Fourth standard model family enhancement to the golden mode at the upgraded Fermilab Tevatron

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We study the observability of a Higgs boson at the upgraded Fermilab Tevatron via the modes $gg\rightarrow h\rightarrow ZZ\rightarrow 4l$ ($l=e,\mu$). We find that the signal can be observed at an integrated luminosity of 30 fb^{-1} if the fourth SM family exists.

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In the standard model (SM) one doublet of scalar fields is assumed, leading to the existence of one neutral scalar particle h. The requirements of the stability of the electroweak vacuum and the perturbative validity of the SM allow us to set upper and lower bounds depending on the cutoff scale Λ up to which the SM is assumed to be valid. Experimentally, constraints on the SM Higgs boson are derived directly from searches at the CERN e^+e^- collider LEP2 which lead to $m_h>114.3$ GeV [1]. The CERN Large Hardron Collider (LHC) should be able to cover the full range of theoretical interest up to about 1000 GeV [2]. A Feynman diagram for the golden mode of Higgs boson production and decays through heavy quark triangle loop is shown in Fig. 1.

On the other hand, the SM does not predict the number of families of fundamental fermions. In the democratic mass matrix (DMM) approach the SM is extended to include a fourth generation of fundamental fermions with masses typically in the range from 300 GeV to 700 GeV [3,4] (for a recent situation see [5]). The fourth SM family quarks will be produced copiously at the LHC [2,6]. At the same time a fourth generation of fermions contributes to the loop-mediated processes in Higgs production ($gg\rightarrow h$) and decays. In this note we consider the influence of the fourth SM family on the Higgs boson search at the upgraded Tevatron. The simulation is performed using the PYTHIA program [7] for both signal and background calculations. Top quark mass and the vacuum expectation value of Higgs field are $m_t=175$ GeV and $v=246$ GeV for the input parameters. We set the related switches to choose the PDFLIB proton parton distribution function library for CTEQ4M [8] instead of the PYTHIA internal one.

Two relevant regions of Higgs boson masses, namely 125–165 GeV and 175–300 GeV, require special attention. For Higgs boson mass above 135 GeV, the decay mode $h\rightarrow WW$ becomes dominant. Hadronic final state is overwhelmed by the QCD background, therefore, one should deal with $W^\star W^\star\rightarrow l\nu jj$ and $W^\star W^\star\rightarrow l\nu l\nu$ modes [9]. However, the channel $h\rightarrow ZZ$ is also important for the final state observation in the leptonic channel. The decay width for Higgs boson in the channel $h\rightarrow ZZ$ and its branching ratio are given in Fig. 2. The calculations are performed using PYTHIA taking into account the 4th SM family. In the mass range 135–180 GeV, the width of the Higgs boson grows rapidly with increasing m_h.

For Higgs boson masses in the range $175<m_h<300$ GeV, the $h\rightarrow ZZ\rightarrow 4l$ decay mode is the most reliable channel for the discovery of a SM Higgs boson at the upgraded Tevatron if the fourth SM family exists. The discovery potential in this channel is primarily determined by the available integrated luminosity.

The leading production mechanism for a SM Higgs boson at the Tevatron is the gluon-fusion process via heavy quark triangle loop

$$p\overline{p}\rightarrow ggX\rightarrow hX. \tag{1}$$

The lowest order cross section is given by

$$\sigma(p\overline{p}\rightarrow hX)=\sigma_0\tau_h\int_{\tau_h}^{1}\frac{dx}{x}g(x,Q^2)g(\tau_h/x,Q^2), \tag{2}$$

where $g(x,Q^2)$ denotes the gluon density of proton and $\tau_h=m_h^2/s$. The natural values are chosen for the factorization scale Q ($Q=m_h$) of the parton densities and the renormalization scale $\mu=m_h$ for the running strong coupling constant $\alpha_s(\mu)$. The partonic cross section is given by [10]

$$\sigma_0(gg\rightarrow h)=\frac{G_F\alpha_s^2(\mu^2)}{\sqrt{2}\,288\pi}\sum_Q |g_QA_Q|^2. \tag{3}$$

The expression for the amplitude A_Q can be found in [10]. The Yukawa coupling is given by $g_Q=m_Q/v$, where v

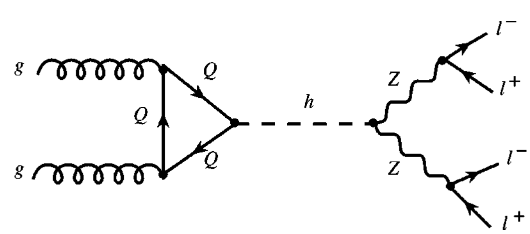

FIG. 1. Feynman diagram for the golden mode $gg\rightarrow h\rightarrow ZZ\rightarrow 4l$ at Tevatron.

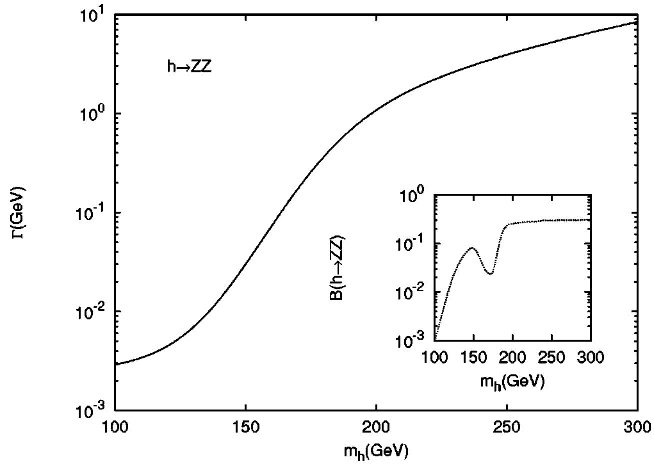

FIG. 2. Decay width and branching ratio for the channel $h \to ZZ$ depending on the mass of Higgs boson.

$=246$ GeV is the vacuum expectation value of the Higgs field and m_Q denotes the heavy quark mass. In spite of the large value of the fourth SM family quark masses, perturbation theory is still applicable for $m_Q < 870$ GeV since $\alpha_Q = g_Q^2/4\pi < 1$. This restriction should be considered as conservative one because as mentioned in [11] the scale of the corrections to Yukawa interactions of the Higgs boson with heavy quarks is given by $g_Q^2/(4\pi)^2$ and these corrections can be neglected for heavy quark masses $m_Q < 3$ TeV.

There are also contributions to h production from vector boson fusion processes, which remain at a low level (2–10)% compared to the gluon-fusion process. Furthermore, gluon fusion process yields the largest cross section, typically a factor of four above the associated production [9,12].

The two-loop QCD corrections enhance the gluon fusion cross section by about 80%. Therefore, we simply rescale the three-level cross sections by a factor $K=1.7$ to match the next leading order (NLO) result for the overall rate [13]. The results are shown in Fig. 3. We have used the CTEQ4M

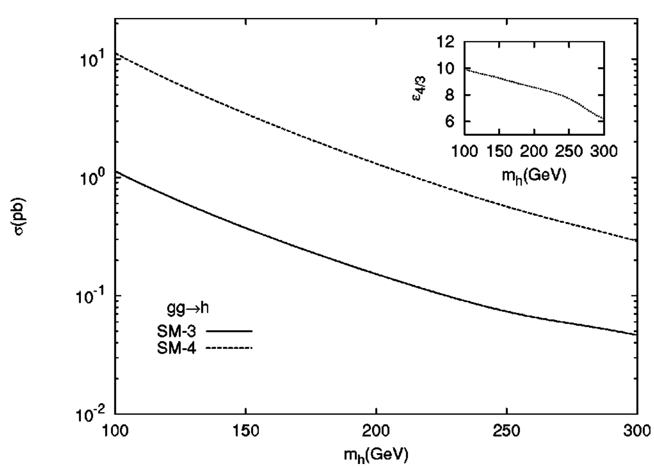

FIG. 3. Total cross sections versus the mass of Higgs boson for three and four family cases. An enhancement factor $\varepsilon_{4/3}$ depending on the Higgs boson mass is also shown.

TABLE I. The expected number of "golden" events in the four SM family case at integrated luminosity 30 fb^{-1}.

m_h (GeV)	$\Gamma(h\to ZZ)$	$B(h\to ZZ)$	σ_4(fb)	$N(4l)$
100	3.9×10^{-3}	6.8×10^{-4}	2.8×10^{-2}	0.8
110	4.6×10^{-3}	2.6×10^{-3}	7.8×10^{-2}	2.3
120	5.6×10^{-3}	9.5×10^{-3}	2.5×10^{-1}	7.5
130	7.4×10^{-3}	2.5×10^{-2}	5.5×10^{-1}	16.5
140	1.1×10^{-2}	4.9×10^{-2}	8.9×10^{-1}	26.7
150	2.0×10^{-2}	6.8×10^{-2}	1.0	30.0
160	8.3×10^{-2}	4.0×10^{-2}	4.9×10^{-1}	14.7
170	3.6×10^{-1}	2.3×10^{-2}	2.4×10^{-1}	7.2
180	6.1×10^{-1}	5.9×10^{-2}	5.0×10^{-1}	15.0
190	9.9×10^{-1}	2.1×10^{-1}	1.4	42.0
200	1.4	2.5×10^{-1}	1.5	45.0
220	2.3	2.8×10^{-1}	1.1	33.0
240	3.4	2.9×10^{-1}	8.4×10^{-1}	25.2
260	4.7	3.0×10^{-1}	6.3×10^{-1}	18.9
280	6.4	3.0×10^{-1}	4.7×10^{-1}	14.1
300	8.4	3.1×10^{-1}	3.6×10^{-1}	10.8

parton distribution functions [8] in our calculations. In the case of three SM families Higgs boson production cross section is roughly 1.0(0.05) pb for $m_h=100(300)$ GeV. However, this cross section is enhanced by a factor 10(6) due to the fourth family quarks. Obviously, the same enhancement takes place for the golden mode and this makes the signal observable over the corresponding background. It is obvious that in the infinitely heavy quark limit [14,15] the expected enhancement factor is equal to 9. Indeed, for $m_t, m_{d_4}, m_{u_4} \gg m_h$ the amplitude for $gg\to h$ process becomes $A_t + A_{d_4} + A_{u_4} = 3A_t$. It should be noted that the heavy-quark approximation for the matrix elements is rather bad, but in [16] it is shown that the approximation is rather good if it is applied to the relative correction factor only. In this approximation, the K factor changes weakly in the considered Higgs boson mass region. For this reason, chosen value ($K=1.7$) can be considered as a good approximation for the qualitative estimations.

In Fig. 4, we present the cross sections for the process $p\bar{p}\to h X \to 4l X$ depending on the Higgs boson mass for three and four SM family cases. The signal is reconstructed by requiring four charged leptons $4l$ ($l=e,\mu$) in the final state. We use the branching ratio $B(Z\to l^+l^-)=3.35\times10^{-2}$ for $l=e,\mu$. In Table I, we present the number of "golden" events in the four SM family case at an integrated luminosity 30 fb^{-1}.

TABLE II. Observability of the "golden" events for integrated luminosity 30 fb^{-1} within the mass window 10 GeV.

	S		B	$S/\sqrt{B}$	
m_h (GeV)	SM-3	SM-4		SM-3	SM-4
200	3.5	33.8	16.4	0.9	8.3
250	2.0	16.0	8.8	0.7	5.4

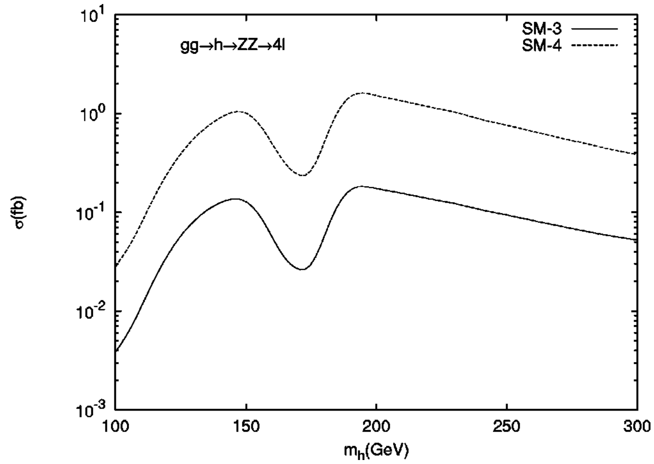

FIG. 4. The cross section of ''golden'' events depending on the Higgs boson mass for the cases of three and four SM families.

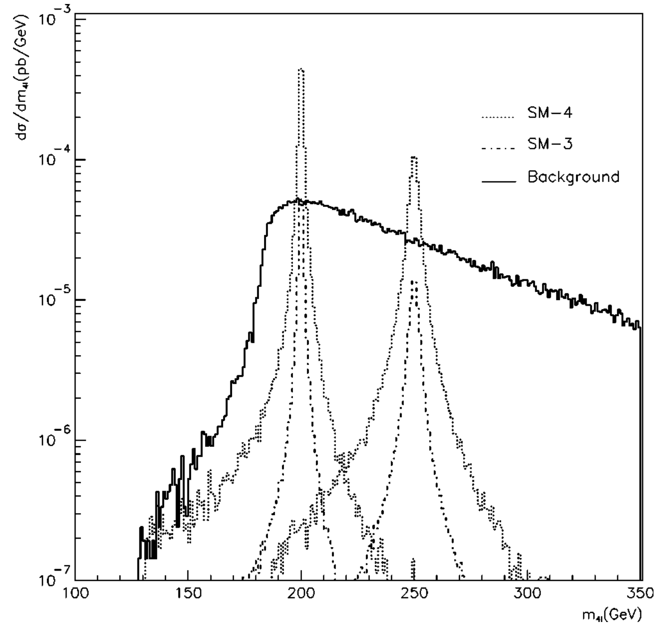

FIG. 5. The invariant mass distributions of the signal and background for $m_h = 200$ and 250 GeV.

The most serious background is the pair production of Z bosons, $p\bar{p} \to ZZX (Z \to l^+ l^-)$, which has $\sigma \approx 8$ fb and should be taken into account for $m_h > 2m_Z$. This background can be suppressed by consideration of the four-lepton invariant mass distribution. Invariant mass distributions of four charged lepton final state are given in Fig. 5 for two values of Higgs boson mass. We assume the mass window of 10 GeV around the Higgs boson mass. In the same figure, we present the main background coming from two Z production. In the four SM family case we use $m_4 = 640$ GeV. Taking the mass value $m_4 = 320$ GeV leads to negligible difference in cross sections. As can be seen from the Table II, we obtain 34 signal events against 16 background events within the mass window 10 GeV if $m_h = 200$ GeV. The statistical significance for $4l$ signal is 8.3 and 5.4 for $m_h = 200$ and 250 GeV, respectively.

In conclusion, the golden mode will be observable for $175 < m_h < 300$ GeV with more than 3σ significance if the fourth SM family exists. The same statement takes place also for $125 < m_h < 165$ GeV, however we do not consider this region in detail because it is covered by the $h \to WW$ mode [9,12].

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