

## Fourth generation $b'$ decays into $b + \text{Higgs boson}$

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(Received 6 August 1999; published 7 February 2000)

If a fourth generation quark exists whose mass is below 255 GeV, then the only two-body charged current decay,  $b' \rightarrow c + W$ , is doubly Cabibbo suppressed. For this reason, CDF has searched for the one-loop neutral current decay  $b' \rightarrow b + Z$ , assuming that the branching ratio into  $b + Z$  is 100%; an analysis giving the bounds on  $m_{b'}$  for smaller branching ratios is in preparation. In this Brief Report, we examine the neutral current decay  $b' \rightarrow b + H$ , which will occur if the Higgs boson mass is less than  $m_{b'} - m_b$ . Four different cases are examined: the sequential case, the non-chiral isosinglet case, the non-chiral isodoublet case, and a two-Higgs-doublet model with flavor-changing neutral currents. In the first three of these, the rates for  $b' \rightarrow b + Z$  and  $b' \rightarrow b + H$  are comparable, assuming comparable phase space factors; in the fourth,  $b' \rightarrow b + H$  is completely dominant. Thus, we emphasize the importance of giving  $b'$  mass bounds as a function of the branching ratio into  $b + Z$ , since the assumption of a 100% branching ratio for  $b' \rightarrow b + Z$  may only be valid if the Higgs boson mass is near or above the  $b'$  mass.

PACS number(s): 14.80.Bn, 12.60.Cn, 14.80.Cp

### I. INTRODUCTION

The Collider Detector at Fermilab (CDF) Collaboration [1] reported last year a search for the neutral current decay of the fourth generation  $b'$  quark into  $b + Z$ . An earlier result from the D0 Collaboration [2] ruled out  $b'$  masses up to 95 GeV from  $b' \rightarrow b + \gamma$ ; above that mass,  $b' \rightarrow b + Z$  dominates. The CDF bound is more stringent; they have excluded  $b'$  quarks with masses up to 148 GeV, depending on the  $b'$  lifetime. They assume that the branching ratio of  $b' \rightarrow b + Z$  is 100%. Currently, they are preparing an analysis [3] which gives the bounds as a function of that branching ratio.

It might seem surprising that the neutral current decay, which occurs through one loop in the standard model, could dominate the tree-level charged current decay. However, the decay  $b' \rightarrow t + W$  is forbidden for  $b'$  masses below 255 GeV (and the three body phase space severely suppresses the decay into  $t + W^*$  for  $b'$  masses below about 230 GeV), and the decay  $b' \rightarrow c + W$  is doubly Cabibbo suppressed. If the mixing angle which connects across two generations is very small, which would not be surprising, then the decay  $b' \rightarrow b + Z$  could very well be dominant. This was first pointed out by Hou and Stuart [4]. If the  $b'$  quark is non-chiral, either an isosinglet or part of an isodoublet, then the Glashow-Iliopoulos-Maiani (GIM) violation will lead to a tree-level  $b' \rightarrow b + Z$  decay. In that case, the neutral current decay will certainly be dominant. A detailed discussion of these possibilities, including a full set of formulas and plots, can be found in Ref. [5]. In the work of Mukhopadhyaya and Roy [6], the neutral current decay of sequential, isosinglet, isodoublet and mirror quarks was considered. Their bounds were below the  $Z$  mass, and thus the primary decay modes were into photons and virtual  $Z$ 's.

In this Brief Report, we look at a decay mode not considered in the above,  $b' \rightarrow b + H$ , where  $H$  is the Higgs boson. This occurs in the standard model at one loop, if kinematically accessible, and in non-chiral models at the tree level. It is, of course, much more difficult to detect, since the  $H$  will

decay into  $b\bar{b}$ , leading to a purely hadronic signature (although see the discussion below). However, it could suppress the overall  $b' \rightarrow b + Z$  branching ratio, weakening the mass bounds, even in the non-chiral case. We will look at four models: the standard model with a sequential  $b'$  quark, a vectorlike isosinglet model, a vectorlike isodoublet model, and a two-Higgs-doublet model with tree-level flavor changing neutral current. The discussion of  $b' \rightarrow b + H$  in the first two of these models is not new; extensive discussions have been previously published. However, these publications are ten years old, and we now know the top quark mass, precision electroweak studies give constraints, and the Cabibbo-Kobayashi-Maskawa (CKM) angles are better known. The decay in the latter two models has not been discussed.

### II. SEQUENTIAL QUARKS

The simplest realization of a fourth family is to add left-handed doublets and right-handed singlets (with a right-handed neutrino necessary to give the extra neutrino a large mass). The first calculations of  $b' \rightarrow b + H$  were carried out by Hou and Stuart [7] and by Eilam, Haeri and Soni [8]. A much more detailed analysis, which was the first to directly compare the rate with that of  $b' \rightarrow b + Z$ , which made no assumptions about mixing angles and which discussed the anomalous thresholds that occur in the calculation, appeared in the subsequent work of Hou and Stuart [9].

First, consider the ratio of the neutral current decay  $b' \rightarrow b + Z$  to the charged current decay  $b' \rightarrow c + W$ . The former decay depends on the mass of the  $t'$  quark and  $|V_{tb'}|$ ; the latter depends on  $|V_{cb'}|$ . For a  $t'$  mass of 250 GeV, the ratio is given by (see Ref [5] for full expressions and a plot)

$$\frac{\Gamma(b' \rightarrow bZ)}{\Gamma(b' \rightarrow cW)} = 0.005 \frac{|V_{tb'}|^2}{|V_{cb'}|^2}. \quad (1)$$

For different  $t'$  masses, the ratio varies roughly as  $(m_{t'}^2 - m_t^2)^2$  (note the GIM cancellation when the masses are equal). We thus see how sensitive the ratio is to the mixing angles. If one were to choose  $|V_{tb'}|/|V_{cb'}|$  to be the same as

$|V_{cb}|/|V_{ub}| = 13 \pm 3$ , then the above ratio is between 0.5 and 1.3. However, the large top quark mass might indicate a very large mixing angle between the third and fourth generations, leading to a much bigger ratio. Thus, the neutral current  $b' \rightarrow b + Z$  decay is certainly similar to, and could dominate, the charged-current decay.

In the ratio of  $b' \rightarrow b + H$  to  $b' \rightarrow b + Z$ , the mixing angles cancel, so there is less arbitrariness in the result. The result, given by Hou and Stuart [9], is a function of  $M_H$ ,  $m_t$ ,  $m_{t'}$  and  $m_{b'}$ . Hou and Stuart give plots of the partial widths as a function of  $m_{b'}$ , for four different values of  $M_H$ , three different values of  $m_t$  and two different values of  $m_{t'}$ . Fortunately, one of the choices for  $m_t$  was 175 GeV (the others were 75 and 125 GeV), and the dependence on  $m_{t'}$ , while important for the individual rates, is very weak in the ratio. For  $m_H = 100$  GeV, the ratio of  $b' \rightarrow b + H$  to  $b' \rightarrow b + Z$  is approximately (1.0, 1.4, 1.7, 2.0, 2.5) for  $m_{b'} = (150, 175, 200, 225, 250)$ , respectively. For  $m_H = 150$  GeV, phase space suppression sets in, and the ratio, for the same  $b'$  masses, is (0, 0.15, 0.7, 1.0, 1.6), respectively. One sees that the two rates are very similar. For a Higgs boson mass of 100 GeV, and a sequential  $b'$  quark, the assumption that the branching ratio for  $b' \rightarrow b + Z$  is 100% is not valid. On the other hand, for a Higgs boson mass of 150 GeV or higher, it may be reasonable.

Could one improve upon Hou and Stuart's calculation? We now know the top quark mass [and can distinguish between the Yukawa coupling modified minimal subtraction scheme  $\overline{\text{MS}}$  mass and the pole mass], we know from precision electroweak data that the  $t'$  mass cannot be much bigger than the  $b'$  mass, we have a much better understanding of the production cross sections for heavy quarks, and  $b$  tagging in hadron colliders is much better understood.

However, it would be premature to carry out this analysis. The reason is that a sequential fourth generation has virtually been ruled out by precision electroweak data. Erler and Langacker [10] note that the  $S$  parameter is in conflict with a degenerate fourth generation by over three standard deviations, or 99.8%. One can weaken this discrepancy slightly by making the fourth generation non-degenerate, but it appears very unlikely that a sequential fourth generation can be accommodated, *if* it is the only source of new physics. One way around this discrepancy is to assume that there is new physics which partially cancels the fourth generation contribution to the  $S$  parameter (such as Majorana neutrinos, additional Higgs doublets, etc.). This certainly can be done, and thus searches for a sequential fourth generation should continue. However, this new physics will likely also contribute to  $b' \rightarrow b + H$  and to  $b' \rightarrow b + Z$ . Thus, without some understanding of the new physics, carrying out a high precision improvement of the Hou-Stuart analysis is premature.

### III. NON-CHIRAL FERMIONS

Of much greater theoretical interest than a sequential fourth generation is a non-chiral (isosinglet or isodoublet) fourth generation. These happen automatically in a wide variety of models, including  $E_6$ -unification models, gauge-

mediated supersymmetric models, the aspon  $CP$ -violation model and so on. The motivations for these non-chiral generations are discussed in detail in Ref. [5]. They only contribute to the  $S$  parameter at higher order, and are thus completely in accord with precision electroweak studies. Because of the GIM violation, these models have tree-level  $b' b H$  and  $b' b Z$  vertices, and thus the charged-current decay of the  $b'$  becomes less competitive. Without the  $b' \rightarrow b + H$  decay, the assumption that the branching ratio of  $b' \rightarrow b + Z$  is 100% would be completely justified.

Let us first consider the case in which  $b'$  is an isosinglet quark. The first discussion of  $b' \rightarrow b + H$  was given in 1989 by del Aguila, Kane, and Quiros (AKQ) [11], who looked at the possibility of using this decay to detect a light Higgs boson (if the  $b'$  mass were less than  $M_Z + m_b$ , it would be the primary decay mode). This work was followed up by a more extensive analysis by del Aguila, Ametller, Kane and Quiros (AAKQ) [12]. A much later analysis of the various phenomenological aspects of isosinglet quarks can be found in the work of Barger, Berger and Phillips [13].

Following AKQ, consider the case in which the  $b'$  only mixes with the  $b$ . The Higgs doublet gives the usual mass term  $m_b \bar{b}_L b_R + \text{H.c.}$ , as well as a term  $m' \bar{b}_L b'_R + \text{H.c.}$  In addition, there are gauge invariant mass terms  $M_b \bar{b}'_L b'_R + \text{H.c.}$  and  $M' \bar{b}_L b'_R + \text{H.c.}$  The  $2 \times 2$  mass matrix can then be diagonalized. The resulting mixing then gives  $b' b Z$  and  $b' b H$  vertices, which are proportional to  $m'$ . Thus, one gets tree level interactions, suppressed only by a single Cabibbo-type angle ( $m'/M_{b'}$ ). The angle cancels in the ratio, giving

$$\frac{\Gamma(b' \rightarrow b + H)}{\Gamma(b' \rightarrow b + Z)} = \frac{M_{b'}^2}{M_{b'}^2 + 2M_Z^2} \left( \frac{M_{b'}^2 - M_H^2}{M_{b'}^2 - M_Z^2} \right)^2. \quad (2)$$

This ratio is unity in the limit of large  $M_{b'}$ , and is 0.7 times the phase space factor for  $M_{b'} = 200$  GeV. There will also be a  $b' c W$  vertex induced by mixing, but this will be doubly Cabibbo suppressed, and thus should be negligible.

One thus sees that, once again, the  $b' \rightarrow b + H$  decay is comparable to the  $b' \rightarrow b + Z$ , assuming the Higgs boson mass is not close to (or greater than) the  $b'$  mass. Again, the charged current  $b' \rightarrow c + W$  decay is expected to be much smaller (and, as shown in Ref. [5], the  $b' \rightarrow t + W^*$  decay will be negligible for all  $b'$  masses below 300 GeV).

Although the isosinglet case is theoretically preferred [since isosinglet quarks automatically appear in all  $E_6$  unified models, as well as all models with a  $5 + \bar{5}$  of  $SU(5)$ ], one can ask what happens if the fourth generation quarks form an isodoublet. The ratio of  $b' \rightarrow b + H$  to  $b' \rightarrow b + Z$  is the same as in the isosinglet case. However, there is one important difference. Although the ratio is the same, the individual rates are much smaller. This is because the GIM mismatch in the isodoublet case occurs in the right-handed sector, and there is a helicity suppression which suppresses the vertex by an additional factor of  $m_b/M_{b'}$ . This means that the charged current decays become much more competitive. It is shown in Ref. [5] that the three-body  $b' \rightarrow t + W^*$  decay becomes competitive with the  $b' \rightarrow b + Z$  decay for  $b'$  masses of 200 GeV, and greatly exceeds it for masses above

220 GeV. For lighter masses, the  $b' \rightarrow c + W$  decay will still be important, and may dominate depending on the value of the  $V_{cb'}/V_{tb'}$  ratio (as in the sequential fermion case).

#### IV. TWO-HIGGS MODELS

In the standard two-Higgs-doublet models, the so-called model I or model II, the Yukawa couplings to a Higgs are multiplied by a factor of  $\cos \alpha / \sin \beta$ , where  $\alpha$  is a Higgs mixing angle and  $\beta$  is a ratio of vacuum expectation values (depending on the specific model and the specific fermion charge,  $v_2/v_1$  will either be  $\tan \beta$  or  $\cot \beta$ ). In most models, Higgs mixing is fairly small, so  $\cos \alpha$  is near unity. In all of the above cases, this factor will change the ratio of  $b' \rightarrow b + H$  to  $b' \rightarrow b + Z$  by a factor which is of order 1. (It cannot enhance the Higgs decay mode too much in the sequential case, since too large an enhancement will make the  $b'$  or  $t'$  Yukawa coupling non-perturbative.)

A bigger effect might be expected in model III [14]. In this model, unlike models I and II, no discrete symmetry is imposed in order to suppress tree level flavor-changing neutral current (FCNC) and thus FCNC arises, even in the sequential case. The observed lack of large FCNC in processes involving first-generation quarks is explained by noting that many models will have a FCNC coupling given by the geometric mean of the Yukawa couplings of the two quarks. In that case, the tree-level  $b'bH$  coupling (neglecting Higgs mixing) is given by  $g\sqrt{m_b m_{b'}}/\sqrt{2}M_W$ . An early discussion of the  $b' \rightarrow b + H$  decay can be found in the unpublished work of Ref. [15].

How does this coupling affect the results? In the isosinglet case, the model III coupling is of the same order of magnitude as the expected coupling induced by the GIM violation, and thus none of our arguments change. However, in the sequential fermion case, the model III coupling is *much* larger than the one-loop induced  $b'bZ$  coupling. Also, in the isodoublet case, the model III coupling is much larger than the GIM-violation induced  $b'bZ$  coupling. Thus, since the Higgs coupling is so much larger in these two models,  $b' \rightarrow b + H$  will dominate all  $b'$  decays. We conclude that in model III, with either a sequential or isodoublet  $b'$ , the  $b'$

decay is dominated by  $b' \rightarrow b + H$ , and thus the CDF and D0 bounds are completely inapplicable.

#### V. CONCLUSIONS

Previous searches for a fourth generation quark assume a 100% branching ratio into  $b + Z$ . The other neutral current decay,  $b' \rightarrow b + H$ , has been examined, in the sequential case, the isosinglet case, the isodoublet case and a two-Higgs-doublet model with tree-level FCNC. In all of these cases, the rate for  $b' \rightarrow b + H$  is comparable to, or greater than,  $b' \rightarrow b + Z$  if the Higgs boson is kinematically accessible.

Currently, the CDF Collaboration [3] is preparing an analysis which will give the bounds as a function of the branching ratio to  $b + Z$ . This analysis assumes that the missing branching ratio goes completely undetected. However, suppose that one  $b'$  decays to  $b + Z$  and the other to  $b + H$ . At least one  $b + Z$  decay is needed to trigger the event, and the three  $b$  final state of the other  $b'$  could then be detected. The b-tag efficiency in these events is expected to be considerably higher than in  $bbZZ$  events because of the  $4 - b$  jets final state in which at least two  $b$  jets have high  $p_T$ , independently of the  $b'$  and Higgs boson masses [16]. This leads to the potential exciting result that the experiment could discover [7,9] both a fourth-generation quark and a Higgs boson.

The only discouraging model is model III, in the sequential or isodoublet cases. Pair production of  $b'\bar{b}'$  would lead to a final state of six  $b$  jets, in which every  $b$  comes from a 2-body decay. This would lead to quite dramatic signatures, but without a lepton trigger, finding such a signature would be very difficult.

#### ACKNOWLEDGMENTS

I thank the CERN Theory Group for its hospitality while this work was written, and Yao Yuan for her assistance. I am also grateful to Joao Guimaraes de Costa for informing me of the continuing interest of CDF in conducting  $b'$  searches, and for many useful discussions. This work was supported by the National Science Foundation.

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