Search for fourth generation quarks and leptons at the Fermilab Tevatron and CERN Large Hadron Collider

I. F. Ginzburg*
Sobolev Institute of Mathematics, Novosibirsk, 630090, Russia

I. P. Ivanov†
Sobolev Institute of Mathematics, Novosibirsk, 630090, Russia and Forschungszentrum, Juelich, Germany

A. Schiller‡
Institut für Theoretische Physik and NTZ, Universität Leipzig, D-04109 Leipzig, Germany

(Received 4 November 1998; revised manuscript received 6 July 1999; published 27 September 1999)

If the next generations of heavy quarks and leptons exist within the standard model (SM), they can manifest themselves in Higgs boson production at the Fermilab Tevatron and the CERN LHC, before being actually observed. This generation leads to an increase of the Higgs boson production cross section via gluon fusion at hadron colliders by a factor 6–9. So, the study of this process at the Tevatron and LHC can finally fix the number of generations in the SM. Using the WW^* Higgs boson decay channel, the studies at the upgraded Tevatron will answer the question about the next generation for mass values 135 GeV $\lesssim M_H \lesssim 190$ GeV. Studying the $\tau\bar{\tau}$ channel we show its large potential for the study of the Higgs boson at the LHC even in the standard case of three generations. At the Tevatron, studies in this channel could explore the mass range 110–140 GeV. [S0556-2821(99)08319-8]

PACS number(s): 12.60.−i, 14.60.Hi, 14.80.Bn

I. INTRODUCTION

The standard model (SM) does not fix the number of fermion generations. So far it is not known why there is more than one generation and what law of nature determines their number.

The studies on the Z peak at the CERN e^+e^- collider LEP proved that there are exactly three generations of quarks and leptons with light neutrinos. However, the existence of next generations with heavy neutrinos is not completely excluded. The S–parameter value obtained from modern electroweak data [1] makes the fourth generation disfavored but only at the level of 2.5 σ accuracy. Anyway, new quarks and leptons should be heavier than the t quark.

At a first glance, one cannot determine the number of generations in the SM before a direct observation of these new particles. Here we propose a simple way *how to determine the number of such families before their direct discovery* provided the simplest variant of the SM (with one Higgs doublet) is valid. The key is given by experiments probing the Higgs boson H production via gluon fusion at hadron colliders [Fermilab Tevatron and CERN Large Hadron Collider (LHC)]. In accordance with modern data, we have in mind that $M_H \gtrsim 95$ GeV [2]. We assume that the masses of new quarks $m_q \gg M_H$.

The proposal stems out from well known facts (see, e.g., [3]). In $p\bar{p}$ or pp collisions, the Higgs boson is produced mainly via gluon fusion. The production cross section is proportional to the two-gluon decay width of the Higgs boson $\Gamma(H\to gg)$. This width is induced by diagrams with quark loops (see Fig. 1). The dominant contribution to $\Gamma(H\to gg)$ comes from heavy quark loops. Indeed, the amplitude corresponding to such a loop is $\propto g_q \alpha_s/\max\{M_H, m_q\}$ (here α_s denotes the strong coupling constant). The Yukawa coupling constant g_q between the Higgs boson and the quarks is $g_q = m_q/v$ (with $v = 246$ GeV — the Higgs boson vacuum expectation value). At $m_q \gg M_H$, the quark contribution is finite and m_q independent. [The light quark contribution is suppressed as $\sim (m_q/M_H)^2$].

Therefore, in our discussion we restrict ourselves to the t quark and the possible fourth generation. Since the new fermion generation contains two extra quarks, the amplitude of this decay increases by a factor of about 3 and the two-gluon width by a factor of about 9 for a light enough Higgs boson.

II. THE TWO-GLUON WIDTH AND GLUON FUSION

In one-loop approximation the two-gluon decay width of the Higgs boson can be written as

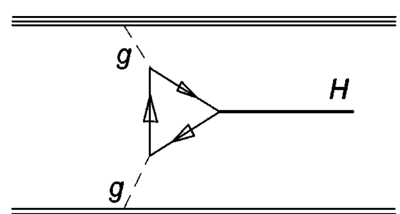

FIG. 1. Dominant diagram for Higgs boson production in hadron collisions.

*Email address: ginzburg@math.nsc.ru
†Email address: i.ivanov@fz-juelich.de
‡Email address: schiller@tph204.physik.uni-leipzig.de

$$\Gamma(H\to gg)=\left(\frac{\alpha_s}{4\pi}\right)^2\frac{M_H^3}{8\pi v^2}|\Phi|^2,\quad \Phi=\sum_q \Phi_q. \tag{2.1}$$

The quantity Φ is the sum of loop integrals Φ_q corresponding to different quarks q:

$$\Phi_q=-2r_q[1+(1-r_q)x^2(r_q)],\qquad r_q=\frac{4m_q^2}{M_H^2}, \tag{2.2}$$

$$x(r)=\frac{\pi}{2}-\theta(r-1)\arctan\sqrt{r-1}+\mathrm{i}\,\theta(1-r)\times\ln\frac{1+\sqrt{1-r}}{\sqrt{r}}.$$

With reasonable accuracy we consider only the t quark and N_q very heavy quarks from next generations (assuming that they are much heavier than H). In this case

$$\Phi=-2r_t[1+(1-r_t)x^2(r_t)]-\frac{4}{3}N_q. \tag{2.3}$$

(If the heavy quark masses are comparable with M_H, all numbers have to changed in a similar way as the effect of the t quark mass seen in Table I at $M_H>200$ GeV).

In the following we denote by Γ_{gg}^k and σ^k the two gluon width and the production cross section in a model with k generations, for $k=4$ we have $N_q=2$. The discussed dependence of the two-gluon width Γ_{gg}^k on the Higgs boson mass M_H in one-loop approximation is shown in Table I. (The effects of radiative corrections are considered below.) Note that for a Higgs boson mass close to the $t\bar{t}$ threshold, the relative contribution of the top quark in Eq. (2.3) grows, which leads to a decrease of the $\Gamma_{gg}^4/\Gamma_{gg}^3$ ratio.

TABLE I. Two-gluon width for three and four generations as function of M_H.

M_H(GeV)	Γ_{gg}^3 (MeV)	Γ_{gg}^4 (MeV)	$\Gamma_{gg}^4/\Gamma_{gg}^3$
100	0.093	0.812	8.77
120	0.155	1.34	8.67
140	0.241	2.06	8.54
160	0.357	3.00	8.40
180	0.507	4.18	8.24
200	0.702	5.65	8.05
250	1.46	10.9	7.47
300	2.87	19.2	6.69
350	6.28	33.9	5.44

The cross section for the Higgs boson production in $pp(p\bar{p})$ collisions is given as the convolution of the cross section for the subprocess $gg\to H$ with the gluon structure functions $g(x,Q^2=W^2)$ ($W^2=x_1x_2s$ is the total two-gluon c.m. energy squared). Since the total Higgs boson width is less than 10 GeV for $M_H<300$ GeV and the distribution of colliding gluons is smooth, the standard narrow-width approximation $\sigma_{gg\to H}=\pi^2\Gamma_{gg}^k\delta(W^2-M_H^2)/(8M_H)$ is used with high precision. With this form of $\sigma_{gg\to H}$, the cross section of interest reads

$$\sigma(p\bar{p}\to H+\cdots)=\frac{\pi^2}{8s}\frac{\Gamma_{gg}^k}{M_H}\int_{M_H^2/s}^1\frac{dx_1}{x_1}g(x_1,M_H^2)g\left(x_2=\frac{M_H^2}{x_1 s},M_H^2\right). \tag{2.4}$$

The relative enhancement of the Higgs boson production due to the fourth generation is simply

$$\frac{\sigma^4(p\bar{p}\to H+\cdots)}{\sigma^3(p\bar{p}\to H+\cdots)}=\frac{\Gamma_{gg}^4}{\Gamma_{gg}^3}. \tag{2.5}$$

The essential radiative corrections are of the following two sources

(i) QCD corrections to the two-gluon width and the production mechanism. Those corrections have been calculated for the SM with three generations in Ref. [4]. They enhance the Higgs boson production cross section (2.4) at the LHC by a factor $K=1.5$–1.7. Varying the Higgs boson mass from 100 GeV to 1 TeV the K factor increases almost monotonously in that region. It changes weakly for heavier quarks.

(ii) Strong Yukawa interaction of the Higgs boson with heavy quarks. The scale of these corrections is given by $g_q^2/(4\pi)^2=m_q^2/(4\pi v)^2$. So, they can be neglected for heavy quark masses $m_q<3$ TeV. (For example, at $m_q\leqslant 1$ TeV these corrections are less than a few percent [5]). For still larger quarks masses our results can be considered as a first rough estimate.

Therefore, the factor K should be added in the cross section (2.4). In accordance with the results of Ref. [4] and the previous discussion, we choose the value $K=1.5$ for both the Tevatron and the LHC and at all Higgs boson masses. A more precise value of K would change our cross sections [and in particular the ratio (2.5)] by less than 10%.

Using the parametrizations of the gluon structure functions from Ref. [6], we obtain the Higgs boson production cross sections for different decay channels at the Tevatron (Fig. 2) and the LHC (Fig. 3) in the SM with three or four generations. To test the sensitivity to the parametrization of the gluon structure functions we have calculated the same cross sections using an alternative parameterization from Ref. [7]. We observe that the obtained cross sections differ weakly from those presented in the figures.

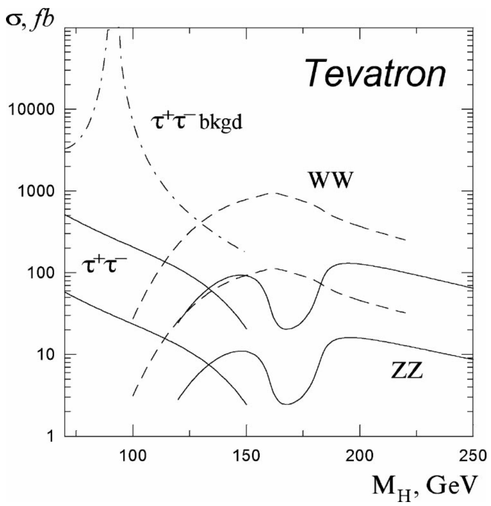

FIG. 2. The cross sections of the Higgs boson production for different decay channels calculated for the Tevatron. The lower curves correspond to three generations, the upper ones to four generations. The $\tau\bar{\tau}$ background is shown by the dash-dotted line.

In the Higgs boson mass range 100–140 GeV the $\tau\bar{\tau}$ decay channel for the three family model has a branching ratio varying from 0.08 ($M_H = 100$ GeV) to 0.04 ($M_H = 140$ GeV). For the four family model the corresponding branching ratio reduces from 0.065 to 0.036. At $M_H > 150$ GeV the effect of the fourth generation changes the observable branching ratios only marginally. The main background for this channel is given by the process $q\bar{q} \to Z(\gamma) \to \tau\bar{\tau}$. It is also shown in Figs. 2 and 3.

The effect of the next generation can also be seen at the LHC using the process $gg \to ZZ$ much above the Higgs resonance position, at $m_q \gg M_{ZZ} \gg M_H$ [8]. The main contribution is given by the diagram with the s-channel Higgs intermediate state. The ggH vertex entering in the measurable cross section is m_q independent (just as for the real Higgs boson production) and the amplitude is M_H independent at $M_{ZZ} \gg M_H$. For Higgs boson masses $M_H < 190$ GeV the smaller

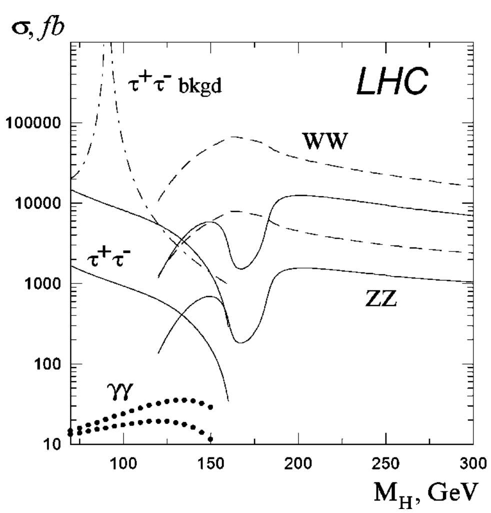

FIG. 3. Same as Fig. 2 for the LHC.

TABLE II. Ratio of the two-photon widths $\Gamma^4_{\gamma\gamma}/\Gamma^3_{\gamma\gamma}$ and of the cross section $gg \to H \to \gamma\gamma$ for four and three generations as function of M_H.

M_H (GeV)	$\Gamma^4_{\gamma\gamma}/\Gamma^3_{\gamma\gamma}$	$(\Gamma^4_{gg}Br^4_{\gamma\gamma})/(\Gamma^3_{gg}Br^3_{\gamma\gamma})$
100	0.158	1.12
120	0.193	1.31
140	0.250	1.78
160	0.403	3.32
180	0.485	4.00
200	0.539	4.34
250	0.710	5.30
300	0.960	6.50
350	1.36	7.40

cross section (far from the resonance) is compensated by the opportunity to use the ZZ final state with low background. The resulting nonresonant effect is observable at the LHC assuming a large enough luminosity integral.

III. THE TWO-PHOTON WIDTH AND THE RELATED CROSS SECTION

The fourth generation also modifies the two-photon decay width of the Higgs boson. This decay originates from similar loops with leptons, quarks and W bosons. Here the W boson and t-quark contributions (other loops give negligible contributions) are of opposite sign and the former dominates strongly at $M_H \ll 2m_t$. Thus the fourth generation results[1] in a significant reduction of the two–photon width (see Table II).

However, at $M_H \gtrsim 2m_t$ (where the t quark contribution exceeds the W boson contribution) a new fermion generation enhances the Higgs boson two-photon width again. This trend can be also seen in Table II. The QCD radiative corrections are small in this case [4].

From the behavior of the two-photon width we conclude that the fourth generation would result in a strong (but destructive in a wide range of masses M_H) effect for the Higgs boson production at photon colliders (see Fig. 4).

Concerning hadron colliders, this decay channel is of specific interest if the Higgs boson will be discovered via the $\gamma\gamma$ decay at the LHC. Note that at $M_H > 100$ GeV the cross section of the process $gg \to H \to \gamma\gamma$, being proportional to $\mathrm{Br}^k_{\gamma\gamma}\Gamma^k_{gg}$, increases if the fourth generation exists (Table II). (Here Br_ϕ is, as usual, the branching ratio for the decay channel ϕ). The influence of an extra family becomes stronger with increasing Higgs boson mass.

IV. SEARCH STRATEGIES AT THE TEVATRON AND THE LHC

For a known luminosity integral $\mathcal{L}$ and detection efficiency of a considered decay channel ε we calculate below

[1]We included both heavy quarks and a charged lepton, assuming that their masses are much larger than M_H.

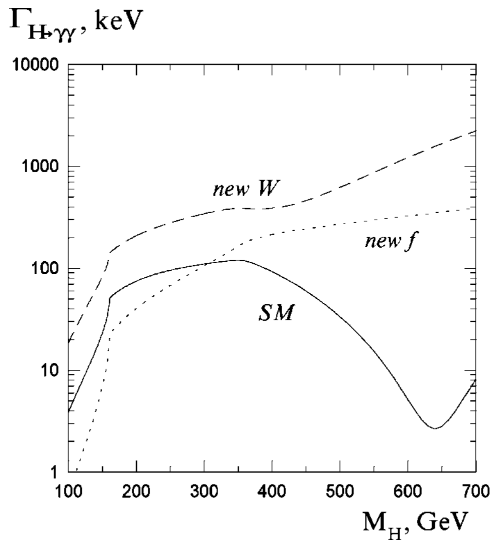

FIG. 4. The cross section of the Higgs boson production at a photon collider (averaged over the photon spectrum) for different discovery modes: three generations (full line), four generations (dotted line), an extra charged vector boson (dashed line).

the significance of an effect as the ratio $S/\sqrt{B}$ with the number of events for the signal S and the background B. The number of events for the signal with k generations is given by $S_k = \varepsilon \mathcal{L} \sigma^k_{\text{signal}}$, the corresponding number for the background by $B = \varepsilon \mathcal{L} \sigma_{\text{bkgd}}$. Both S and B are calculated with necessary cuts. In our calculations we use the integrated luminosity $\mathcal{L} = 30\ \text{fb}^{-1}$ for the upgraded Tevatron and $\mathcal{L} = 100\ \text{fb}^{-1}$ for the LHC.

A. Different decay channels

1. The $b\bar{b}$ decay channel

At $M_H < 135$ GeV the dominant decay channel is $b\bar{b}$. The signal to background ratio S/B can be easily estimated since the main contribution to the nonresonant background is given by the $b\bar{b}$ production in the same gluon collisions. Therefore, it is sufficient to compare the nonresonant $b\bar{b}$ production with that occurring in the Higgs boson decay ignoring the particular distribution of the gluon flux. Using the just mentioned procedure to calculate the cross sections, we find that the ratio $S/B < 0.001$ even in the case of four generations (more than 10^7 events are necessary to obtain a significance $S/\sqrt{B} > 3$). As a result, the $b\bar{b}$ channel cannot be used for our problem.

2. The $\tau\bar{\tau}$ decay channel

In spite of the relatively low branching ratio for this channel, the relative value of the background is not so huge. The possibility to use the $\tau\bar{\tau}$ decay channel for discovering the Higgs boson of the minimal supersymmetric extension of the SM (MSSM) at the LHC and SSC was considered in Ref. [9]. A more detailed study for the LHC has been performed recently in Ref. [10].

When searching for a single τ lepton in pp collisions, its leptonic decay channel should be used which has the branching ratio 1/8.5. Just this value of the detection efficiency was achieved in the CDF experiment [11]. For the $\tau\bar{\tau}$ pair the leptonic channel for one τ and the hadronic jet channel for the another τ can be used [9,10]. This procedure results in a branching ratio $\tau\bar{\tau} \to l\nu + \text{jet}$ of 0.09. However, realizing the presence of other background processes, various sources of detection imperfection, etc., we prefer to use a *twice lower value* $\epsilon = 0.04$ to obtain cautious estimates. Using suitable cuts we hope that the resolution $\Delta M \approx 10$ GeV is achievable in the effective mass M of the produced $\tau\bar{\tau}$ system. In the calculations we use a cutoff $p_\perp > 30$ GeV in the transverse momenta of the produced τ and a rapidity cutoff $|\eta| < 1.5$ for the Tevatron and $|\eta| < 2.5$ for the LHC.

We consider here the main source of a ''physical'' background — the process $q\bar{q} \to Z(\gamma) \to \tau\bar{\tau}$. The cutoff in $p_\perp$ keeps 80% of the signal and 72% of the background at $M_H = 100$ GeV, 90% of S and 85% of B at $M_H = 140$ GeV. The rapidity cuts leads to 88–94 % of the signal and 76–85 % of the background (depending on the Higgs boson mass) and improve the $S/\sqrt{B}$ ratio by 1–2 % for the Tevatron. At the LHC these cuts keep 84–90 % of the signal and 66–71 % of the background (depending on M_H) and improve the $S/\sqrt{B}$ ratio by 4–7 %. From these estimates it follows that both cuts do not cause any significant improvement of the $S/\sqrt{B}$ ratio. However, these cuts are still useful because they cut off background processes of other origin.

Figures 2, 3, and Table III show the corresponding signal and background cross sections at the Tevatron and the LHC (with a common K factor $K = 1.5$). The last columns in that table show the significance $S/\sqrt{B}$ defined above (both three and four generations are considered in the case of the LHC) with a detection efficiency $\varepsilon = 0.04$, a luminosity integral $30\ \text{fb}^{-1}$ for the Tevatron and $100\ \text{fb}^{-1}$ for the LHC and the cuts mentioned above. One can see that the effect of four generations will be observable at the Tevatron in the Higgs boson mass range $M_H = 110 - 140$ GeV. At the LHC the effect will be huge for a standard one-year luminosity $100\ \text{fb}^{-1}$. Going from the Tevatron to the LHC the improvement of the ratio $S/\sqrt{B}$ is very natural, since with decreasing of $x \approx M_H/\sqrt{s}$ the gluon structure function increases much faster than the quark structure functions.

More detailed calculations can either improve these estimates or make them worse. To this end additional backgrounds like $t\bar{t} \to W^+W^- b\bar{b} \to \tau\bar{\tau} + \cdots \to \cdots$ should be considered as it was made in Ref. [10]. Those backgrounds need detailed simulations with some additional cuts (for example, the anticoincidences with b quarks can be useful). The relative value of this background is essential at the LHC [10]. At the Tevatron it corresponding value is much smaller since the ratio $2m_t/\sqrt{s}$ is larger, resulting in a much lower cross section for the $t\bar{t}$ pair production. Furthermore, in our calculations we have averaged the cross sections over an effective mass interval 10 GeV. Detailed studies should answer, whether this mass resolution is achievable or whether it it should be improved.

3. The $\mu^+\mu^-$ decay channel

At the LHC this channel can be used as an additional opportunity to search for a new generation. The branching

TABLE III. Cross sections of the processes $pp \to \cdots + gg \to H \to \tau\bar{\tau}$ for three and four generations and for the background $pp \to q\bar{q} + \cdots \to Z(\gamma) \to \tau\bar{\tau}$ at the Tevatron and the LHC (in fb). The $S_4(\mu)/\sqrt{B}$ for the $H \to \mu^+\mu^-$ decay channel is shown additionally.

Tevatron				
M_H (GeV)	3 generations	4 generations	background	$S_4/\sqrt{B}$
100	30	219	7400	2.75
110	24	166	1740	4.4
120	18	121	790	4.7
130	13	86.5	456	4.4
140	7	52	296	3.3

LHC						
M_H (GeV)	3 generations	4 generations	background	$S_3/\sqrt{B}$	$S_4/\sqrt{B}$	$S_4(\mu)/\sqrt{B}$
100	1170	8270	35 200	6.2	44	5.8
110	990	6330	8180	10.5	75	8.8
120	810	5550	3640	13.3	92	10
130	523	4210	2085	11.3	91	10.2
140	402	2840	1350	10.7	78	8.8
150	208	1610	946	6.7	51	5.9
160	31.5	257	690	1.0	8.6	1.1

ratio of this channel is $(m_\tau/m_\mu)^2 \approx 283$ times smaller than that for the $\tau\bar{\tau}$ channel. However, the mass resolution here can be 1 GeV or even better [12], the signal is very clean, the detection efficiency is close to 1 and the background is reduced by a factor $\gtrsim 10$. The last column in Table III for the LHC shows the $S_4(\mu)/\sqrt{B}$ value for the $\mu^+\mu^-$ channel with a mass resolution of 1 GeV.

4. The $\gamma\gamma$ decay channel

This channel is also proposed for the Higgs boson study at the LHC [14]. The accuracy needed to detect extra generations can be seen from Table II.

5. The WW^* decay channel

This channel is dominant at $M_H > 135$ GeV. The simulation of the process $gg \to H \to WW^*$ with background was performed within the SM with three generations in Ref. [13]. It was shown that the Higgs boson can be excluded at 95% confidence level at 135 GeV$< M_H <$190 GeV (which means that $S/\sqrt{B} \geqslant 2$) with a total luminosity integral $\mathcal{L} = 30$ fb^{-1}. Since the signal in our case increases by a factor $p = 8.2$–8.5 with an unchanged background, the luminosity integral needed for the same significance is reduced by p^2 to less than 0.5 fb^{-1}. Enhancing $\mathcal{L}$ by a factor r, the $S/\sqrt{B}$ ratio increases by $\sqrt{r}$. Therefore, in the case of four generations a luminosity integral of 3 fb^{-1} is sufficient to see the Higgs boson in this mass interval with $S/\sqrt{B} > 5$. An additional simulation is necessary to find the lower bound of the accessible mass interval for the luminosity integral 30 fb^{-1}.

Figure 3 shows that the opportunities at the LHC are significantly richer.

6. The ZZ decay channel

At $M_H > 190$ GeV this channel is best suited for the Higgs boson search. The value of the signal with reasonable kinematical limitations can be estimated using the results of Ref. [8] as input. For the resonance production the signal is $\sim M_{ZZ}^2/(M_H \Gamma_H)$ times larger than that calculated in Ref. [8]. This factor is larger than 100 at $M_{ZZ} > M_H$ and $M_H < 250$ GeV. In accordance with the numbers of Table III, the ratio of products of gluon fluxes varies quickly with M_H: very roughly it decreases by a factor of the order of 100 from the LHC to the Tevatron in this mass region. Therefore, with a production cross section being 8 times larger (Table I) the effect is expected to be sizable even at the Tevatron (run III). The opportunity to observe the effect at lower values of M_H (the ZZ^* channel) should be also explored.

B. Different colliders

1. Studies at the upgraded Tevatron

Summarizing the previous discussion, we conclude that the direct Higgs boson production in the $\tau\bar{\tau}$ channel for the Higgs boson mass interval 110–140 GeV and in the WW^* channel for $M_H = 135$–190 GeV will answer the question about the next generation for the Higgs boson mass interval 110–190 GeV. This statement is beyond doubts for the WW^* channel, and it should be tested in more detail for the $\tau\bar{\tau}$ channel. These studies could reveal the existence of the fourth generation even if the Higgs boson is not discovered in the associative production.

2. Studies at the LHC

At the LHC the Higgs boson is expected to be visible in different channels depending on its mass [14]. In all cases, strong signals of the fourth generation provide the opportunity to study the problem of new heavy generations in the SM even if the new particles are so heavy that they cannot be directly produced. Using the $\mu^+\mu^-$ channel with a possible mass resolution of about 1 GeV and with a very clean signature is also possible despite the very low branching ratio.

Besides, one can hope that the $\tau\bar{\tau}$ channel can be used to observe the Higgs boson via gluon fusion even for the SM with three generations in the M_H interval 100–150 GeV. Comparing the data in the $\tau\bar{\tau}$, WW^*, $ZZ^*(ZZ)$, and $\gamma\gamma$ decay channels will be essential to test the coupling constants of the Higgs boson with different particles and thus verify the Higgs mechanism of the mass generation in the SM. If $M_H < 190$ GeV, the nonresonant $gg \to H^* \to ZZ$ process [8] will be a cross check of the results obtained at the Tevatron.

V. CONCLUDING REMARKS

Certainly, the presented numerical estimates are rough. Detailed Monte Carlo simulations should take into account specific features of the detectors (to account for the detection and triggering efficiency in more details). They will show the exact regions of the Higgs boson mass where the effect of the fourth generation could be seen in particular channels at the Tevatron and the LHC. For the WW^* channel the simulation of Ref. [13] can be repeated using the cross section with the fourth generation included. For the $\tau\bar{\tau}$ and ZZ channels new simulations in a wide Higgs boson mass interval are necessary.

The large effect in the gluon fusion discussed can be imitated by other mechanisms, for example, in two Higgs doublet models or in MSSM at some values of the mixing angles β and α. In this respect, additional measurements of the Higgs boson production in $\gamma\gamma$ or $e\gamma$ collisions can help to solve our problem. Indeed, adding to the SM the fourth generation changes strongly the relevant cross sections (see, e.g., Fig. 4). Fortunately, the parameters which imitate the effect of the fourth generation in the gluon fusion do not give such an imitation for the photon fusion ($H\gamma\gamma$ vertex) or the process $e\gamma \to eH$ [15]. Therefore, the study of these processes at photon colliders is very useful to obtain an unambiguous conclusion about the existence of next heavy generations.

ACKNOWLEDGMENTS

We acknowledge very useful discussions with S. Abdulin, R. Kinnunen, G. Landsberg, M. Krawczyk, N. Mokhov, A. Nikitenko, E. Richter–Was, and P. Zerwas. I.F.G. is grateful to David Finley, Peter Lucas, and Hugh Montgomery for their hospitality to stay at Fermilab. This work is supported by grants of INTAS, RFBR 99-02-17211, and the Volkswagen Stiftung I/72302.

[1] C. Caso *et al.*, Eur. Phys. J. C **3**, 1 (1998).
[2] P. Bock *et al.*, CERN Report No. CERN-EP-98-046, 1998; V. Ruhlmann, report at hadronic Moriond, 1998.
[3] F. Wilczek, Phys. Rev. Lett. **39**, 1304 (1977); A.I. Vainshtein, M.B. Voloshin, V.I. Zakharov, and M.A. Shifman, Yad. Fiz. **30**, 1368 (1979) [Sov. J. Nucl. Phys. **30**, 711 (1979)]; L.B. Okun, *Leptons and Quarks* (North–Holland, Amsterdam, 1982); B.A. Kniehl, Phys. Rep. **240**, 211 (1994).
[4] M. Spira, A. Djouadi, D. Graudenz, and P.M. Zerwas, Nucl. Phys. **B453**, 17 (1995); S. Dawson and R.P. Kauffman, Phys. Rev. D **47**, 1264 (1993); V. Del Duca and C.R. Schmidt, *ibid.* **49**, 177 (1994); K. Melnikov, M. Spira, and O. Yakovlev, Z. Phys. C **64**, 401 (1994).
[5] Yi Liao and Xiao-yuan Li, Phys. Lett. B **396**, 225 (1997); K. Melnikov (private communication).
[6] M. Glück, E. Reya, and A. Vogt, Z. Phys. C **67**, 433 (1995).
[7] A.D. Martin, R.G. Roberts, M.G. Ryskin, and W.J. Stirling, Eur. Phys. J. C **2**, 287 (1998).
[8] M.S. Chanowitz, Phys. Lett. B **352**, 376 (1995).
[9] Z. Kunszt and F. Zwirner, Nucl. Phys. **B385**, 3 (1992).
[10] R. Kinnunen and A. Nikitenko, CERN-CMS Note 1997/106. It seems that the estimates here can be improved changing some cuts.
[11] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 3585 (1997).
[12] R. Kinnunen (private communication).
[13] T. Han, A.S. Turcot, R.-J. Zhang, Phys. Rev. D **59**, 093001 (1999).
[14] J.F. Gunion *et al.*, Davies University Report No. UCD-97-5, 1997, hep-ph/9703330, and references therein.
[15] I. F. Ginzburg, M. Krawzcyk, and P. Olsen (in preparation).