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Consequences of the extra SM families on the Higgs boson production at Fermilab Tevatron and CERN LHC

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The latest electroweak precision data allow the existence of additional chiral generations in the standard model. We study the influence of extra generations on the production of the standard model Higgs boson at hadron colliders. Because of the enhancement of the gluon fusion channel, the "golden mode" becomes more promising even at the upgraded Fermilab Tevatron. Furthermore, the formation of the fourth family quarkonia with the subsequent $\eta\to Zh$ decay introduces an additional tool for investigation of Higgs boson properties.

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Two years ago, the existence of extra standard model (SM) generations seemed to be "excluded" by precision electroweak data [1]. However, with the latest electroweak data, the situation has changed. In a recent paper [2], it was shown that the quality of the fit for one new generation is as good as for zero new generations; moreover, two and even three partially heavy generations are allowed when neutral fermions are relatively light, $m_N\approx 50$ GeV. Using CERN e^+e^- collider LEP2 data for the process $e^+e^-\to Z^\star\to N\bar{N}\gamma$ one can exclude three partially heavy generations which contain such a light N at a level of 3σ while one or even two such generations may exist [3]. Then, according to [4] a single extra chiral family with a constrained spectrum is consistent with precision data without requiring any other new physics source, and the precision bound on the SM-like Higgs boson mass is significantly relaxed in the presence of an extra relatively light chiral family, namely, a SM Higgs boson mass up to about 500 GeV is allowed.

Direct searches for new leptons (N,L) and quarks (u_4,d_4) lead to the following lower bounds on their masses [5]: $m_L>92.4$ GeV, $m_N>45$ GeV (Dirac), $m_N>39.5$ GeV (Majorana), $m_{d_4}>199$ GeV (neutral current decays), $m_{d_4}>128$ GeV (charged current decays).

It is known that the SM does not predict the number of generations. In the democratic mass matrix approach, the SM is extended to include extra generations (see [6] and references therein).

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

$$p\bar{p}\to ggX\to hX. \tag{1}$$

To the lowest order, the cross section is given by

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

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^2 $(=m_h^2)$ 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 [7]

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

The expression for the amplitude $A_Q$can be found in [7]. The Yukawa coupling is given by $g_Q=m_Q/v$, where $v=246$ 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 because the scale of the corrections to Yukawa inter-

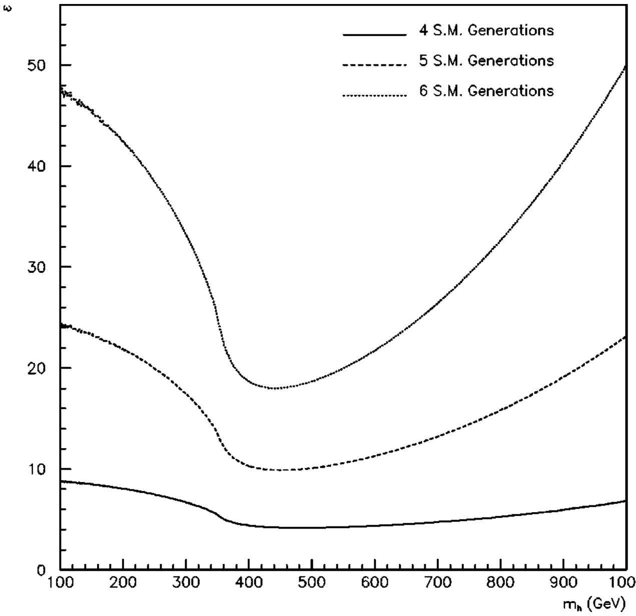

FIG. 1. Enhancement factor ϵ as a function of Higgs boson mass, where quarks from extra generations are assumed to be infinitely heavy.

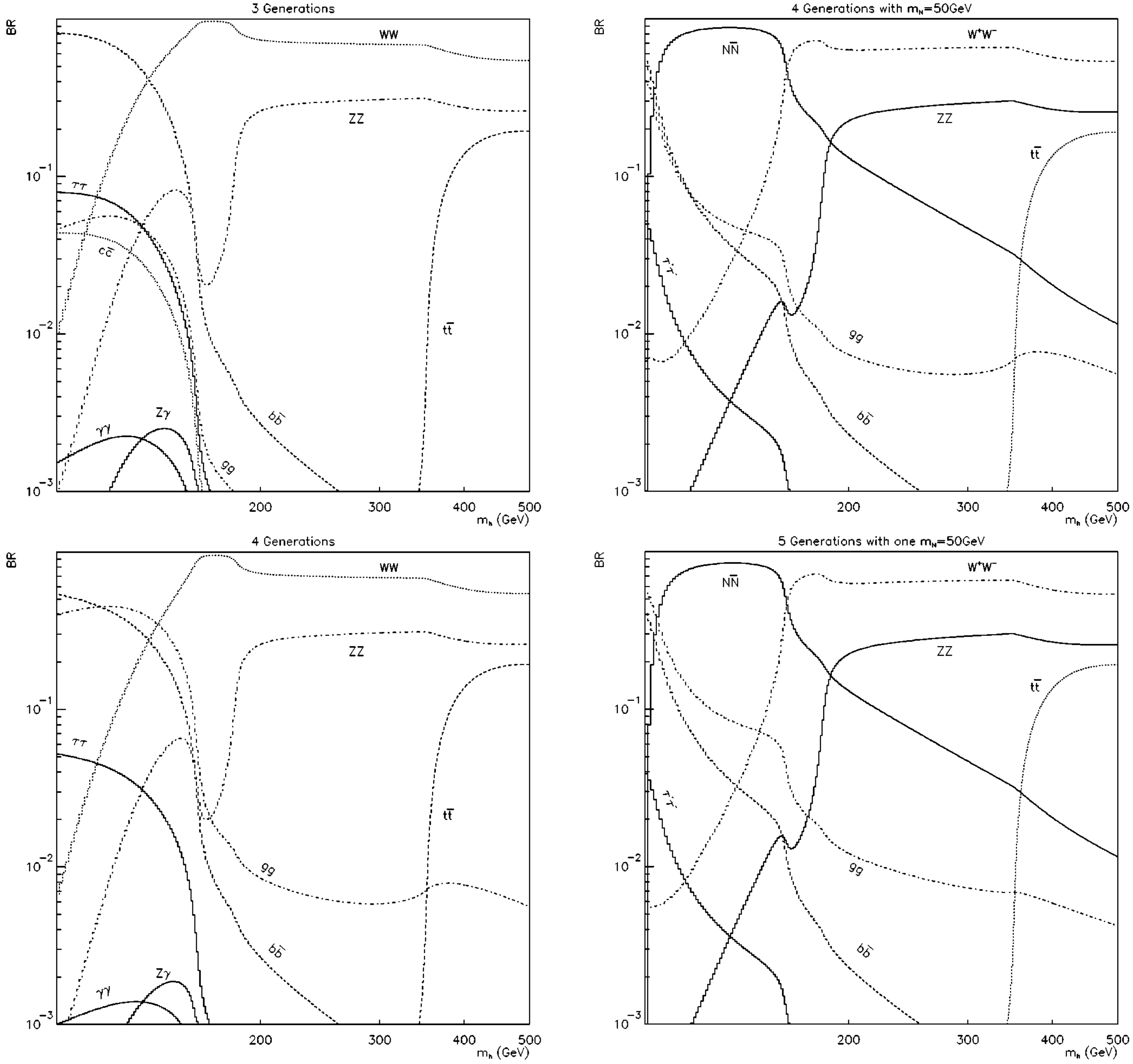

FIG. 2. Branching ratios of the main decay modes of the SM Higgs boson.

actions 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 up to $m_Q \approx 3$ TeV [8].

Quarks from extra generations contribute to the loop-mediated process in Higgs boson production $gg \to h$ at hadron colliders resulting in an enhancement of σ_0 by a factor of ϵ. It is obvious that in the infinitely heavy quark mass limit [9], the expected enhancement factors are $\epsilon = 9$, 25, and 49 in the case of one, two, and three extra generations, respectively. In Fig. 1 we plotted ϵ as a function of m_h, assuming quarks from extra generations to be infinitely heavy.

Extra generations will also effect $h \to \gamma\gamma$, $Z\gamma$ decay widths. In addition, if $m_h > 2m_N$ a new channel, namely $h \to N\bar{N}$, appears. Branching ratios of the main decay modes of the Higgs boson are plotted in Fig. 2 for zero, one, and two extra SM generations. In our calculations, we use [7] with minor modifications due to extra SM generations. According to [10], extra generations will give negative corrections to the hZZ vertex. Since the same corrections take place also for the hWW vertex, this effect can be neglected for $m_h > 150$ GeV where the $h \to WW^{(\star)}$ channel is dominant. For $m_h < 150$ GeV these corrections can be neglected for relatively light extra generations ($m_Q < 300$ GeV).

In this study, we concentrate on the golden mode $h \to ZZ^{(\star)} \to 4l$, where $l = e, \mu$. In Table I we present a production cross section for golden events in the cases of three, four, five, and six SM generations at the Fermilab Tevatron with $\sqrt{s} = 2$ TeV. The cross sections for the CERN Large Hadron Collider (LHC) with $\sqrt{s} = 14$ TeV are given in Table II. In our calculations we use PYTHIA 6.2 [11] with the

TABLE I. The production cross sections in fb for golden events at Tevatron. The asterisk denotes that the calculations are performed assuming one neutrino with $m_N=50$ GeV.

m_h (GeV)	SM-3	SM-4	SM-4*	SM-5*	SM-6*
100	0.003	0.019	0.019	0.040	0.051
110	0.010	0.055	0.014	0.036	0.060
120	0.030	0.157	0.023	0.061	0.108
130	0.061	0.332	0.041	0.108	0.194
140	0.085	0.500	0.064	0.170	0.309
150	0.086	0.577	0.098	0.262	0.480
160	0.036	0.283	0.114	0.307	0.571
170	0.016	0.128	0.092	0.249	0.476
180	0.033	0.271	0.213	0.578	1.103
190	0.115	0.932	0.787	2.129	4.084
200	0.116	0.926	0.805	2.176	4.173
220	0.088	0.686	0.617	1.659	3.178
240	0.068	0.511	0.469	1.254	2.396
260	0.052	0.383	0.357	0.948	1.808
300	0.047	0.314	0.300	0.779	1.474
350	0.037	0.201	0.195	0.481	0.889
400	0.027	0.117	0.114	0.268	0.484
450	0.019	0.081	0.080	0.189	0.341
500	0.016	0.066	0.065	0.157	0.290

TABLE II. The production cross sections in fb for golden events at LHC. The asterisk denotes that the calculations are performed assuming $m_N=50$ GeV.

m_h (GeV)	SM-3	SM-4	SM-4*	SM-5*	SM-6*
100	0.19	1.09	1.09	2.26	2.89
110	0.64	3.48	0.92	2.32	3.83
120	1.93	10.13	1.52	3.96	6.95
130	4.55	24.74	3.04	8.04	15.37
140	6.57	38.60	4.95	13.17	23.91
150	7.16	47.77	8.17	21.77	39.81
160	3.31	26.10	10.61	28.39	52.61
170	1.61	13.10	9.45	25.60	48.94
180	3.58	29.02	22.85	61.88	118.16
190	12.80	102.82	87.31	235.53	453.28
200	14.40	114.45	99.14	269.00	517.89
220	13.30	102.70	92.51	249.69	479.23
240	12.40	93.60	85.99	230.41	440.72
260	11.10	80.85	75.70	201.26	383.32
300	9.60	64.09	61.08	158.87	298.71
350	9.88	53.42	51.68	127.54	234.81
400	8.30	36.30	35.55	83.25	149.36
450	6.04	25.26	24.92	58.59	106.38
500	4.23	17.64	17.43	42.03	77.52

CTEQ5L parton distribution [12] and have normalized our signal cross section to include next leading order (NLO) QCD corrections [13].

The most important background is the pair production of Z bosons, $p\overline{p}(pp)\rightarrow ZZ^{(\star)}X$ $(Z\rightarrow l^+l^-)$, which has $\sigma\approx 8$ fb at Tevatron and $\sigma\approx 45$ fb at LHC. Since the Higgs boson width grows rapidly with m_h, a variable mass window of width σ_m (given by the convolution of the Higgs boson decay width Γ_h and of the experimental resolution estimated to be 2% of the Higgs boson mass),

$$\sigma_m=\sqrt{\left(\frac{\Gamma_h}{2.36}\right)^2+(0.02m_h)^2}, \tag{4}$$

is used in order to estimate the numbers of signal and background events. In this case, the acceptance for signal events is 90% in a mass window of $\pm 1.64\sigma_m$around m_h. The integral luminosities needed to achieve a 3σ (5σ) significance level of Higgs boson observation at Tevatron and LHC are shown in Fig. 3 (Fig. 4). In our calculations we assume a rather conservative value of 25% for the overall acceptance in four lepton final states, and the integrated luminosities to achieve the desired statistical significances are obtained using Poisson statistics.

From Fig. 3 one can see that the Higgs boson with mass around 150 and 200 GeV will be observed at upgraded Tevatron with $L_{int}=30$ fb^{-1} if the fourth SM family exists. In this case, the Higgs boson with $110<m_h<500$ GeV will be seen at LHC via the golden mode even at low luminosity of $L_{int}=10$ fb^{-1}. In the case of partially heavy extra generations, $m_N=50$ GeV, Higgs boson with mass $180<m_h<350$ GeV ($170<m_h<450$ GeV) will be observed at a 3σ level at an upgraded Tevatron if there are five (six) SM generations. In other words, the Tevatron can exclude two (three) extra generations at 3σ level if the Higgs boson mass lies between 180 (170) GeV and 350 (450) GeV and the golden mode is not seen.

Figure 4 shows that two extra generations can be excluded at 5σ level by upgraded Tevatron (before the LHC starts) if Higgs boson mass lies between 180 and 250 GeV. Three extra generations will be excluded for $175<m_h<350$ GeV. On the other hand, LHC with moderate integrated luminosity of 10 fb^{-1} will exclude (or confirm) degenerate extra SM generations via the golden mode practically for the whole region of Higgs boson masses. In the case of partially heavy extra generations and $m_h<140$ GeV, higher integrated luminosity (up to 100 fb^{-1}) is needed.

A nondegenerate multiplet of heavy extra fermions will affect the parameter ρ [1]. For example, assuming degenerate fourth generation quarks, one can easily obtain a condition for nondegenerate leptons:

$$1+x^2-\frac{4x^2}{1-x^2}\ln\frac{1}{x}\leqslant\frac{3\times 10^4}{m_N^2}, \tag{5}$$

where $x=m_L/m_N$. Therefore, fourth generation charged lepton mass limits are $m_L\leqslant 208$ GeV and $350\leqslant m_L\leqslant 650$ GeV for $m_N=50$ GeV and $m_N=500$ GeV, respectively.

According to [2] in the case of partially heavy extra generations with $m_N\simeq 50$ GeV, the preferable mass value of the fourth generation charged lepton is around 130 GeV. For the Higgs mass larger than $2m_L$ the decay channel $h\rightarrow L^+L^-$ will contribute to Higgs decay and branchings. Concerning

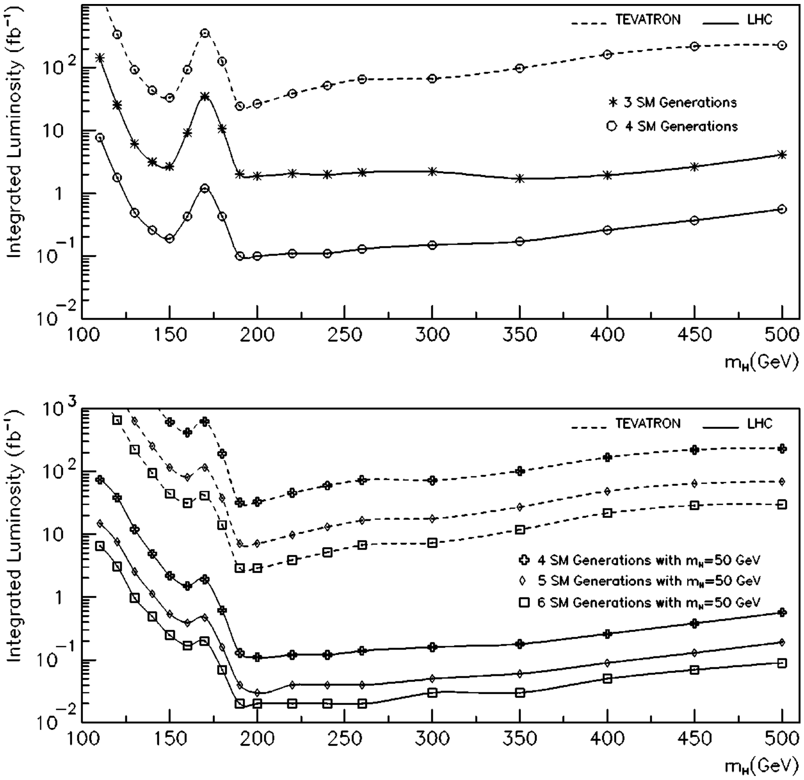

FIG. 3. The luminosity needed to achieve 3σ significance for the golden mode at Tevatron and LHC.

the golden mode this contribution will decrease the branching ratio approximately 5%. Our results will not change for $m_h < 2m_L$ and slightly change for $m_h > 2m_L$.

An additional opportunity for the investigation of Higgs boson properties at hadron colliders appears if the quarks from extra generations form a quarkonia. The condition for forming $(Q\overline{Q})$ quarkonia states with new heavy quarks is [14]

$$m_Q \leq (125\ \text{GeV}) |V_{Qq}|^{-2/3}, \tag{6}$$

where Q and q denote new heavy quarks and known quarks,

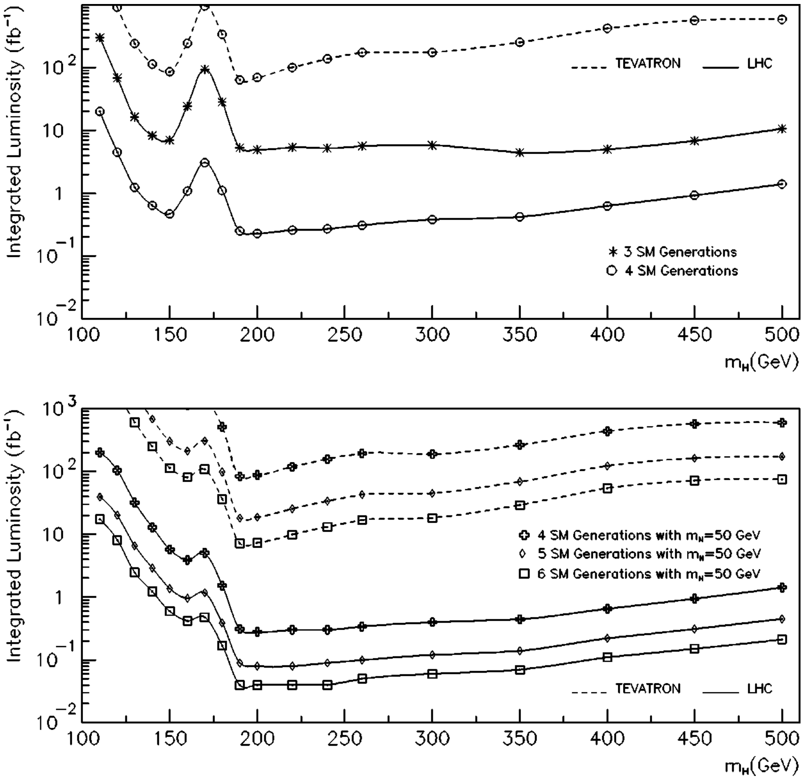

FIG. 4. The luminosity needed to achieve 5σ significance for the golden mode at Tevatron and LHC.

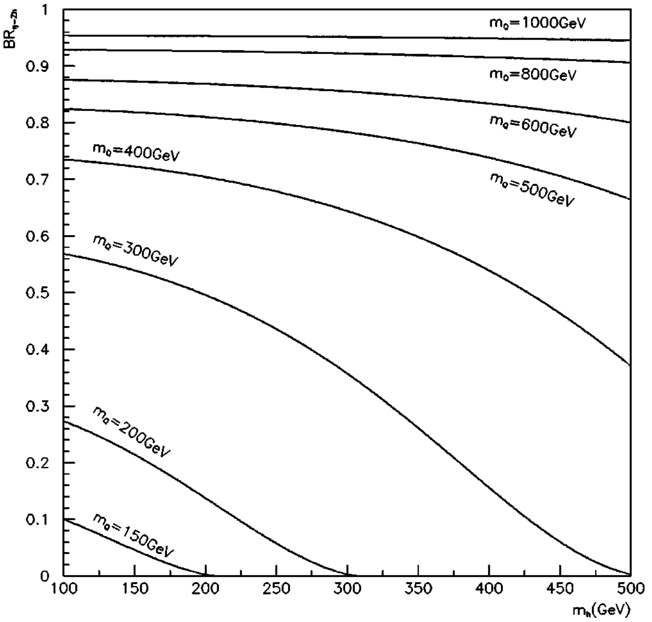

FIG. 5. Branching ratio for the process $\eta\to Zh$.

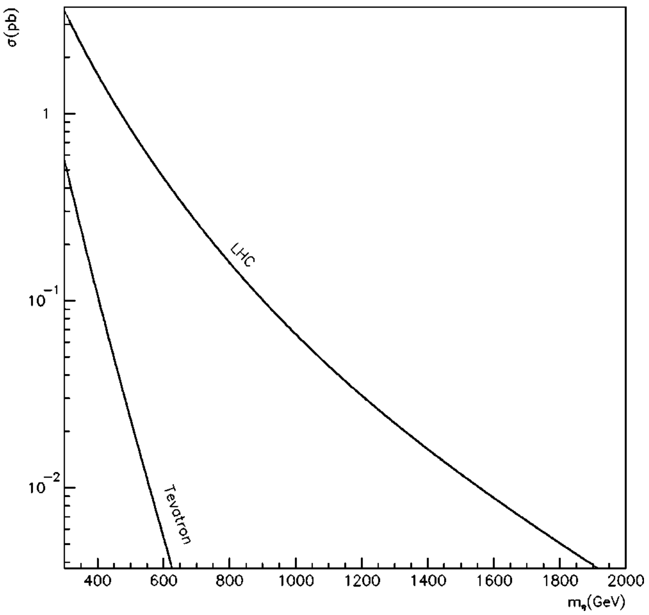

FIG. 6. Production cross section for η quarkonia.

respectively; $V_{Qq}$is the corresponding Cabibbo-Kobayashi-Maskawa (CKM) matrix element. In the case of four SM generations this condition is satisfied by parametrization given in [15,16]. The Higgs boson will be produced via the subprocess $gg\to\eta(Q\overline{Q})\to Zh$. In Fig. 5 we plot the branching ratio $BR(\eta\to Zh)$ as a function of m_h for different values of the masses of the fourth SM generation quarks. Here, we use corresponding formulas from [17] in the framework of the Coulomb potential model. Production cross sections for η quarkonia at Tevatron and LHC are plotted in Fig. 6. At Tevatron, it is obvious that the considered mechanism is a matter of interest only for relatively light new quarks. For example, if $m_\eta = 400$ GeV and $m_h = 150$ GeV, one expects 600 Zh events at $L_{int} = 30$ fb^{-1}. This channel seems to be much more promising at LHC: with the same statements we expect more than 3×10^4 Zh events for $L_{int}=100$ fb^{-1}. More comprehensive results on the subject, including the effects of specific mass patterns on quarkonia decays, will be reported elsewhere [18].

In conclusion, existence of the extra generations will significantly affect Higgs boson production at hadron colliders. In this paper we examined the golden mode $h\to ZZ^{(\star)}\to 4l$. Of course, the same statement is valid for other decay channels, too. For example, the modes $h\to WW^{(\star)}\to l\nu jj$ and $h\to WW^{(\star)}\to l\nu\overline{l}\nu$ are very promising at Tevatron for $135 < m_h < 180$ GeV [19,20]. Another promising channel for Higgs boson production is the formation of pseudoscalar η quarkonia with subsequent decay $\eta\to Zh$. Finally, both the upgraded Tevatron and LHC will give the opportunity to determine the actual number of SM generations.

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