ TeV and 400 GeV.

to be consistent with the constraint of electroweak precision data. The maximum enhancement factor of about 9 is reached at the small Higgs boson mass $m_H$ value where $I_b \to 0$ and $I_t, I_{t_4}, I_{d_4} \to 1$. At low $m_H$, the enhancement is independent of the quark mass value of the fourth generation. At higher Higgs mass values, the heavier the quark mass, the smaller the enhancement factor. The heavy $m_{d_4}$ scenario may not be physical as when it is beyond about 500 GeV the weak interaction among heavy particles becomes strong and perturbation theory breaks down. However, since the enhancement is the smallest, the resulting exclusion limits would be more conservative. This is the scenario used by CMS in their recent publication [14]. The other scenario with $m_{d_4} = 400$ GeV corresponds to one of the scenarios used by the Tevatron experiments [13].

In Fig. 1, the enhancement based on LO cross sections is also compared with the corresponding factor in NLO calculated with a modified HIGLU program [20]. The cross sections $\sigma^{SM}(gg \to H)_{SM,SM4}$ are calculated for $pp$ collisions at 7 TeV center-of-mass energy [3]. As far as the ratio $R^{SM/SM4}_{\sigma^{gg\to H}}$ is concerned, the difference between NLO and LO is small. This means that one may use this ratio (e.g. in NLO) and precisely predicted SM cross section values in higher orders to derive the corresponding higher-order cross section in a fourth generation model:

$$\sigma_{SM4}(gg \to H) = \sigma_{SM}(gg \to H) \times R^{SM4/SM}_{\sigma^{gg\to H}}.$$  \hspace{1cm} (11)

Following the suggestion of the author, the SM electroweak corrections are not applied (by setting ELW=0 in the steering file higlu.in) as they are not valid for a fourth generation model.

Whereas the cross section values depend strongly on the center-of-mass energy, we have checked that the ratio $R^{SM4/SM}_{\sigma^{gg\to H}}$ has essentially no dependence on it.
Indeed, use this relation and take the NNLO cross section value $\sigma_{SM}(gg \rightarrow H) = 19.81 \text{ pb}$ at $m_H = 110 \text{ GeV}$ as an example (Table 1 in \cite{21}) and the corresponding enhancement factor of 9.223 (see the linked web page below), we obtain 182.79 pb for the low mass scenario. This derived cross section value $\sigma_{SM}(gg \rightarrow H)$ is in excellent agreement with the independent prediction of 182.51 pb given in Table 1 in \cite{22}.

3. Modified Higgs decay branching fractions

The SM Higgs decay branching fractions calculated using HDECAY \cite{23} is displayed in Fig. \ref{fig:branching}. The decay mode $H \rightarrow gg$ is the reverse of the gluon-gluon fusion process $gg \rightarrow H$. The partial decay width of the decay mode $H \rightarrow gg$ in a fourth generation model with respect to that of the SM is thus enhanced by the same factor as the corresponding Higgs production cross section in the gluon-gluon fusion process (Eq.(9)).

The decay mode $H \rightarrow \gamma\gamma$ is similar to $H \rightarrow gg$ except that charged leptons, the $W$-boson and charged Higgs bosons also contribute to the loop. The partial decay width is \cite{19}

$$\Gamma(H \rightarrow \gamma\gamma) = \frac{G_F m_H^3}{8 \sqrt{2} \pi} \left( \frac{\alpha^2}{\pi} \right) |I|^2,$$

where $\alpha$ is the fine-structure coupling constant. The quark, lepton, $W$-boson and colorless charged scalar contributions are \cite{19}:

$$I = \sum_q Q_q^2 I_q + \sum_l Q_l^2 I_l + I_W + I_S$$

Figure 2: Branching fractions of the SM Higgs decays calculated using HDECAY.
where $Q_f$ denotes the charge of fermion $f$ in units of $e$ and
\begin{align}
I_q &= 3 \left[ 2\lambda_q + \lambda_q (4\lambda_q - 1) f(\lambda_q) \right], \\
I_l &= 2\lambda_l + \lambda_l (4\lambda_l - 1) f(\lambda_l), \\
I_W &= 3\lambda_W (1 - 2\lambda_W) f(\lambda_W) - 3\lambda_W - \frac{1}{2}, \\
I_S &= -\lambda_S \left[ 1 + 2\lambda_S f(\lambda_S) \right],
\end{align}
and $\lambda_i = m_i^2/m_H^2$. In a fourth generation model, both $I_Q$ and $I_l$ terms receive additional contributions from fourth generation quark $q_4$ and lepton $l_4$. 

Finally the partial decay width $\Gamma(H \rightarrow \gamma Z)$ is also affected by additional fourth generation quark loops. Therefore the branching fractions (Fig. 3) in a fourth generation model look different from that of the SM in particular for $gg$, $\gamma\gamma$ and $\gamma Z$ modes at low Higgs mass values.

In Fig. 3 the two mass scenarios are compared. The $l_4$ mass is further assumed to be the same as that of $d_4$. But as far as these fourth generation quark and lepton masses are heavy enough ($> m_H/2$), the difference in branching fractions is hardly visible. The branching fractions in a fourth generation model are calculated without applying the electroweak and higher-order QCD corrections as they do not apply to the fourth generation quarks.

For the relevant decay modes $\gamma\gamma$ and $WW, ZZ$, the ratio of the branching fractions in a fourth generation model over that in the SM
\begin{align}
R_{B(H \rightarrow X)}^{SM4/SM} = \frac{B(H \rightarrow X)_{SM4}}{B(H \rightarrow X)_{SM}}
\end{align}
is compared in the two mass scenarios in Fig. 4(left), which shows that the effect of the mass scenarios is indeed small. The effect of the electroweak and higher-order QCD corrections on the branching fraction ratio is also small as it is illustrated in Fig. 4(right).
Figure 4: Branching fraction ratio of Higgs decays in a fourth generation model over that in the SM for two mass scenarios (left) and with or without electroweak and higher-order corrections in the SM (right).

4. Results and discussions

The overall enhancement of the product of the Higgs production cross section and the Higgs branching fraction in a fourth family over that in the SM

\[ R_{\text{SM4}/\text{SM}} \equiv \frac{[\sigma(gg \to H) \times B(H \to X)]_{\text{SM4}}}{[\sigma(gg \to H) \times B(H \to X)]_{\text{SM}}} \]  

is shown in Fig. 5 as a function of the Higgs mass for decay modes \( X = \gamma\gamma, WW, \) and \( ZZ \) and for the two mass scenarios. The numerical values for \( R_{\text{SM4}/\text{SM}} \) for 59 Higgs mass points ranging from 110 GeV to 600 GeV are given in linked web pages [24, 25].

One advantage of reporting \( R_{\text{SM4}/\text{SM}} \) instead of \( \sigma(gg \to H)_{\text{SM4}} \) that we mentioned in Sec. 2 is that the ratio is less sensitive to higher order corrections. It is also less sensitive to other theoretical uncertainties. One example is the dependence on the choice of parton distribution functions (PDFs). In Fig. 6, the variation of choosing two different PDFs (MSTW2008NLO [26] and HERAPDF1.0 [27]) has been compared with the default choice of CTEQ6M [28]. In the considered Higgs mass range, the difference on \( R_{\sigma(gg \to H)} \) is well within 0.2%.

5. Summary

We have discussed the implication in the Higgs production cross sections in the gluon-gluon fusion process and the Higgs decay branching fractions in modes \( gg, \gamma\gamma, \) and \( \gamma Z \) when including quarks and leptons of a fourth generation model. The enhancement/modification on the gluon-gluon fusion cross section \( R_{\sigma(gg \to H)} \) and the Higgs decay branching fractions \( R_{B(H \to X)} \) of a fourth generation model over the SM as a function of the Higgs mass \( m_H \) in the range of 100 – 600 GeV has been calculated and shown for two
Figure 5: The enhancement of the product of the cross section and the branching fraction in a fourth family over the SM shown as a function of the Higgs mass for the two mass scenarios.

Figure 6: The variation due to the choice of different PDFs on $R_{gg\to H}^{SM}/R_{gg\to H}^{SM}$ shown for the high mass quark scenario as a function of the Higgs mass $m_H$. 
mass scenarios. These ratios are found to have little sensitive to theoretical variations such as the higher order corrections for both $R_{0(gg\to H)}^{SM/SM}$ and $R_{0(B\to X)}^{SM/SM}$ and PDFs for $R_{0(gg\to H)}^{SM/SM}$.

Acknowledgments

The authors wish to thank M. Spira for help and advice in using the HIGLU and HDECAY codes. Z. Zhang is also grateful to F. Richard and E. Kou for discussions.

References

[1] P.H. Frampton, P.Q. Hung and M. Sher, Quarks and leptons beyond the third generation, Phys. Rept. 330 (2000) 263 [hep-ph/9903387].
[2] H.-J. He, N. Polonsky and S.-f. Su, Extra families, Higgs spectrum and oblique corrections, Phys. Rev. D64 (2001) 053004 [hep-ph/0102144].
[3] B. Holdom, W.S. Hou, T. Hurth, M.L. Mangano, S. Sultansoy and G. Unel, Four statements about the fourth generation, PMC Phys. A3 (2009) 4 [arXiv:0904.4698 [hep-ph]].
[4] O. Eberhardt, A. Lenz and J. Rohrwild, Less space for a new family of fermions, Phys. Rev. D82 (2010) 095006 [arXiv:1005.3505 [hep-ph]].
[5] M.S. Chanowitz, Higgs mass constraints on a four family: upper and lower limits on CKM mixing, Phys. Rev. D82 (2010) 035018 [arXiv:1007.0043 [hep-ph]] and references therein.
[6] R.C. Cotta, J.L. Hewett, A. Ismail, M.-P. Le and T.G. Rizzo, Higgs properties in the fourth generation MSSM: boosted signals over 3G plan, arXiv:1105.0039 [hep-ph].
[7] K. Nakamura et al., (The Particle Data Group), Review of particle physics, J. Phys. G37 (2010) 075021.
[8] T. Aaltonen et al., (The CDF Collaboration), Search for heavy bottom-like quarks decaying to an electron or muon and jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 106 (2011) 141803 [arXiv:1105.5728 [hep-ex]].
[9] T. Aaltonen et al., (The CDF Collaboration), Search for heavy top $t\to Wq$ in lepton plus jet events, CDF conference note 10110 (2010).
[10] M.S. Chanowitz, M.A. Furman and I. Hinchliife, Weak interactions of ultraheavy fermions, Nucl. Phys. B153 (1979) 402.
[11] G.D. Kribs, T. Plehn, M. Spannowsky and T.M.P. Tait, Four generations and Higgs physics, Phys. Rev. D76 (2007) 075016 [arXiv:0706.3718 [hep-ph]].
[12] N. Becerici Schmidt, S.A. Çetin, S. Istin and S. Sultansoy, The fourth Standard Model family and the competition in Standard Model Higgs boson search at Tevatron and LHC, Eur. Phys. J. C66 (2010) 119 [arXiv:0908.2653 [hep-ph]].
[13] T. Aaltonen et al., (The CDF and D0 Collaborations), Combined Tevatron upper limit on $gg\to H\to W^{+}W^{-}$ and constraints on the Higgs boson mass in fourth-generation fermion models, (2010) [arXiv:1005.3216 [hep-ex]].
[14] S. Chatrchyan et al. (The CMS Collaboration), Measurement of $W^{+}W^{-}$ production and search for the Higgs boson in $pp$ collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B699 (2011) 25 [arXiv:1102.3529 [hep-ex]].
[15] A.N. Rozanov and M.I. Vysotsky, Tevaton constraints on the Higgs boson mass in the fourth-generation fermion models, arXiv:1012.1483 [hep-ph].
[16] K. Belousky, D. Fargion, M. Khlopov, R. Konoplch and K. Shibaev, Invisible Higgs boson decay into massive neutrinos of 4th generation, Phys. Rev. D68 (2003) 054027 [hep-ph/0210153].
[17] W.-Y. Keung and P. Schwaller, Long lived fourth generation and the Higgs, arXiv:1103.3765 [hep-ph].
[18] S.S. Balanov, A.N. Rozanov and M.I. Vysotsky, $Z$-lineshape versus 4th generation masses, Phys. Atom. Nucl. 66 (2003) 2169 [hep-ph/0301268].
[19] Vernon D. Barger and Roger J.N. Phillips, Collider Physics (updated edition), Addison-Wesley Publishing Company, Inc., 1997.
[20] M. Spira, A program for the calculation of the total Higgs production cross section at hadron colliders via gluon fusion including QCD corrections, (1995) [hep-ph/9510347].
[21] S. Dittmaier et al., (LHC Higgs Cross Section Working Group), Handbook of LHC Higgs cross section: 1. Inclusive observables, arXiv:1101.0593 [hep-ph].
[22] C. Anastasiou, S. Buehler, E. Furlan, F. Herzog and A. Lazopoulos, Higgs production cross-section in a Standard Model with four generations at the LHC, arXiv:1103.3645 [hep-ph].
[23] A. Djouadi, J. Kalinowski and M. Spira, HDECAY: a program for Higgs boson decays in the Standard Model and its supersymmetric extension, Comput. Phys. Commun. 108 (1997) 56 [hep-ph/9704448].
[24] High mass scenario: http://users.lal.in2p3.fr/zhangzq/atlas/4th/sm4-md-10TeV.txt
Low mass scenario: [http://users.lal.in2p3.fr/zhangzq/atlas/4th/sm4-md-400GeV.txt](http://users.lal.in2p3.fr/zhangzq/atlas/4th/sm4-md-400GeV.txt).

A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Parton distributions for the LHC*, Eur. Phys. J. C63 (2009) 189 [arXiv:0901.0002 [hep-ph]].

F.D. Aaron *et al.*, (The H1 and ZEUS Collaborations), *Combined measurement and QCD analysis of the inclusive $e^p$ scattering cross sections at HERA*, JHEP 1001 (2010) 109 [arXiv:0911.0884 [hep-ex]].

J. Pumplin *et al.*, *New generation of parton distributions with uncertainties from global QCD analysis*, JHEP 0207 (2002) 012 [hep-ph/0201195].