Observability of the Higgs Boson in the Presence of Extra Standard Model Families at the Tevatron

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Abstract

The observability of the Higgs boson via the WW^* decay channel at the Tevatron is discussed taking into account the enhancements due to the possible existence of the extra standard model (SM) families. It seems that the existence of new SM families can give the Tevatron experiments (D0 and CDF) the opportunity to observe the intermediate mass Higgs boson before the LHC.

I. INTRODUCTION

It is known that the number of fermion generations is not fixed by the standard model (SM). Asymptotic freedom of the quantum chromodynamics (QCD) suggests that this number is less than eight. Concerning the leptonic sector, the large electron positron collider (LEP) data determine the number of light neutrinos to be N= 2.994 ± 0.012 [1]. On the other hand, the flavor democracy (i.e. democratic mass matrix approach [2-5]) favors the existence of the fourth SM family [6-9].

Direct searches for the new leptons (ν_4, ℓ_4) and quarks (u_4, d_4) led to the following lower bounds on their masses [1]: $m_{\ell_4} > 100.8$ GeV; $m_{\nu_4} > 45$ GeV (Dirac type) and $m_{\nu_4} > 39.5$ GeV (Majorana type) for stable neutrinos; $m_{\nu_4} > 90.3$ GeV (Dirac type) and $m_{\nu_4} > 80.5$ GeV (Majorana type) for unstable neutrinos; $m_{d_4} > 199$ GeV (neutral current decays), $m_{d_4} > 128$ GeV (charged current decays). The precision electroweak data does not exclude the fourth SM family, even a fifth or sixth SM family is allowed provided that the masses of their neutrinos are about 50 GeV [14, 15].

In the Standard Model, the Higgs boson is crucial for the understanding of the electroweak symmetry breaking and the mass generation for the gauge bosons and the fermions. Direct searches at the CERN e^+e^- collider (LEP) yielded a lower limit for the Higgs boson mass of $m_H > 114.4$ GeV at 95% confidence level (C.L.) [1].

In this study, we present the observability of the Higgs boson at the Tevatron and find the accessible mass limits for the Higgs boson in the presence of extra SM fermion families (SM-4, SM-5 and SM-6).

II. ANTICIPATION FOR THE FOURTH SM FAMILY

According to the SM with three families, before the spontaneous symmetry breaking, quarks are grouped into the following SU(2) x U(1) multiplets:

$$\begin{pmatrix} u_L^0 \\ d_L^0 \end{pmatrix} u_R^0\,,\, d_R^0 \qquad \begin{pmatrix} c_L^0 \\ s_L^0 \end{pmatrix} c_R^0\,,\, s_R^0 \qquad \begin{pmatrix} t_L^0 \\ b_L^0 \end{pmatrix} t_R^0\,,\, b_R^0 \tag{1}$$

where 0 denotes the SM basis. In one family case, e.g. d-quark mass is obtained due to the Yukawa interaction

$$L_Y^{(d)} = a^d \; \left(\bar{u}_L \, \bar{d}_L \right) \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_R + h.c. \tag{2}$$

which yields

$$L_m^{(d)} = m^d \bar{d}d \tag{3}$$

where $m^d = a^d \eta/\sqrt{2}$ and $\eta = 2\, m_W/g_W = 1/\sqrt{\sqrt{2}\, G_F} \approx 246$ GeV. In the same manner, $m^u = a^u \eta/\sqrt{2}$, $m^e = a^e \eta/\sqrt{2}$ and $m^{\nu_e} = a^{\nu_e}\eta/\sqrt{2}$ if ν_e is a Dirac particle.

In n-family case

$$L_Y^{(d)} = \sum_{i,j=1}^{n} a_{ij}^d \; \left(\bar{u}_{Li}^0 \, \bar{d}_{Li}^0 \right) \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d_{Rj}^0 + h.c. \Rightarrow \sum_{i,j=1}^{n} m_{ij}^d \, \bar{d}_i^0 d_j^0 \tag{4}$$

where d_1^0 denotes d^0, d_2^0 denotes s^0 etc. and $m_{ij}^d \equiv a_{ij}^d \eta/\sqrt{2}$.

Before the spontaneous symmetry breaking, all quarks are massless and there are no differences between d^0, s^0, b^0, etc. In other words, fermions with the same quantum numbers are indistinguishable. This leads us to the first assumption [2, 3]:

- Yukawa couplings are equal within each type of fermion families

$$a_{ij}^d \approx a^d \, , \; a_{ij}^u \approx a^u \, , \; a_{ij}^\ell \approx a^\ell \, , \; a_{ij}^\nu \approx a^\nu \, . \tag{5}$$

The first assumption results in $n-1$ massless particles and one massive particle with $m = n a^F \eta/\sqrt{2}\, (F = u, d, \ell, \nu)$ for each type of fermion F. If there is only one Higgs doublet which gives Dirac masses to all four types of fermions (u, d, ℓ, ν), it seems natural to make the second assumption [6, 8]:

- Yukawa couplings for different types of fermions should be nearly equal

$$a^d \approx a^u \approx a^\ell \approx a^\nu \approx a \, . \tag{6}$$

Considering the mass values of the third SM generation

$$m_{\nu_\tau} << m_\tau < m_b << m_t \, , \tag{7}$$

the second assumption leads to the statement that according to the flavor democracy, the fourth SM family should exist. In terms of the mass matrix, the above arguments mean

$$M^0 = \frac{a\,\eta}{\sqrt{2}} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \tag{8}$$

which leads to

$$M^m = \frac{4a\,\eta}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{9}$$

where m denotes the mass basis.

Now let us state the third assumption:

- The coupling $a/\sqrt{2}$ is between $e = g_W \sin\theta_W$ and $g_Z = g_W / \cos\theta_W$.

Therefore, the fourth family fermions are almost degenerate, in agreement with the experimental value $\rho = 0.9998 \pm 0.0008$ [1], and their common mass lies between 320 GeV and 730 GeV. The last value is close to the upper limit on heavy quark masses which follows from the partial-wave unitarity at high energies [10]. It is interesting to note that with the preferable value of $a \approx \sqrt{2}\, g_W$ the flavor democracy predicts the mass of the fourth generation to be $m_4 \approx 4a\eta/\sqrt{2} \approx 8m_W \approx 640$ GeV.

The masses of the first three families of fermions, as well as observable inter-family mixings, are generated due to the small deviations from the full flavor democracy [7, 11, 12]. The parametrization proposed in [12] gives the values for the fundamental fermion masses and at the same time predicts the values of the quark and the lepton CKM matrices. These values are in good agreement with the experimental data. In principle, flavor democracy provides the possibility to obtain the small masses for the first three neutrino species without the see-saw mechanism [13].

The fourth SM family quark pairs will be produced copiously at the LHC [16, 17] and at the future lepton-hadron colliders [18]. Furthermore, the fourth SM generation can manifest itself via the pseudo-scalar quarkonium production at the hadron colliders [19]. The fourth family leptons will clearly manifest themselves at the future lepton colliders [20, 21]. In addition, the existence of the extra SM generations leads to an essential increase in the Higgs boson production cross section via gluon fusion at the hadron colliders (see [22-25] and references therein). This indirect evidence may soon be observed at the Tevatron.

III. IMPLICATIONS FOR THE HIGGS PRODUCTION

The cross section for the Higgs boson production via gluon-gluon fusion at the Tevatron is given by

$$\sigma(p\bar{p} \to HX) = \sigma_0 \tau_H \int_{\tau_H}^{1} \frac{dx}{x} g(x, Q^2) g(\tau_H/x, Q^2) \tag{10}$$

where $\tau_H = m_H^2/s$, $g(x, Q^2)$ denotes the gluon distribution function and

$$\sigma_0(gg \to H) = \frac{G_F\, \alpha_s^2(\mu^2)}{288\,\sqrt{2}\,\pi}\, |I|^2 \tag{11}$$

is the partonic cross section. The amplitude I is the sum of the quark amplitudes I_q which is a function of $\lambda_q \equiv (m_q/m_H)^2$, defined as [26]

$$I_q = \frac{3}{2}\left[4\lambda_q + \lambda_q(4\lambda_q - 1) f(\lambda_q)\right] , \tag{12}$$

$$f(\lambda_q) = -4\,(\arcsin(\frac{1}{\sqrt{4\lambda_q}}))^2 \qquad \text{for} \qquad 4\lambda_q > 1 \tag{13}$$

$$f(\lambda_q) = (\ln\frac{1+\sqrt{1-4\lambda_q}}{1-\sqrt{1-4\lambda_q}} - i\pi)^2 \qquad \text{for} \qquad 4\lambda_q < 1 \ . \tag{14}$$

The numerical calculations for the Higgs boson production cross sections in the three SM family case are performed using the HIGLU software [27] which includes next to leading order (NLO) QCD corrections [28]. In HIGLU, CTEQ6M [29] distribution is selected for $g(x, Q^2)$, the natural values are chosen for the factorization scale $Q^2 (= m_H^2)$ of the parton densities and the renormalization scale $\mu\,(= m_H)$ for the running strong coupling constant $\alpha_s(\mu)$.

Quarks from the fourth SM generation contribute to the loop mediated process in the Higgs boson production $gg \to H$ at the hadron colliders resulting in an enhancement of σ_0 by a factor of $\epsilon \cong |I_t + I_{u_4} + I_{d_4}|^2/|I_t|^2$. Fig. 1 shows this enhancement factor as a function of the Higgs boson mass in the four SM families case with $m_4 = 200$, 320, 640 GeV. For the extra SM families we find that b-quark loop contribution increases ϵ by $9\% - 4\%$ depending on the

Higgs boson mass in the range $100 - 200$ GeV. In the infinitely heavy quark mass limit, the expected enhancement factors are 9, 25, and 49 for the cases of four, five, six generations, respectively. Fig. 2 shows the enhancement factor ϵ in the four, five and six SM families cases where quarks from extra generations are assumed to ber infinitely heavy whereas $m_t = 175$ GeV. We also include the QCD corrections [28] in the decay of the Higgs boson by using the program HDECAY [30]. Below we deal with the mass region $115 < m_H < 200$ GeV, therefore the formulation of ϵ with obvious modifications for five and six SM families cases can be a good approximation. Theoretical uncertainties in the prediction of the Higgs boson production cross section originate from two sources, the dependence of the cross sections on parton distributions (estimated to be around 10%) and higher order QCD corrections.

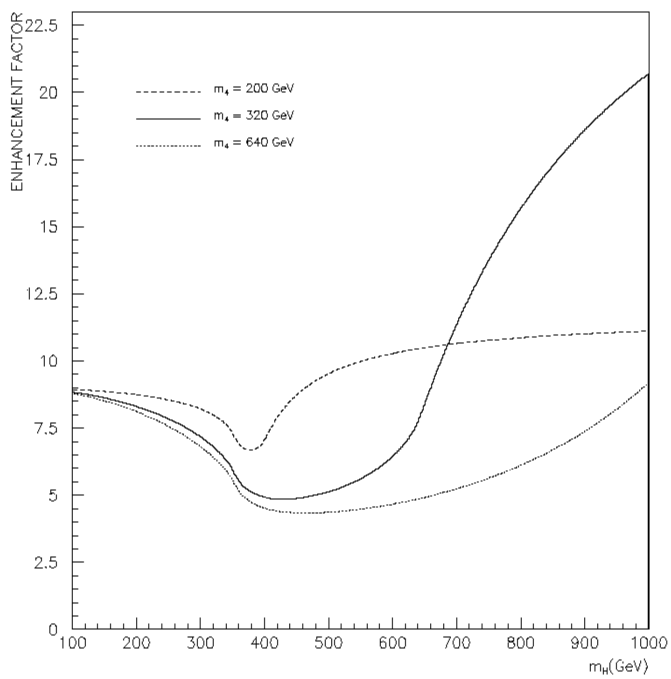

FIG. 1: The enhancement factor ϵ as a function of the Higgs boson mass in the four SM families case with $m_4 = 200$, 320, 640 GeV (upper, mid and lower curves, respectively).

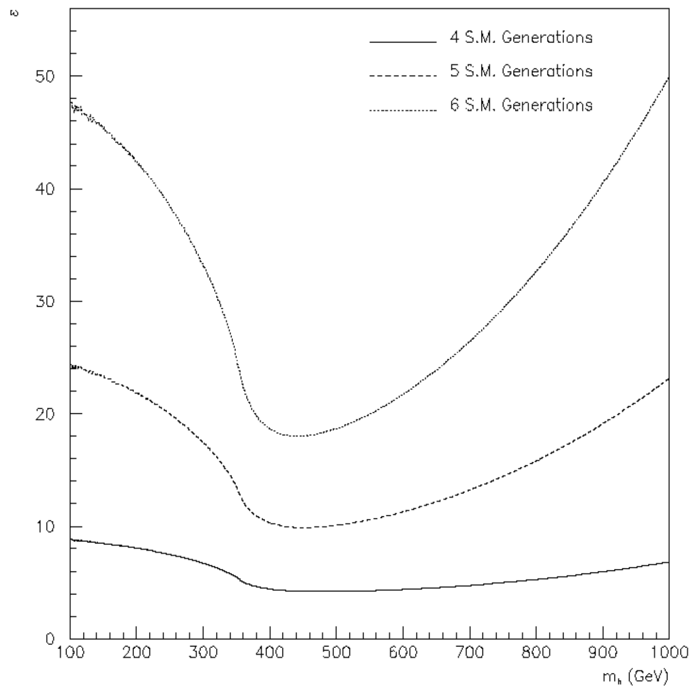

FIG. 2: The enhancement factor ϵ as a function of the Higgs boson mass in the four, five and six SM families cases where quarks from the extra generations are assumed to be infinitely heavy.

Recently, D0 and CDF collaborations have presented their results on the search for the Higgs boson in the channel $H \to WW^{(*)} \to l\nu l\nu$ [31-36]. Further luminosity upgrade of the Tevatron could give a chance to observe the Higgs boson at the Tevatron if the fourth SM family exists.

The Higgs decay width $\Gamma(H \to gg)$ is altered by the presence of the extra SM generations, due to this effect, the $H \to WW^{(*)}$ branching ratio changes as shown in Fig. 3. The decay widths and branching ratios for the Higgs decays are calculated using HDECAY program [30] after some modifications for extra SM families. Details on how the branching ratios of all Higgs decay channels change for extra SM families can be found in [25]. In this figure 4n, 5n and 6n denote the cases of one, two and three extra SM generations with neutrinos of mass $\cong$ 50 GeV, respectively. We present the numerical values of the branching ratios depending on the Higgs boson mass in Table I. SM-4 and SM-5 denote the extra SM families with unstable heavy neutrinos, whereas SM-4*, SM-5* and SM-6* correspond to the extra SM families with $m_\nu \cong$ 50 GeV. The difference between SM-4 (SM-5) and SM-4* (SM-5*) is due to additional $H \to \nu_4\bar{\nu}_4$ decay channel in the latter case.

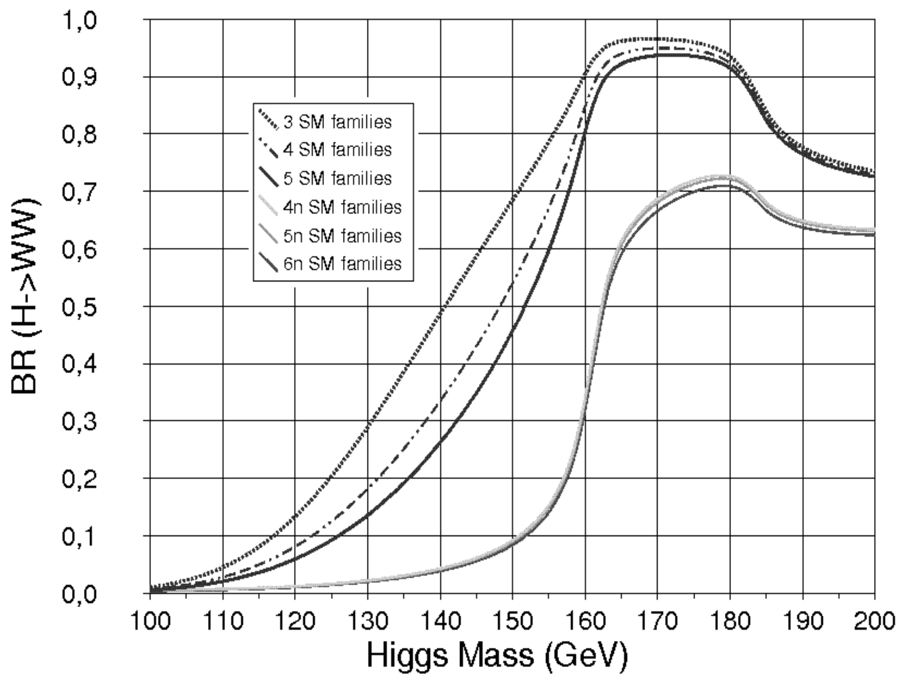

FIG. 3: The branching ratios for the decay mode $H \to WW^{(*)}$ in various scenarios.

TABLE I: The branching ratios depending on the mass of the Higgs boson in the three, four, five and six SM families cases. The asterisk denotes that the calculations are performed assuming $m_\nu = 50$ GeV for the extra families.

Mass(GeV)	SM-3	SM-4	SM-5	SM-4*	SM-5*	SM-6*
100	1.02×10^{-2}	6.73×10^{-3}	5.05×10^{-3}	6.73×10^{-3}	5.05×10^{-3}	3.30×10^{-3}
120	1.33×10^{-1}	8.11×10^{-2}	5.95×10^{-2}	1.21×10^{-2}	1.15×10^{-2}	1.03×10^{-2}
140	4.86×10^{-1}	3.35×10^{-1}	2.63×10^{-1}	4.29×10^{-2}	4.15×10^{-2}	3.86×10^{-2}
160	9.05×10^{-1}	8.48×10^{-1}	8.05×10^{-1}	3.43×10^{-1}	3.35×10^{-1}	3.20×10^{-1}
180	9.35×10^{-1}	9.23×10^{-1}	9.14×10^{-1}	7.27×10^{-1}	7.21×10^{-1}	7.09×10^{-1}
200	7.35×10^{-1}	7.29×10^{-1}	7.25×10^{-1}	6.34×10^{-1}	6.31×10^{-1}	6.24×10^{-1}

IV. RESULTS AND CONCLUSIONS

In Fig. 4, we added our theoretical predictions for the case of two extra SM families (SM-5) with unstable heavy neutrinos ($m_\nu > 100$ GeV) as well as the possible exclusion limits for the integrated luminosity $L_{int} = 2$ fb^{-1} and 8 fb^{-1}. It is seen that the recent Tevatron data excludes SM-5 at 95% C.L., if the Higgs mass lies in the region 160 GeV

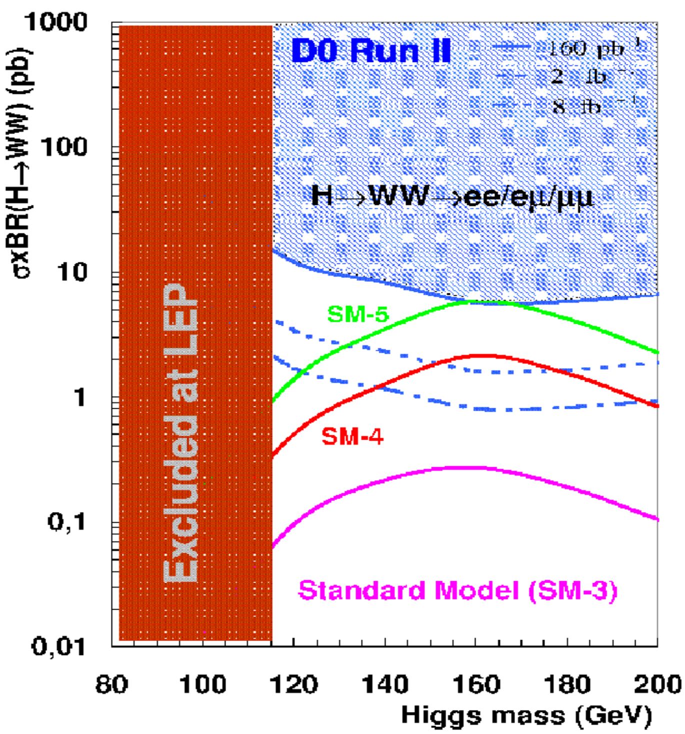

FIG. 4: The excluded region of $\sigma\times$ BR(H $\rightarrow WW^{(*)}$) at 95 % C.L. together with the expectations from the SM model Higgs boson production and the enhancements due to the extra SM generations with heavy neutrinos.

$< m_H <$ 170 GeV (i.e. this mass region is excluded if there are two extra SM families with unstable heavy neutrinos). With 2 fb^{-1} integrated luminosity, the fourth SM family with an unstable neutrino (SM-4) can be verified or excluded for the region 150 GeV $< m_H <$ 180 GeV. Similarly, SM-5 can be verified or excluded for the region $m_H >$ 130 GeV with 2 fb^{-1}. The upgraded Tevatron is expected to reach an integrated luminosity of 8 fb^{-1} before the LHC operation, which means that SM-4 (SM-5) will be verified or excluded for the Higgs mass region $m_H >$ 140 GeV (120 GeV). However, the LHC will be able to cover the whole region via the golden mode H $\rightarrow$ ZZ $\rightarrow \ell\ell\ell\ell$ and detect the Higgs signal during the first year of operation if the fourth SM family exists [25].

In Fig. 5, we present our $\sigma \times BR(H \rightarrow WW^{(*)})$ predictions for the cases of one, two and three extra SM families with $m_\nu \cong$ 50 GeV, SM-4*, SM-5* and SM-6* respectively. If the Higgs mass lies in the region 165 GeV $< m_H <$ 185 GeV, SM-6* is excluded at 95 % C.L..

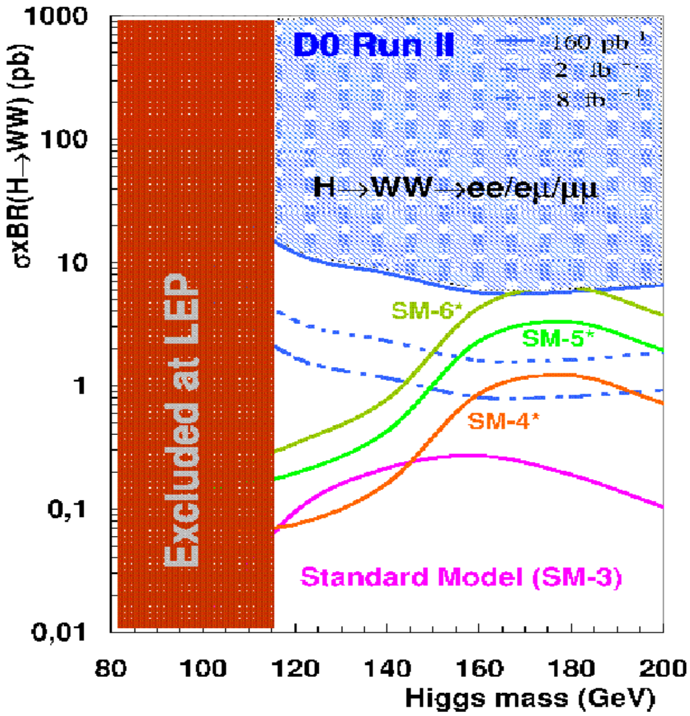

FIG. 5: The excluded region of $\sigma\times$ BR(H $\to$ W W$^{(*)}$) at 95 % C.L. together with the expectations from the SM model Higgs boson production and the enhancements due to extra SM generations with $m_\nu = 50$ GeV.

When $L_{int} = 2$ fb^{-1} is reached, the Tevatron data will be able to exclude or verify SM-6* (SM-5*) for the mass region $m_H > 150$ GeV (155 GeV). With 8 fb^{-1} integrated luminosity, this limit changes to $m_H > 145$ GeV (150 GeV) and SM-4* will be observed or excluded in the range 160 GeV $< m_H <$ 195 GeV.

In Table II, we present the accessible Higgs mass limits at the Tevatron with $L_{int} = 2$ fb^{-1} and 8 fb^{-1} for the extra SM families.

TABLE II: Accessible mass limits of the Higgs boson at the Tevatron with $L_{int} = 2$ fb^{-1} and 8 fb^{-1} for extra SM families.

	2 fb^{-1}	8 fb^{-1}
SM-4	$150 < m_H < 180$ GeV	$140 < m_H < 200$ GeV
SM-5	> 135 GeV	> 125 GeV
SM-4*	–	$160 < m_H < 195$ GeV
SM-5*	> 155 GeV	> 150 GeV
SM-6*	> 150 GeV	> 145 GeV

Another possibility to observe the fourth SM family quarks at the Tevatron will be due to their anomalous production via the quark-gluon fusion process $qg \to q_4$, if their anomalous couplings have sufficient strength [37]. Note that the process $qg \to q_4$ is analogous to the single excited quark production [38].

In conclusion, the existence of the fourth SM family can give the opportunity to observe the intermediate mass Higgs boson production at the Tevatron experiments D0 and CDF before the LHC. The fourth SM family quarks can manifest themselves at the Tevatron as: Significant enhancement (~ 8 times) of the Higgs boson production cross section via gluon fusion; Pair production of the fourth family quarks, if m_{d_4} and/or $m_{u_4} < 300$ GeV; Single resonant production of the fourth family quarks via the process $qg \to q_4$.

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