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With four standard model families, the LHC could discover the Higgs boson with a few fb^{-1}

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Abstract. The existence of a 4th SM family would produce a large enhancement of the gluon fusion channel of Higgs boson production at hadron colliders. In this case, the SM Higgs boson could be seen at the CERN Large Hadron Collider (LHC) via the golden mode ($H^0 \to 4l$) with an integral luminosity of only a few fb^{-1}.

One of the primary goals at the LHC is to observe the standard model (SM) Higgs particle (H^0). The LEP data already set a lower bound on the Higgs boson mass at 114.1 GeV [1]. Proton–proton collisions at a center of mass energy of 14 TeV at the LHC will produce H^0, mainly through gluon–gluon fusion [2], with a mass up to 1 TeV.

The main contribution to the production of the Higgs boson in the three SM family case comes from the well-known triangular diagram with a t-quark loop. If the 4th SM family [3–5] exists, we have two additional diagrams where the t-quark is replaced by u_4- and d_4-quarks.

The number of SM families with light neutrinos are limited by the LEP data to $N = 3.0 \pm 0.06$ [6]. Latest precision electroweak data allow for the existence of a 4th SM family with heavy Dirac neutrinos [5,7]. On the other hand, there are serious arguments favoring the existence of a heavy 4th SM family, with members having almost equal masses [3,4]. Experimental lower bounds on the 4th SM family fermions are as follows: $m_Q > 199\,\mathrm{GeV}$ [6], $m_L > 93.5\,\mathrm{GeV}$ [6], $m_N > 50\,\mathrm{GeV}$ [5]. In this work, all 4th family fermion masses are assumed to be the same.

In order to see the effect of u_4 and d_4 on the $gg \to H^0$ process, the decay width of $H^0 \to gg$ is calculated using the following formula [8]:

$$\Gamma(H \to gg) = \frac{G_\mathrm{F} m_H^3}{36\sqrt{2}\pi}\left(\frac{\alpha_\mathrm{s}(m_H^2)}{\pi}\right)^2 |I|^2. \tag{1}$$

The quantity I is expressed as $I = \Sigma I_q = I_t + I_{u_4} + I_{d_4}$, where I_q is given by $I_q = 3[2\lambda_q + \lambda_q(4\lambda_q - 1)f(\lambda_q)]$, and $\lambda_q = (m_q/m_H)^2$. Here the function $f(\lambda_q)$ takes two different forms:

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

$$f(\lambda_q) = \frac{1}{2}\left(\ln\frac{\eta^+}{\eta^-}\right)^2 - \frac{\pi^2}{2} - \mathrm{i}\pi\ln\frac{\eta^+}{\eta^-}, \quad \text{for} \quad \lambda_q < \frac{1}{4}, \tag{3}$$

where

$$\eta^\pm = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \lambda_q}.$$

Figure 1 shows the enhancement factor K of the H^0 production cross-section via gluon–gluon fusion defined as

$$K = \frac{|I_t + I_{u_4} + I_{d_4}|^2}{|I_t|^2}. \tag{4}$$

In this figure, the 4th family quark masses $m_{u_4} = m_{d_4} = 320$ and 640 GeV are considered [4]. In addition, the $m_{u_4} = m_{d_4} = 200\,\mathrm{GeV}$ case is shown as an illustration.

This enhancement will improve the signal of H^0 in all decay modes [9]. In our opinion, the most promising channel is the so-called “golden mode” in which the Higgs boson decays into four charged leptons. For example [10], if the 4th SM family exists, the upgraded Tevatron, with an integral luminosity of 15 fb^{-1} per experiment and with $\sim 25\%$ overall detector acceptance, may already get indications of the Higgs boson via the golden mode with significance of 2–3σ for $175 < m_H < 300\,\mathrm{GeV}$.

Since the existence of the 4th SM family provides an increase in H^0 production, and the background will not be affected, the significance of the signal at the LHC will be improved. In the 3 family case, the most promising decay channels for the detection of the SM Higgs boson at the LHC-ATLAS experiment are [2] $H^0 \to \gamma\gamma$ ($m_H = 80$–$120\,\mathrm{GeV}$), $H^0 \to ZZ^*, ZZ \to 4l$ ($m_H = 130$–$800\,\mathrm{GeV}$) and $H^0 \to ZZ, W^\pm W^\mp \to lljj, ll\nu\nu, l\nu jj$ ($m_H = 500$–$1000\,\mathrm{GeV}$); here l denotes e or μ, and j denotes jet.

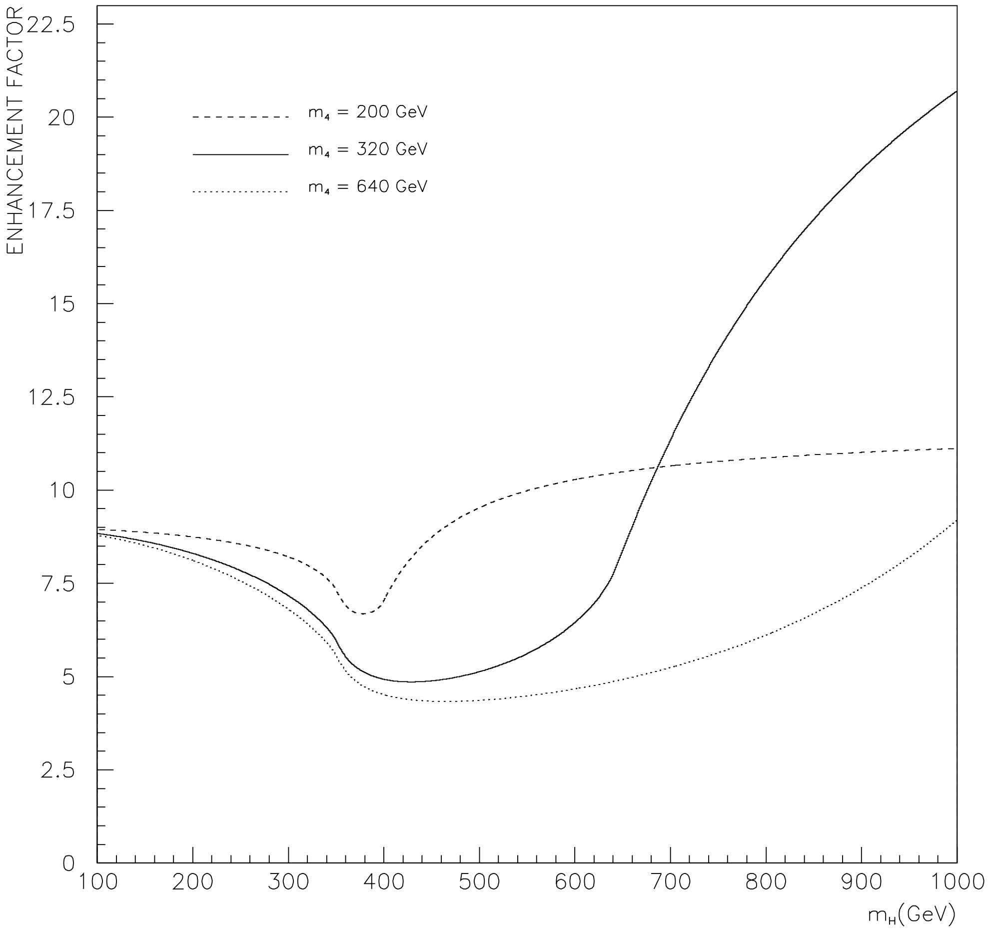

Fig. 1. Enhancement factor of the Higgs boson production ($gg \to H^0$) due to the 4th SM family quarks

Table 1. Signal (S), background (B) and statistical significance (SS) values for the $pp \to H^0 + X$, $H^0 \to 4l$ channel with $30\,\mathrm{fb}^{-1}$ in 3 SM family case

m_H (GeV)	120	130	150	170	180	200	240	280	320	360	400	500	600
S	4.1	11.4	26.8	7.6	19.7	134.0	127.0	110.0	105.0	105.0	86.0	44.0	23.0
B	1.4	2.6	3.0	3.1	3.1	74.0	57.0	43.0	33.0	29.0	29.0	17.0	15.0
SS	2.4	4.8	> 8	3.2	7.1	> 8	> 8	> 8	> 8	> 8	> 8	> 8	4.9

In this work, only the $H^0 \to 4l$ (golden mode) channel is considered. The signal (S) and background (B) events expected in ATLAS [11] in the 3 family case with $30\,\mathrm{fb}^{-1}$ are given in Table 1. The statistical significance (SS) values are calculated using Poisson statistics and expressed in terms of Gaussian σ units. Both here and in [11] the analysis cuts are less restrictive for $m_H \geq 200\,\mathrm{GeV}$, where H^0 decays to two real Z.

The $H^0 \to ZZ^{(*)}, WW$ decay processes do not have any quark loops, hence the decay widths are not affected by the 4th family. The enhancement factor K will increase the total decay width of H^0 and slightly decrease the branching ratios (BRs) of WW and ZZ modes [9]. In Table 2, the signal, background and significance values of $H^0 \to 4l$ are given in the presence of the 4th SM family, by extrapolating the values given in Table 1 for different luminosities. In the calculations, $m_{u_4} = m_{d_4} = 320\,\mathrm{GeV}$ is assumed. Figure 1 shows that using $m_{u_4} = m_{d_4} = 640\,\mathrm{GeV}$ does not change the results much up to $m_H = 600\,\mathrm{GeV}$.

As seen in Table 2, the existence of the 4th family will result in a very conspicuous improvement of the significance of the golden mode signal at $L_{\mathrm{int}} = 30\,\mathrm{fb}^{-1}$. Moreover, almost all of the Higgs boson mass region will be covered even at $L_{\mathrm{int}} = 3\,\mathrm{fb}^{-1}$. This situation is clearly demonstrated in Fig. 2, which represents the integral luminosities needed to achieve a 5σ significance level.

Finally, in the presence of the 4th SM family, the upgraded Tevatron would get indications of the Higgs boson via the golden mode for $175 < m_H < 300\,\mathrm{GeV}$ when an integrated luminosity of $15\,\mathrm{fb}^{-1}$ per experiment is reached. On the other hand, at the LHC, the region of $125 \leq m_H \leq 600\,\mathrm{GeV}$ would be fully covered with 5σ or more significance even at $L_{\mathrm{int}} = 3\,\mathrm{fb}^{-1}$.

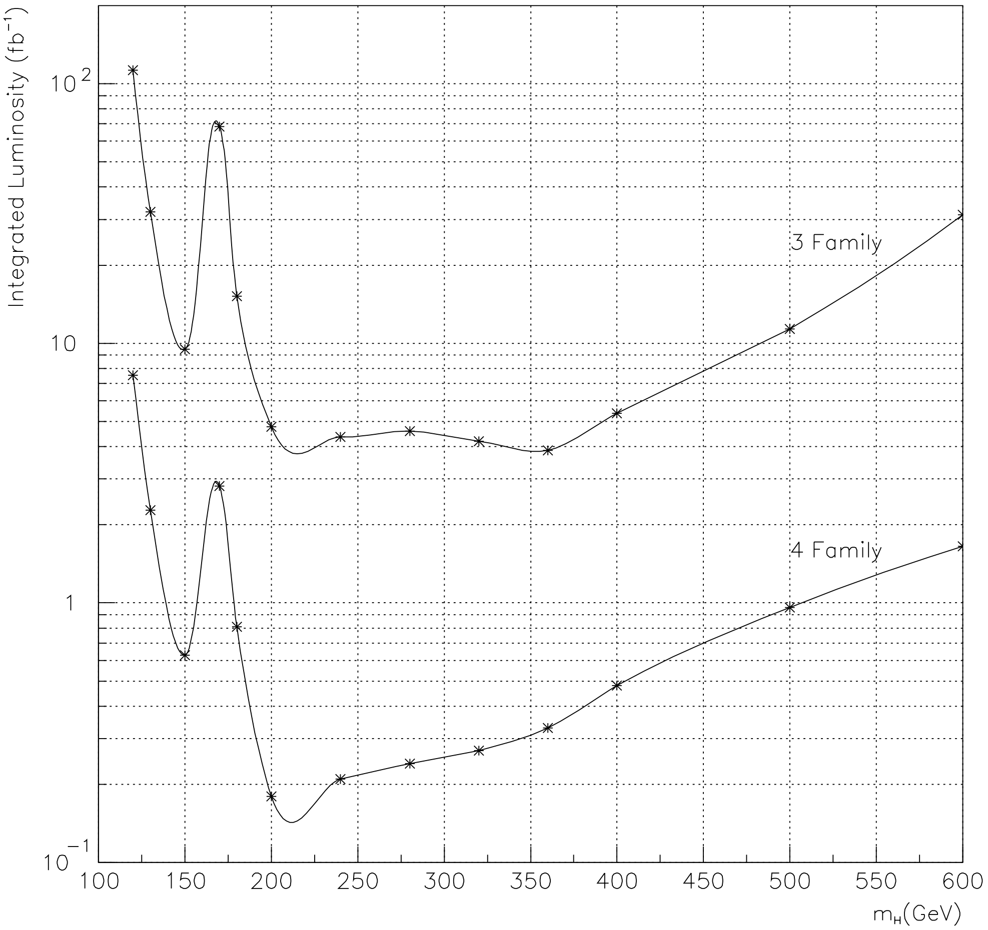

Fig. 2. LHC luminosity values corresponding to 5σ significance level of the golden mode signal for 3 and 4 family cases

Table 2. Signal (S), background (B) and statistical significance (SS) values for the $pp \to H^0 + X$, $H^0 \to 4l$ channel in the 4 SM family case ($m_4 = 320\,\mathrm{GeV}$) for various luminosities

m_H	$L_{\mathrm{int}} = 30\,\mathrm{fb}^{-1}$			$L_{\mathrm{int}} = 3\,\mathrm{fb}^{-1}$		
(GeV)	S	B	SS	S	B	SS
120	25.1	1.4	> 8	2.5	0.1	3.2
130	71.4	2.6	> 8	7.1	0.3	5.6
150	197.0	3.0	> 8	19.7	0.3	> 8
170	64.0	3.1	> 8	6.4	0.3	5.2
180	165.1	3.1	> 8	16.5	0.3	> 8
200	1106.8	74.0	> 8	110.7	7.4	> 8
240	1005.8	57.0	> 8	100.6	5.7	> 8
280	819.5	43.0	> 8	82.0	4.3	> 8
320	711.9	33.0	> 8	71.2	3.3	> 8
360	578.6	29.0	> 8	57.8	2.9	> 8
400	422.2	29.0	> 8	42.2	2.9	> 8
500	225.3	17.0	> 8	22.5	1.7	> 8
600	148.1	15.0	> 8	14.8	1.5	6.8

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