Window on the Higgs boson: Fourth generation b' decays reexamined

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Direct and indirect searches of the Higgs boson suggest that 113 GeV$\lesssim m_H \lesssim$170 GeV is likely. With the CERN LEP era over and the Fermilab Tevatron run II search via $p\bar{p}\to WH+X$ arduous, we reexamine a case where WH or $ZH+$ jets could arise via strong $b'\bar{b'}$ pair production. In contrast with ten years ago, the tight electroweak constraint on t'-b' (hence t'-t) splitting reduces FCNC $b'\to bZ$, bH rates, making $b'\to cW$ naturally competitive. Such a "cocktail solution" is precisely the mix that could evade the CDF search for $b'\to bZ$, and the b' may well be lurking below the top quark. In light of the Higgs program, this two-in-one strategy should be pursued.

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The search for the standard model (SM) Higgs boson is the holy grail of present day high energy physics. The global electroweak (EW) fit, assuming the SM, gives [1] $m_H = 62^{+53}_{-39}$ GeV, or $m_H < 170$ GeV at 95% confidence level (C.L.). Together with the direct search limit [2] of $m_H > 113.3$ GeV at the CERN e^+e^- collider LEP, the Higgs boson seems "just around the corner." Surely enough, just before LEP shutdown, there were exciting hints [3,4] for $m_H \simeq 115$ GeV, and the shutdown was postponed by a month. The extra data collected did not greatly strengthen the case, but it was argued that a further run with about 200 pb^{-1} per experiment at $\sqrt{s}=208.2$ GeV might lead to a 5σ discovery [4]. Unfortunately, the wish was not granted, fearing it might jeopardize the schedule for the CERN Large Hadron Collider (LHC)—the main goal of which is the Higgs boson. As LEP is now closed, we have to wait for run II at the Fermilab Tevatron which starts in 2001, or the turn on of LHC in 2005.

Not surprisingly, the Higgs boson search in the 110–190 GeV range is now one of the prime objectives for Tevatron run II. The main process $q\bar{q}\to V^*\to VH(V=W, Z)$ followed by $H\to b\bar{b}$ and leptonic V decays [5] suffer from a small electroweak cross section: $\sigma(q\bar{q}\to W^{\pm}H)\simeq 0.3$ to 0.002 pb at run II energies for 100 GeV$\leqslant m_H \leqslant$200 GeV. A very recent study [6] claims that, with suitable cuts that exploit the kinematic differences between signal versus background, a statistically significant signal can be extracted if one has *sufficient* luminosity. However, with the 2 fb^{-1} expected by the end of 2002, one can barely rule out the LEP hint of $m_H \sim 115$ GeV at 95% C.L., while, to have a 5σ discovery, one would need 10–15 fb^{-1}. Since this seems to be the amount of data one may realistically be expected before the start of LHC physics, the Tevatron path to the Higgs boson search is arduous.

It is clear that a premium should be placed on processes with higher cross sections (but manageable background) that could aid the Higgs search at the Fermilab Tevatron. In this paper we revisit a case [7] where the WH or ZH signatures arise from strong $p\bar{p}\to b'\bar{b'}+X$ production of sequential fourth generation b' pairs, followed by $b'\to cW$, bZ, bH decays that are all of comparable strength. The effective $p\bar{p}\to WH+X$ or $ZH+X$ cross sections could be at a few pb^{-1}.

The main new observations we make are as follows. EW precision data give stringent constraint on $m_{t'}-m_{b'}$ [8]. For $m_{b'}<m_t$, the t'-t splitting is considerably smaller than assumed in [7], and Glashow-Illiopoulos-Maiani (GIM) suppression of $b'\to bZ$, bH decays is more severe [9], hence the $b'\to cW$ channel becomes more prominent. Furthermore, recent direct search by Collider Detector at Fermilab (CDF) [10] has ruled out $b'\to bZ$ decay for $m_{b'}<200$ GeV if $\mathcal{B}(b'\to bZ)=100\%$, but may be evaded if $b'\to cW$ (but *not* $b'\to bH$) dilutes $\mathcal{B}(b'\to bZ)$. Note that a dominant but not predominant [11] $b'\to cW$ decay could help explain some irregularities of the $t\bar{t}$ signal. We argue that the Cabibbo-Kobayashi-Maskawa (CKM) mixing element $V_{cb'}\sim 10^{-3}$ is plausible, and is just the right amount to allow a "cocktail solution" of $b'\to cW$, bZ, and bH that can evade the CDF bound. This offers new possibilities for the Higgs search up to $m_H<m_{b'}-m_b$.

It is known that, if the b' quark exists and $m_{b'}<m_t$, it may decay in unusual ways: the charged current (CC) $b'\to tW$ decay is kinematically forbidden, the $b'\to cW$ decay is highly Cabibbo suppressed, hence flavor changing neutral current (FCNC) $b'\to b$ transitions would likely dominate [12]. The suggestion was pursued [8] by collider experiments at KEK TRISTAN, SLAC Linear Collider (SLC), LEP, and Tevatron, with LEP setting the unequivocal bound of $m_F > m_Z/2$ on all new fermions F that couple to the Z. The D0 Collaboration [13] excluded the range $m_Z/2<m_{b'}<m_Z+m_b$ by a null search for $b'\to b\gamma$ and $b'\to bg$. We remark that, with $N_\nu \cong 3$ as measured by SLC and LEP since 1989, the existence of a sequential fourth generation is not strongly motivated (for a recent review, see Ref. [9]). However, the observation of neutrino oscillations does imply an enlarged neutrino sector. A more important motivation comes from the intense competition for the Higgs search as just stated.

For $m_{b'}>m_Z+m_b$, the decay $b'\to bZ$ [12] is expected to dominate over the other FCNC decay processes, except for $b'\to bH$ [7,14] if $m_{b'}>m_H+m_b$ also. Recently, the CDF Collaboration [10] gave an upper limit on the product $\sigma(p\bar{p}\to b'\bar{b'})\times[\mathcal{B}(b'\to bZ)]^2$ as a function of $m_{b'}$, which excludes at 95% C.L. the range 100 GeV$<m_{b'}<$199 GeV if $\mathcal{B}(b'\to bZ)=100\%$. For $\mathcal{B}(b'\to bH)\neq 0$, so long that $\mathcal{B}(b'\to bZ)$ does not vanish, the CDF bound still largely applies since hadronic final states of $b' \to bZ$ and bH are rather similar, and in fact, the bH mode has better b-tagging efficiency. What CDF apparently did not pursue in any detail is the $b' \to cW$ possibility. Clearly the b-tagging efficiency for cW mode would be much worse than bZ or bH. Since b tagging is an important part of the CDF $b' \to bZ$ search strategy, one may evade the CDF search if $\mathcal{B}(b' \to cW)$ is sizable.

Precision EW data provide stringent constraints on the fourth generation: there is a 2.5σ discrepancy between $S = -0.07 \pm 0.11$ [8] and $S = 2/3\pi \cong 0.21$ for a heavy degenerate fourth generation. However, using exact expressions for gauge boson self-energies for $m_{b'} = m_{t'} = 150$ GeV, $m_E = 200$, and $m_N = 100$ GeV (E, N are fourth generation charged and neutral leptons), one finds [9] $S \approx 0.11$ instead of 0.21, and the discrepancy drops below 2σ. Given the excellent agreement between SM and EW data, a discrepancy at this level in a few measurables is not tantalizing. For $S = 0.2$, the 2σ upper bound on T is approximately 0.2 ($\delta\rho \approx 0.0015$). Using the analytic expression of $\delta\rho$ [8], we find $\Delta_Q = |m_{t'} - m_{b'}| \leqslant 60$ GeV and $\Delta_L = |m_E - m_N| \leqslant 104$ GeV, which can be weakened if we just take the $\delta\rho$ constraint. At the 2σ level and for $m_H \lesssim 1$ TeV, one finds [8] $\rho_0 = 0.9998^{+0.0034}_{-0.0012}$ or $-0.0014 < \delta\rho < 0.0032$, hence, $\Delta_Q \leqslant 86$ GeV and $\Delta_L \leqslant 148$ GeV.

In the following, we shall take the conservative range $\Delta_Q = |m_{t'} - m_{b'}| \leqslant 60$ GeV. For $m_{b'} < m_t$, this implies that the t'-t splitting is far less [9] than assumed ten years ago [7], and FCNC $b' \to bZ$, bH decays are more GIM suppressed. Thus, the CC $b' \to cW$ mode, though highly Cabibbo suppressed, can be more competitive. Note that $m_t \sim m_{b'} \sim m_{t'}$ would *in general imply near maximal mixing*, or $V_{tb'} \simeq V_{t'b} \simeq 1/\sqrt{2}$.

What is the "natural" strength of $V_{cb'}$? We cannot know for certain, but we give two plausible arguments here. Since each involves two generation jumps, perhaps $V_{cb'} \sim V_{ub}$, or one could guess that $V_{cb'} \sim m_s/m_{b'}$ since $V_{cb} \sim m_s/m_b$ [15]. Both cases suggest $V_{cb'} \sim 10^{-3}$, just what is needed to make $b' \to cW \sim b' \to bZ$ in rate, as we will show. Thus, EW precision data, while not strongly supporting the existence of a fourth generation, together with the hierarchical pattern of quark masses and mixings, *lead naturally to the cocktail solution* of $b' \to cW \sim bZ \gtrsim bH$ that can evade the CDF search for $b' \to bZ$. This is in contrast to previous expectations [7,12,14] that $b' \to cW$ would be considerably below $b' \to bZ, bH$ decays. We remark here that comparison of $b' \to cW$ and $b' \to bZ$ were made recently in Ref. [9], but not in conjunction with $b' \to bH$; the importance of the latter mode was emphasized in Ref. [16] in the context of evading CDF bound on $b' \to bZ$, but a detailed discussion of the cocktail solution was not given.

We perform a one-loop calculation of $b' \to bZ$, bH using the FEYNARTS and FEYNCALC [17] packages, where the full set of diagrams (see Fig. 1 of [7]) are generated and computed, and we use the *FF* package [18] for our numerical analysis. We keep both external and internal masses, except the m_b (and m_c, m_u) which can be neglected to a good approximation. Several analytic and numerical checks are carried out following [7,12,14], with complete agreement found. Further numerical checks against $t \to cH$, cZ [19,20] in the SM again give full agreement. In the following, we take 115 GeV$< m_H <$170 GeV, $m_t = 175$ GeV, $\Delta_Q = m_{t'} - m_{b'} \leqslant 60$ GeV, and $r_{\rm CKM} \equiv |V_{cb'}/V_{tb}V_{tb'}|$ in the 10^{-3} range.

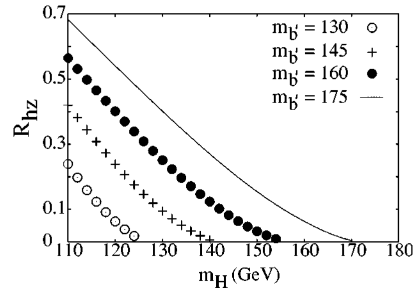

FIG. 1. The ratio $R_{hz} = \Gamma(b' \to bH)/\Gamma(b' \to bZ)$ vs m_H for several $m_{b'}$ values and $\Delta_Q = m_{t'} - m_{b'} = 55$ GeV.

The CKM factors $|V_{t'b}V_{tb'}| \approx |V_{tb}V_{tb'}|$ actually cancel in the ratio $R_{hz} = \Gamma(b' \to bH)/\Gamma(b' \to bZ)$, and it depends on $m_{b'}$, $m_{t'}$, and m_H. In Fig. 1, we show R_{hz} vs m_H for several $m_{b'}$ values with Δ_Q fixed at 55 GeV. It is clear that, for light m_H and relatively large $m_{b'}$, R_{hz} can be of order 0.5–1, which means $b' \to bH$ is competitive with $b' \to bZ$ so long that it is phase space allowed [7].

For the actual branching ratios [21],

$$\mathcal{B}(b' \to \{cW, bZ, bH\}) = \Gamma(b' \to \{cW, bZ, bH\})/\Gamma_{b'},$$

we assume $\Gamma_{b'} = \Gamma(b' \to cW) + \Gamma(b' \to bZ) + \Gamma(b' \to bH)$. Since $\Gamma(b' \to cW) \propto |V_{cb'}|^2$ while $\Gamma(b' \to \{bZ, bH\}) \propto |V_{tb}V_{tb'}|^2$, the branching fractions depend critically on $r_{\rm CKM}$. In Fig. 2, we illustrate $\mathcal{B}(b' \to \{cW, bZ, bH\})$ vs $r_{\rm CKM} \equiv |V_{cb'}/V_{tb}V_{tb'}|$ for $m_{b'}$, m_H, $\Delta_Q = 130$, 115, 20 GeV and 160, 130, 40 GeV. For $r_{\rm CKM} > 3 \times 10^{-3}$, $\mathcal{B}(b' \to cW)$

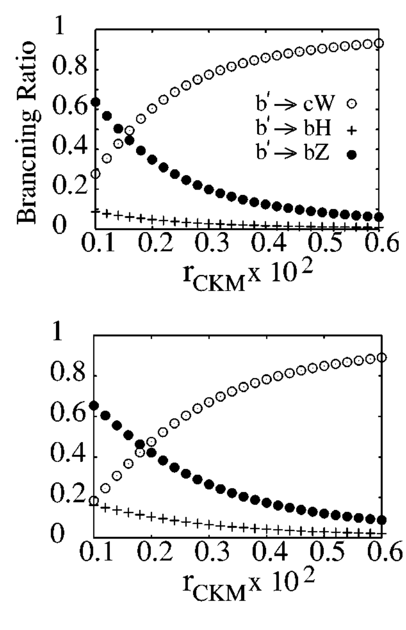

FIG. 2. $\mathcal{B}(b' \to \{cW, bZ, bH\})$ vs $r_{\rm CKM}$ for $m_{b'}$, m_H, $\Delta_Q = 130$, 115, 20 GeV (upper) and 160, 130, 40 GeV (lower).

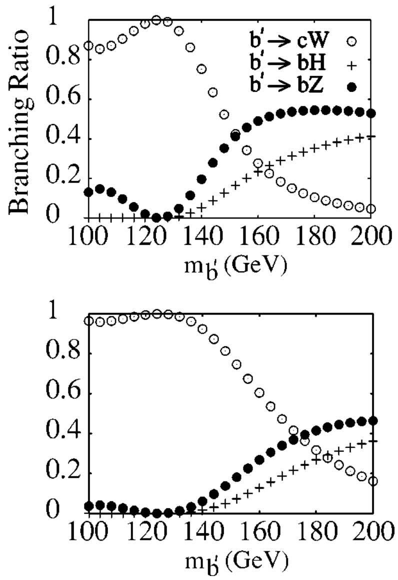

FIG. 3. $\mathcal{B}(b'\to\{cW,bZ,bH\})$ vs $m_{b'}$ with m_H, $\Delta_Q=115$, 50 GeV for $r_{\rm CKM}=0.002$ (upper), 0.004 (lower).

$>80\%$ which would unlikely survive the standard top search. On the other hand, for $r_{\rm CKM}\approx(1-3)\times10^{-3}$, we find that $\mathcal{B}(b'\to bZ)\sim64$–20 % (65–26 %), $\mathcal{B}(b'\to cW)\sim28$–78 % (18–67 %), and $\mathcal{B}(b'\to bH)\sim8.7$–2.7 % (16–6.5 %), hence $b'\to bZ$ and cW are comparable, and may allow the b' quark to evade the CDF $b'\to bZ$ search.

We illustrate, in Fig. 3, $\mathcal{B}(b'\to\{cW,bZ,bH\})$ vs $m_{b'}$ for two values of $r_{\rm CKM}$ with $\Delta_Q=50$ GeV held fixed. For 100 GeV$<m_{b'}<135$ GeV hence 150 GeV$<m_{t'}<185$ GeV, $b'\to bZ$, bH are suppressed by small t'-t splitting, and $b'\to cW$ predominance can be seen from the left-hand side of Fig. 3. Away from this range where the GIM mechanism is severe, $\mathcal{B}(b'\to cW)$ decreases as we increase $m_{b'}$ while $\mathcal{B}(b'\to bZ)$ and $\mathcal{B}(b'\to bH)$ grow. It appears from this plot that for $m_{b'}>150$ GeV, the three decays we are considering have the same order of magnitude with no single mode fully dominating. For example, for $r_{\rm CKM}\simeq0.004$ and $m_{b'}$, $m_H=170$, 115 GeV, the modes $cW{:}bZ{:}bH\simeq2{:}2{:}1$ in rate.

To illustrate that this scenario can evade the CDF search for $b'\to bZ$, we reproduce Fig. 2 of Ref. [10] in our Fig. 4. The dotted curve is the predicted cross section $\sigma(p\bar{p}\to b'\bar{b}')$ at 1.8 TeV, the solid curve corresponds to the 95% C.L. upper limit on $\sigma(p\bar{p}\to b'\bar{b}')\times[\mathcal{B}(b'\to bZ)]^2$. From the crossing of the two curves, CDF rules out $m_{b'}\lesssim200$ GeV if $\mathcal{B}(b'\to bZ)=100\%$. Our results are shown as open and black circles for $r_{\rm CKM}=0.001$ and 0.002, respectively. For larger $r_{\rm CKM}$ values, they drop out from the plot. We have held the splitting $\Delta_Q=m_{t'}-m_{b'}=50$ GeV fixed. This leads to the valley around $m_{b'}\sim125$ GeV, caused by $m_{t'}\simeq m_t$. Very low cross sections in the $b'\to bZ$ mode can evade the search of Ref. [10], but it would likely be ruled out by past top searches since $b'\to cW$ is predominant [11]. The reverse situation illustrates the power of the CDF study: the region GeV140$<m_{b'}<160$ GeV for $r_{\rm CKM}=0.001$ is ruled out because $\mathcal{B}(b'\to bZ)$ is predominant. However, it is clear that the theoretical prediction is smaller than the 95% C.L.

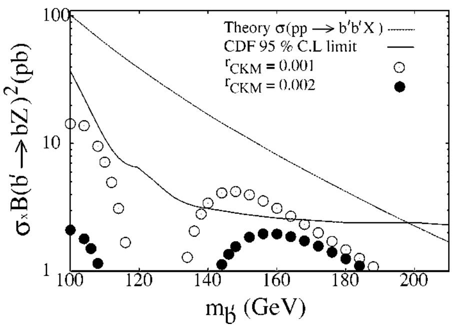

FIG. 4. Comparison of CDF search for $b'\to bZ$ and our scenario with $m_H=115$, $\Delta_Q=50$ GeV. The dotted curve is the predicted $\sigma(p\bar{p}\to b'\bar{b}')$ at 1.8 TeV, while the solid curve is the 95% C.L. upper limit on $\sigma(p\bar{p}\to b'\bar{b}')\times[\mathcal{B}(b'\to bZ)]^2$ [10]. The open (black) circles correspond to $\mathcal{B}(b'\to bZ)$ as computed in our model for $r_{\rm CKM}=0.001$ (0.002).

upper limit of CDF for a broad range of parameter space, as illustrated by the $r_{\rm CKM}=0.002$ case for $m_{b'}\gtrsim140$ GeV. This is consistent with Figs. 2 and 3. We note that a light $m_{b'}$ around 110 GeV is still allowed, although this case would not help in the Higgs boson search.

We now compare the cross section for $p\bar{p}\to b'\bar{b}'\to(\bar{c}W)(bH)$ or $(\bar{b}Z)(bH)$ with the direct Higgs production mechanism $p\bar{p}\to WH$, ZH. For illustration and clarity, we recapitulate our numerical results from Fig. 2 for run II energies (2 TeV) at the Fermilab Tevatron in Table I. The cross sections for $p\bar{p}\to WH$, ZH and $p\bar{p}\to b'\bar{b}'$ are taken from [22] and [23], respectively. It is clear that the cross sections for $WH\bar{c}b$ or $ZHb\bar{b}$ are larger than the corresponding ones for direct associated WH or ZH production, unless $r_{\rm CKM}=|V_{cb'}/V_{tb}V_{tb'}|$ becomes considerably larger than few $\times10^{-3}$, or when $b'\to bH$ is kinematically suppressed. Thus, our suggestion should be welcome news for the Higgs boson search program at the Fermilab Tevatron run II. In any case, the search for b' below the top should continue by taking into account the $b'\to cW$ mode. By so doing, one may uncover the Higgs boson.

Curiously, there are some indications that the cocktail solution of $b'\to cW$, bZ, and bH should be taken seriously and hence revisited even for run I data. It is known that the $t\bar{t}$ events at the Fermilab Tevatron have some irregularities

TABLE I. Comparison of $\sigma(p\bar{p}\to b'\bar{b}'\to WH\bar{c}b,\ ZHb\bar{b})$, and $\sigma(p\bar{p}\to WH,\ ZH)$ (in pb) for $m_{b'}$, m_H, Δ_Q (in GeV) and $r_{\rm CKM}\equiv|V_{cb'}/V_{tb}V_{tb'}|$ taken from Fig. 2.

$m_{b'}$	m_H	Δ_Q	$r_{\rm CKM}$	WH	$WH\bar{c}b$	ZH	$ZHb\bar{b}$
130	115	20	0.001	0.20	0.65	0.11	1.49
130	115	20	0.002	0.20	0.78	0.11	0.45
130	115	20	0.004	0.20	0.39	0.11	0.06
160	130	40	0.001	0.13	0.60	0.07	2.14
160	130	40	0.002	0.13	1.00	0.07	0.88
160	130	40	0.004	0.13	0.68	0.07	0.15

that are, though not yet statistically significant, somewhat tantalizing. First, *both* CDF and D0 [24] report a lower $m_t \simeq 167$–168 GeV in the dilepton channel, where b tagging is not used. Second, for single lepton plus jets channel, D0 and CDF [25] are in good agreement on m_t, but the CDF cross section extracted from soft lepton tag (SLT) is almost twice as high from the displaced vertex (SVX) tag, with fitted m_t as low as 142 GeV. Third, the all hadronic study of CDF [26], which relies heavily on b tagging, gives $m_t \simeq 186$ GeV, the highest of all studies. Interestingly, if one demands two SVX-tagged b jets for single lepton plus jets sample, the fit following CDF dilepton procedure also gives a high mass of $m_t \simeq 182$ GeV [24].

For sake of illustration, we show that the combination $m_t \sim 175$ GeV and $m_{b'}$, $m_{t'} \sim 160$, 210 GeV, with $t,t' \to bW$ [27] and the cocktail solution of $b' \to cW \sim bZ > bH$, can account for these curiosities. For dileptons without b tagging, one largely probes $b\bar{b}W^+W^-$ for top and t', and $c\bar{c}W^+W^-$ for b'. One would get lower "m_t" and a somewhat larger cross section. For single lepton plus jets with SVX b-tag, one is less sensitive to $b'\overline{b'}$, thereby getting an average "m_t." However, applying SLT tag but no SVX tag, one is then sensitive to both b and c semileptonic decays with similar efficiencies, and one would be more sensitive to $b' \to cW$ decay which has a larger $b'\overline{b'}$ cross section and a lower fitted "m_t." For all hadronic final states since one demands an SVX b tag to suppress QCD background, one is more sensitive to $t,t' \to bW$ hence a higher "m_t" is found.

The pattern in cross sections could also be reflecting the presence of both b' and t' besides the top, as already stated in the larger SLT versus SVX tagged cross section. The dilepton and all hadronic cross sections are also somewhat larger than theory expectation of order 5 pb^{-1}. However, not much more can be said because of experimental errors at the run I level of statistics. One would also need detailed knowledge of experimental efficiencies. Although one cannot draw a definite conclusion, it may still be worthwhile even to reinvestigate the run I "$t\bar{t}$" data, keeping in mind the possibility of the cocktail solution: There may actually be charm jet content in $t\bar{t}$-like events. At run II, such a study would be imperative, for not only one would have the statistical power to distinguish, a more exciting Higgs boson search program could be at stake. One could be discovering the Higgs boson together with two new quarks.

We have shown in this analysis that, once the constraints from precision measurements are taken into account, $m_{b'} \sim m_{t'} \sim m_t$ could be the case. This suppresses FCNC $b' \to bZ$, bH decays so the CC $b' \to cW$ decay becomes important. It should be welcome since this is just what is needed to evade the CDF null search for $b' \to bZ$. In a rather plausible parameter space and if the GIM suppression of FCNC modes is not overly strict, one can have the cocktail solution of $b' \to cW \sim bZ > bH$, and there could be actual charm jet content of observed $t\bar{t}$ events. Such a signal should be considered for better scrutiny of top-like events, and might uncover the Higgs boson handily at the Fermilab Tevatron run II via $p\bar{p} \to \bar{c}bWH + X$ or $b\bar{b}ZH + X$ signatures.

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[1] B. Pietrzyk, in *30th International Conference on High Energy Physics* (ICHEP2000), edited by C. S. Lin and T. Yamanaka, (World Scientific, Singapore, 2000).
[2] P. Igo-Kemenes, plenary talk at ICHEP2000 [1].
[3] R. Barate *et al.*, Phys. Lett. B **495**, 1 (2000); M. Acciarri *et al.*, *ibid.* **495**, 18 (2000).
[4] See the LEP Higgs Working Group webpage, http://lephiggs.web.cern.ch/LEPHIGGS/
[5] A. Stange, W. Marciano, and S. Willenbrock, Phys. Rev. D **49**, 1354 (1994); **50**, 4491 (1994).
[6] M. Carena *et al.*, hep-ph/0010338, and references therein.
[7] W. S. Hou and R. G. Stuart, Phys. Lett. B **233**, 485 (1989); Phys. Rev. D **43**, 3669 (1991).
[8] Particle Data Group, D. E. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).
[9] P. H. Frampton, P. Q. Hung, and M. Sher, Phys. Rep. **330**, 263 (2000).
[10] T. Affolder *et al.*, Phys. Rev. Lett. **84**, 835 (2000).
[11] If $\mathcal{B}(b' \to cW) \cong 100\%$, then an old bound of 128 GeV on top search from the D0 Collaboration, then S. Abachi *et al.*, Phys. Rev. D **52**, 4877 (1995), is applicable to b' also.
[12] W. S. Hou and R. G. Stuart, Phys. Rev. Lett. **62**, 617 (1989); Nucl. Phys. **B320**, 277 (1989).
[13] S. Abachi *et al.*, Phys. Rev. Lett. **78**, 3818 (1997).
[14] B. Haeri, G. Eilam, and A. Soni, Phys. Rev. Lett. **62**, 719 (1989); Phys. Rev. D **41**, 875 (1990).
[15] K. S. Babu and R. N. Mohapatra, Phys. Rev. Lett. **64**, 2747 (1990).
[16] M. Sher, Phys. Rev. D **61**, 057303 (2000).
[17] J. Küblbeck, M. Böhm, and A. Denner, Comput. Phys. Commun. **60**, 165 (1990); R. Mertig, M. Böhm, and A. Denner, *ibid.* **64**, 345 (1991).
[18] G. J. van Oldenborgh, Comput. Phys. Commun. **66**, 1 (1991).
[19] B. Mele, S. Petrarca, and A. Soddu, Phys. Lett. B **435**, 401 (1998).
[20] G. Eilam, J. L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991); **59**, 039901(E) (1999).
[21] We take into account $b' \to tW^*$ for $175 < m_{b'} < 200$ GeV, but it is numerically insignificant.
[22] M. Spira, hep-ph/9810289.
[23] E. L. Berger and H. Contopanagos, Phys. Rev. D **57**, 253 (1998).
[24] F. Abe *et al.*, Phys. Rev. Lett. **80**, 2767 (1998); B. Abbott *et al.*, Phys. Rev. D **60**, 052001 (1999).
[25] F. Abe *et al.*, Phys. Rev. Lett. **82**, 271 (1999); S. Abachi *et al.*, *ibid.* **79**, 1203 (1997).
[26] F. Abe *et al.*, Phys. Rev. Lett. **79**, 1992 (1997).
[27] In our scenario or small t'-t splitting and large $V_{t'b}$, the t' quark also dominantly decays via bW mode.