Window on Higgs Boson: Fourth Generation $b'$ Decays Revisited

Abdesslam Arhrib and Wei-Shu Hou
Department of Physics, National Taiwan University, Taipei, Taiwan 10764, R.O.C.

Direct and indirect searches of the Higgs boson suggest that 113 GeV $\lesssim m_H \lesssim$ 170 GeV is likely. With the LEP era over and the Tevatron Run II search via $p\bar{p} \rightarrow WH + X$ arduous, we revisit a case where $WH$ or $ZH + j$ could arise via strong $b'\bar{b}'$ pair production. In contrast to 10 years ago, the tight electroweak constraint on $t'\bar{t}'$ (hence $t'\bar{t}$) splitting reduces FCNC $b' \rightarrow bZ$, $bH$ rates, making $b' \rightarrow cW$ naturally competitive. Such a “cocktail solution” is precisely the mix that could evade the CDF search for $b' \rightarrow bZ$, and the $b'$ may well be lurking below the top. 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 SM, gives $m_H = 62^{+53}_{-39}$ GeV, or $m_H < 170$ GeV at 95% confidence level (CL). Together with the direct search limit [4] of $m_H > 113.3$ GeV at LEP, the Higgs boson seems “just around the corner”. Surely enough, just before LEP shutdown, there were exciting hints [3] for $m_H \approx 115$ 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 5$\sigma$ discovery [4]. Unfortunately, the wish was not granted, fearing it might jeopardize the schedule for LHC — the main goal of which is the Higgs boson! As LEP is now closed, we have to wait for Run II at Tevatron which starts in 2001, or the turn on of LHC in 2005.

Not surprisingly, Higgs boson search in the 110–190 GeV range is now one of the prime objectives for Tevatron Run II. The main process, $q\bar{q} \rightarrow V^* \rightarrow VH (V = W, Z)$ followed by $H \rightarrow b\bar{b}$ and leptonic $V$ decays [3], suffers from a small electroweak cross section: $\sigma(q\bar{q} \rightarrow V^* \rightarrow VH) \simeq 0.3$ to 0.002 pb at Run II energies for 100 GeV $\lesssim m_H \lesssim$ 200 GeV. A very recent study [7] claims that, with suitable cuts that exploit the kinematic differences between signal vs background, a statistically significant signal can be extracted if one has sufficient luminosity. However, with the 2 fb$^{-1}$ expected by end of 2002, one can barely rule out the LEP hint of $m_H \approx 115$ GeV at 95% CL, while to have a 5$\sigma$ discovery, one would need 10–15 fb$^{-1}$. Since this seems to be the amount of data one may realistically expect before the start of LHC physics, the Tevatron path to Higgs 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 Tevatron. In this Letter we revisit a case [3] where the $WH$ or $ZH$ signatures arise from strong $pp \rightarrow b'\bar{b}' + X$ production of sequential fourth generation $b'$ pairs, followed by $b' \rightarrow cW$, $bZ$, $bH$ decays that are all of comparable strength. The effective $pp \rightarrow WH + X$ 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 $m_{\nu} - m_{\nu'}$ [5]. For $m_{\nu'} < m_{\nu}$, the $t'\bar{t}'$ splitting is considerably smaller than assumed in [4] and Glashow-Illiopoulos-Maiani (GIM) suppression of $b' \rightarrow bZ$, $bH$ decays is more severe [4], hence the $b' \rightarrow cW$ channel becomes more prominent. Furthermore, recent direct search by CDF [10] has ruled out $b' \rightarrow bZ$ decay for $m_{\nu'} < 200$ GeV if $B(b' \rightarrow bZ) = 100\%$, but may be evaded if $b' \rightarrow cW$ (but not $b' \rightarrow bH$) dilutes $B(b' \rightarrow bZ)$. Note that a dominant but not predominant $b' \rightarrow cW$ decay could help explain some irregularities of the $t\bar{t}$ signal. We argue that the Cabibbo-Kobayashi-Maskawa (CKM) mixing element $V_{ub'} \sim 10^{-3}$ is plausible, and is just the right amount to allow a “cocktail solution” of $b' \rightarrow cW$, $bZ$ and $bH$ that can evade the CDF bound. This offers new possibilities for Higgs search up to $m_H < m_{\nu} - m_{\nu'}$.

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

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

Precision EW data provide stringent constraints on the fourth generation: there is a $2.5\sigma$ discrepancy between $S = -0.07\pm0.11$ [8] and $S = 2/3\pi \equiv 0.21$ for a heavy degenerate fourth generation. However, using exact expressions for gauge boson self-energies for $m_{bH} = m_{bV} = 150$ GeV, $m_E = 200$ and $m_N = 100$ GeV ($E,N$ are fourth generation charged and neutral leptons), one finds $S \approx 0.11$ instead of 0.21, and the discrepancy drops below $2\sigma$. Given the excellent agreement between SM and EW data, a discrepancy at this level in a few measurable $\sigma_{low 2}$ is not tantalizing. For $EW$ data, a discrepancy at this level in a few measurables $\sigma$ below $170$ GeV, $m_h = 100$ GeV ($E,N$ are fourth generation charged and neutral leptons), one finds $S \approx 0.11$ instead of 0.21, and the discrepancy drops below $2\sigma$. Clearly the $b$-tagging efficiency for $cW$ would be much worse than $bZ$ or $bH$. Since $b$-tagging is an important part of the CDF $b\rightarrow bZ$ search strategy, one may evade the CDF search if $B(b\rightarrow cW)$ is sizable.

What is the “natural” strength of $V_{tbH}$? We cannot know for certain, but give two plausible arguments here: Since each involve two generation jump, perhaps $V_{tbH} \sim V_{ub}$; or one could guess that $V_{tbH} \sim m_s/m_{bH}$ since $V_{ub} \sim m_s/m_b$ [15]. Both cases suggest $V_{tbH} \sim 10^{-3}$, just what is needed to make $b\rightarrow cW$ while $b\rightarrow bZ$ 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 $b\rightarrow cW \sim bZ \sim bH$ that can evade CDF search for $b\rightarrow bZ$. This is in contrast to previous expectations [14] that $b\rightarrow cW$ would be considerably below $b\rightarrow bZ$, $bH$ decays. We remark here that comparison of $b\rightarrow cW$ and $b\rightarrow bZ$ were made recently in [9], but not in conjunction with $b\rightarrow bH$; the importance of the latter mode was emphasized in [14] in the context of evading CDF bound on $b\rightarrow bZ$, but a detailed discussion of the “cocktail solution” was not given.

We perform a one-loop calculation of $b\rightarrow bZ$, $bH$ 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 $m_s$ (and $m_t$, $m_b$) which can be neglected to good approximation. Several analytic and numerical checks are carried out following [2,3,19], with complete agreement found. Further numerical checks against $t\rightarrow cZ$, $cH$ [10,19] in SM again give full agreement. In the following, we take $115$ GeV $< m_{bH} < 170$ GeV, $m_t = 175$ GeV, $\Delta Q = m_{bH} - m_{bV} \leq 60$ GeV, and $r_{CKM} = \frac{|V_{cb}/V_{tb}|}{|V_{cb}/V_{tb}|}$ in the $10^{-3}$ range.

The CKM factors $|V_{tbH}/V_{tb}| \approx |V_{cb}/V_{tb}|$ actually cancel in the ratio $R_{bzz} = \frac{\Gamma(b\rightarrow bH)/\Gamma(b\rightarrow bZ)}{\Gamma(b\rightarrow bH)/\Gamma(b\rightarrow bZ)}$, and it depends on $m_{bH}$, $m_{bV}$, and $m_{bV}$. In Fig. 1 we show $R_{bzz}$ vs $m_{bV}$ for several $m_{bH}$ values with $\Delta Q$ fixed at $55$ GeV. It is clear that, for light $m_{bH}$ and relatively large $m_{bV}$, $R_{bzz}$ can be of order $0.5 - 1$, which means $b\rightarrow bH$ is competitive with $b\rightarrow bZ$ so long that it is phase space allowed [7].

For the actual branching ratios [21],

$$B(b\rightarrow \{cW, bZ, bH\}) = \Gamma(b\rightarrow \{cW, bZ, bH\})/\Gamma_b,$$

we assume $\Gamma_b = \Gamma(b\rightarrow cW) + \Gamma(b\rightarrow bZ) + \Gamma(b\rightarrow bH).$ Since $\Gamma(b\rightarrow cW) \propto |V_{cb}|^2$ while $\Gamma(b\rightarrow \{bZ, bH\}) \propto |V_{cb}/V_{tb}|^2$, the branching fractions depend critically on $r_{CKM}$. In Fig. 2 we illustrate $B(b\rightarrow \{cW, bZ, bH\})$ vs $r_{CKM} = |V_{cb}/V_{tb}|$ for $m_{bV}$, $m_{bH}$, $\Delta Q = 130, 115,$

![FIG. 1. The ratio $R_{bzz} = \Gamma(b\rightarrow bH)/\Gamma(b\rightarrow bZ)$ vs $m_{bH}$ for several $m_{bV}$ values and $\Delta Q = m_{bH} - m_{bV} = 55$ GeV.](image1)

![FIG. 2. $B(b\rightarrow \{cW, bZ, bH\})$ vs $r_{CKM}$ for $m_{bV}$, $m_{bH}$, $\Delta Q = 130, 115, 20$ GeV (left) and 160, 130, 40 GeV (right).](image2)
For $r_{\text{CKM}} > 3 \times 10^{-3}$, $B(b' \to cW)$ is much suppressed due to the small CKM matrix elements $|V_{tb}/V_{tb}^{\text{SM}}|$. We reproduce the scenario in our Fig. 2. The dotted curve is the predicted cross section $\sigma(p\bar{p} \to b'\bar{b})$ at 1.8 TeV, while the solid curve is the 95% CL upper limit on $\sigma(p\bar{p} \to b'\bar{b}) \times |B(b' \to bZ)|^2$. From the crossing of the two curves, CDF rules out $m_{b'} < 200$ GeV if $B(b' \to bZ) = 100%$. Our results are shown as open and black circles for $r_{\text{CKM}} = 0.001$ and 0.002, respectively. For larger $r_{\text{CKM}}$ values, they drop out from the plot. We have held the splitting $\Delta m = m_{b'} - m_{b} = 50$ GeV fixed. This leads to the valley around $m_{b'} \sim 125$ GeV, caused by $m_{b'} \approx m_t$. Very low cross section in $b' \to bZ$ mode can evade the search of $b' \to cW$.

To illustrate that this scenario can evade CDF search for $b' \to bZ$, we reproduce Fig. 2 of [11] 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% CL upper limit on $\sigma(p\bar{p} \to b'\bar{b}) \times |B(b' \to bZ)|^2$. From the crossing of the two curves, CDF rules out $m_{b'} \lesssim 200$ GeV if $B(b' \to bZ) = 100%$. Our results are shown as open and black circles for $r_{\text{CKM}} = 0.001$ and 0.002, respectively. For larger $r_{\text{CKM}}$ values, they drop out from the plot. We have held the splitting $\Delta m = m_{b'} - m_{b} = 50$ GeV fixed. This leads to the valley around $m_{b'} \sim 125$ GeV, caused by $m_{b'} \approx m_t$. Very low cross section in $b' \to bZ$ mode can evade the search of $b' \to cW$.

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lepton plus jets channel, D0 and CDF [27] 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 [28], 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 [23].

For sake of illustration, we show that the combination $m_t \sim 175$ GeV and $m_{\nu}$, $m_{t'} \sim 160$, 210 GeV, with $t,\ t' \to bW$ and the “cocktail solution” of $b' \to cW \sim bZ > bH$, can account for these curiosities. For dileptons without $b$-tagging, one largely probes $bbW^+W^-$ 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 $b'b'$, 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 larger $b'b'$ cross section and a lower fitted “$m_t$”. For all hadronic final state, since one demands 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 vs 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 would one have the statistical power to distinguish, a more exciting Higgs search program could be at stake! One could be discovering the Higgs together with two new quarks.

We have shown in this analysis that, once the constraints from precision measurements are taken into account, $m_t \sim m_{\nu} \sim m_{t'}$ 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 Tevatron Run II via $p\bar{p} \to \bar{b}bW + X$ or $\bar{b}bZH + X$ signatures.

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