Bounds on the mass of the b' quark, reexamined

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Recent results from the DELPHI Collaboration led us to review the present bounds on the b' quark mass. We use all available experimental data for $m_{b'}>96$ GeV to constrain the b' quark mass as a function of the Cabibbo-Kobayashi-Maskawa elements in a sequential four generation model. We find that there is still room for a b' with a mass larger than 96 GeV.

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I. INTRODUCTION

It has long been known that a sequential fourth generation within the standard model (SM) needs both quarks and leptons. Half a generation would imply that the gauge anomalies associated with triangle diagrams would not cancel. It is also known [1] that the SLAC linear collider and then CERN e^+e^- collider LEP have set a bound on the number of light neutrinos ($m_\nu < M_Z/2$), which is indisputably equal to 3. This bound applies to all new fermions that couple to the Z and one has to be extremely open minded to accept a fourth neutrino with a mass larger than around 45 GeV. Thus, there seems to be no strong motivation for the search of a sequential fourth generation (for a review see [2]). So why look for it?

Despite the strength of the previous arguments one should try to experimentally exclude the existence of a fourth generation. In fact such evidence does not yet exist. The most recent precision electroweak results [3] allow a sequential fourth generation if the quark masses are not too far apart.[1] The same results also disfavor a degenerate fourth family if both the leptonic and hadronic sectors are degenerate. This is in agreement with the conclusions of Erler and Langacker [1]. However, as discussed in Ref. [2], there are several reasons to keep investigating this subject, starting with the fact that precision results vary with time. In Ref. [2] it can be seen that even if one takes a degenerate fourth family of quarks with 150 GeV masses, it is enough to choose a nondegenerate family of leptons with masses of 100 GeV and 200 GeV and a Higgs boson mass of 180 GeV for the discrepancy with experimental data to fall from roughly three to two standard deviations.[2] Moreover, it is clear that any new physics will also influence these results.

It was shown in Refs. [2,4] that the mass range $|m_{t'} - m_{b'}| \leq 60$ GeV, where t' and b' are the fourth generation quarks, is consistent with all available precision electroweak data. This range enables us to say that even if $m_{b'} > m_{t'}$, the decay $b' \to t'W$ is forbidden. The decay $b' \to t'W^*$ although allowed is phase space suppressed [5] and consequently extremely small in the mass range under study (from now on we consider $m_{b'} < m_{t'}$). Experimental data allow us to go only up to $m_{b'}$ close to 180 GeV. Hence, the b' cannot decay to a top quark. Furthermore, while some recent studies [6,7] have constrained the Cabibbo-Kobayashi-Maskawa (CKM) elements of the fourth generation, they do not influence our results. Nevertheless we will take into account the 2σ bound $|V_{tb}|^2 + 0.75|V_{t'b}|^2 \leq 1.14$ [6] coming from $Z \to b\bar{b}$ to constrain the CKM element $V_{cb'}$ as a function of the b' mass.

Present experimental bounds on the b' mass above 96 GeV suffer from the drawback of assuming a 100% branching ratio for a specific decay channel. As stated before the strongest bound on the b' mass comes from LEP [8] and is $m_{b'} > 46$ GeV. Here all b' decays were considered. There are presently three bounds on the b' mass for $m_{b'} > 96$ GeV. The first one [9] $m_{b'} > 199$ GeV assumes that $\mathrm{Br}(b' \to bZ) = 100\%$. We will drop this condition and use instead their plot of $\sigma(p\bar{p} \to b'\bar{b'} + X) \times \mathrm{Br}^2(b' \to bZ)$ as a function of the b' mass. The second one [10] $m_{b'} > 128$ GeV is based on the data collected in the top quark search. Because the D0 Collaboration looked for $t \to bW$, the analysis can be used to set a limit on $\sigma(p\bar{p} \to b'\bar{b'} + X) \times \mathrm{Br}^2(b' \to cW)$. By doing so we assume that the b and c quark masses are negligible and that $\sigma(p\bar{p} \to b'\bar{b'}) \approx \sigma(p\bar{p} \to t\bar{t})$. The obtained limit $m_{b'} > 128$ GeV assumes

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[1] This result is a strong bound on the mass difference of a possible fourth generation. Nevertheless, it should be noticed that the authors assume no mixing of the extra families with the SM ones.

[2] Notice that we make no assumptions on the values of the masses and couplings of the leptonic sector of the model.

$\mathrm{Br}(b'\to cW)=100\%$. The third bound is from CDF [11] and is based on the decay $b'\to bZ$ followed by the search for $Z\to e^+e^-$ with displaced vertices. Their excluded region is inside a rectangle in the lifetime $(c\tau)$, $m_{b'}$ plane with 9×10^{-3} cm$<c\tau<12$ cm and $m_b+M_Z<m_{b'}<148$ GeV sides. Hence, the excluded region depends heavily on the b' lifetime. But, contrary to the top quark which has a lifetime of around 10^{-24} s, the lifetime of a sequential b' quark is expected to be extremely large, especially knowing that we are considering a heavy b'. In fact, depending on the CKM values and on the b' and t' masses, the decay length can be as large as 10^{-4} cm or even 10^{-3} cm in extreme cases. Nevertheless, in this model, it is very hard to go beyond that value. It is worth mentioning that even with this huge lifetime, the b' always decays inside the detector and hadronization occurs before it decays. Thus, the limit obtained in [11] which on top of what was said assumes $\mathrm{Br}(b'\to bZ)=100\%$ cannot be used in our analysis.

Hence, we think it is worthwhile to reexamine the limits on the b' mass. We will use the CDF and the D0 data which, together with the new DELPHI data [12], is all that is available for $m_{b'}>96$ GeV. We will draw exclusion plots in the plane $(R_{CKM},m_{b'})$, where $R_{CKM}=|V_{cb'}/V_{tb'}V_{tb}|$, from 96 GeV to 180 GeV without assuming a definite value for the branching ratios of specific channels. In some regions it is possible to combine all experimental data allowing a larger exclusion area. Notice that the use of the R_{CKM} variable provides a new way to look at the experimental results. This variable enables us to actually use and combine all the available data. Moreover, the new form in which the results are presented will serve as a guide to future experiments since it is possible to know how far one has to go to exclude the regions that are still allowed.

To end this section we note that there is, at present, no bound on a sequential 2/3 charged quark in the PDG but if we assume a 100% decay to cW the bound is again 128 GeV [10].

The paper is organized as follows. In Sec. II we define the model and discuss the production and the decays of b' quarks. In Sec. III we combine the theoretical and the experimental results to produce exclusion plots in the parameter space. Section IV summarizes our results and conclusions.

II. b' PRODUCTION AND DECAY

There are several ways of extending the SM to accommodate a fourth family of quarks and/or leptons. A review of the different models in the literature is available in [2]. Obviously, the most natural and straightforward way to introduce a fourth family in the SM is just to add a (t',b') family with the same quantum numbers and similar couplings to all other known quarks. The same can be done for the lepton sector.[3] This is called a sequential fourth generation model and is sometimes referred to as SM4. The resulting CKM matrix has a very similar structure to the SM one. It is a 4×4 unitary matrix and it is assumed to be approximately symmetric. Besides the four new masses, there are nine additional parameters compared to the SM: six mixing angles instead of three and three complex phases instead of one. Because we are not concerned with CP violation we take all CKM values to be real. In the SM4, the CKM elements that are not determined experimentally have more freedom due to the extra parameters introduced. This model has been the subject of wide study in the literature. Production cross sections for lepton and hadron colliders and b' branching fractions were calculated long ago.

At LEP, a pair of heavy quarks is produced through the reaction $e^+e^-\to q\bar{q}$. For consistency with the experimental analysis, the process $e^+e^-\to b'\overline{b'}$ was calculated using PYTHIA [13], with initial state radiation, final state radiation (FSR) and QCD corrections turned on. We have cross-checked the results using a simple program with the formulas of Refs. [14,15], which also include QCD corrections and ISR. Since the larger contribution to the cross section comes from ISR we have double checked by making use of the formulas presented in [16]. The results agree very well with the PYTHIA results. It should be noticed that near the threshold bound states would surely be formed. Without a detailed analysis of such bound states it is impossible to evaluate whether their contribution to the cross section would be relevant or not. So, if bound states do exist above the threshold, we are assuming that they give a negligible contribution to the cross section. Far away from the threshold the problem ceases to exist and the results we will show for hadron colliders are not affected by this approximation.

The equivalent production reaction at the Tevatron is $p\bar{p}\to b'\overline{b'}+X$, with the relevant processes being $gg(q\bar{q})\to b'\overline{b'}$. Even though this cross section cannot be found in the literature it is generally recognized that all massive quark pair production cross sections are very similar due to its hadronic nature. The same is true for the subsequent decays into leptons and for the detector efficiency. Thus we can use the exact order α_s^3 corrected cross section for the production of top quarks [17]. This approximation is used both by the CDF and the D0 Collaborations in their studies on b' production and decay. In [10] it is also assumed that the final states are exactly the same as the top quark ones. Notice that the error in calculating the hadronic cross section is much larger than the corresponding error in the leptonic one. For $m_q=100$ GeV the error is about 38% falling to 12% for $m_q=200$ GeV. This will be reflected in the exclusion plots.

All b' decays were exhaustively studied by Hou and Stuart in [18–21] and by Haeri, Eilam, and Soni [22]. Hou and Stuart have shown that the b' is peculiar in the sense that one-loop flavor change decays (flavor change neutral current) can dominate over charged current (CC) decays. Depending on the values of the CKM matrix elements and as long as the Higgs boson channel remains closed, there are mainly two processes in competition: $b'\to bZ$ and $b'\to cW$. As soon as the Higgs boson channel opens the decay $b'\to bH$ can be as large as $b'\to bZ$. Other decays such as

[3]Now that it is finally accepted that neutrinos have mass, the SM has to be changed to accommodate this new feature. We do not restrict ourselves to any specific mechanism that generates the very high neutrino mass needed in SM4.

$b'\to bg$ and $b'\to b\gamma$ and three body decays give smaller contributions but can sometimes be relevant.

The three body decays $b'\to be^+e^-$, $b'\to b\nu\bar{\nu}$, and $b'\to bq\bar{q}$, including box diagrams, were calculated in [20]. At that time, the top mass was still unknown and the t' was taken to be much larger than the top mass. Under these conditions and for the range of the b' mass in study, the sum of all three body decays could be as large as $b'\to bg$. It could be even larger for a "small" t mass and a very large t' mass [20]. But it turned out that the top mass is ≈ 175 GeV and electroweak precision measurements force $m_{t'}$ to be close to $m_{b'}$ for the range of b' mass under consideration. In our case we estimate all three body decays plus the decay $b'\to b\gamma$ to be smaller than $b'\to bg$. Nevertheless, because we want to make a conservative estimate we will take it to be as large as $b'\to bg$.

Using the unitarity of the CKM matrix, its approximate symmetry $V_{t'b'}V_{t'b}\approx -V_{tb}V_{tb'}$, and taking $V_{ub'}V_{ub}\approx 0$ and $V_{cb}\approx 10^{-2}$ we can write all branching fractions as a function of three quantities alone: R_{CKM}, $m_{t'}$, and $m_{b'}$. Notice that the last two conditions do not play a significant role in the final result. Using a very large value as for instance $V_{ub'}V_{ub}\approx 10^{-4}$ gives a contribution much less than 1% to the $b'\to bZ$ decay width. The same is true when we relax the condition $V_{t'b'}V_{t'b}\approx -V_{tb}V_{tb'}$ near to a Glashow-Iliopoulos-Maiani (GIM) cancellation region. Relaxing this condition leads to an increase by several orders of magnitude of the values of the neutral current (NC) decay widths but they are always much smaller than the CC decays in that region.

One-loop calculations of the NC b' decays were performed using the FeynArts and FeynCalc [23] packages for generating and computing the complete set of diagrams and the LoopTools/FF [24] packages for the numerical analysis. We have carried out several checks in the four generation model following [4,18–21] and in the SM against [25,26]. We have found full agreement in both cases.

The branching ratios depend on three quantities alone and 96 GeV$\lesssim m_{b'}\lesssim 180$ GeV. So, we just have to decide on what values of R_{CKM} and $m_{t'}$ to use. Since we know that $m_{t'}$ is limited by precision data we will study two extreme cases $m_{t'}=m_{b'}+50$ GeV and the almost degenerate case $m_{t'}=m_{b'}+1$ GeV. In the exclusion plots R_{CKM} is a free parameter and so no assumptions on its variation range were made. However, there is a hint on its most significant values coming from the fact that the competing NC and CC cross at $10^{-3}\lesssim R_{CKM}\lesssim 10^{-2}$. We will come back to this point later.

In Fig. 1 we present the branching ratios as a function of the b' mass with $R_{CKM}=0.001$ and $m_{t'}-m_{b'}=50$ GeV. The closer to $m_{b'}=96$ GeV we are the larger $b'\to bg$ gets due to phase space suppression of the competing NC $b'\to bZ$. In fact, for an almost degenerate fourth family and small values of R_{CKM}, $b'\to bg$ can be the dominant NC for $m_{b'}=96$ GeV. As soon as one moves away from this value, $b'\to bZ$ becomes the dominant NC. If the Higgs boson channel is closed , for $m_{b'}\geqslant 97$ GeV, the competition is always between $b'\to cW$ and $b'\to bZ$. As $m_{b'}$ rises so does the NC except if the GIM mechanism gets in the way. It can be clearly seen in the figure the GIM mechanism acting for $m_{b'}\approx 125$ GeV, that is, $m_{t'}-m_t=0$. Then the NC rises again and the CC falls crossing at 140 GeV. When R_{CKM} grows so does $b'\to cW$ and the crossing point is shifted to the left. As the mass difference tends to zero the GIM effect is shifted to $m_{b'}\approx m_t$.

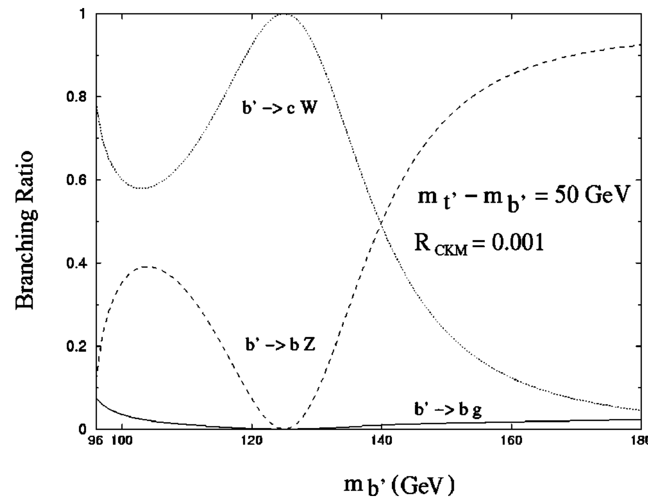

FIG. 1. Branching ratios as a function of the b' mass. The Higgs boson channel is closed. $R_{CKM}=0.001$ and $m_{t'}=m_{b'}+50$ GeV. The dashed line is $b'\to bZ$; the full line is $b'\to bg$ and the dotted line is $b'\to cW$.

In Fig. 2 we show the branching ratios as a function of R_{CKM} with $m_{b'}=110$ GeV and $m_{t'}-m_{b'}=1$ GeV. As we already knew, the NC's are favored by small values of R_{CKM} because R_{CKM} is a direct measure of the charged currents. Again, when $m_{b'}$ grows so does $b'\to bZ$ and the crossing point is shifted to the left. The same happens when $m_{t'}-m_{b'}$ decreases as explained above.

III. RESULTS AND DISCUSSION

We are now in a position to draw exclusion plots on the plane (R_{CKM},$m_{b'}$) with $m_{t'}$ as a parameter. Using the latest

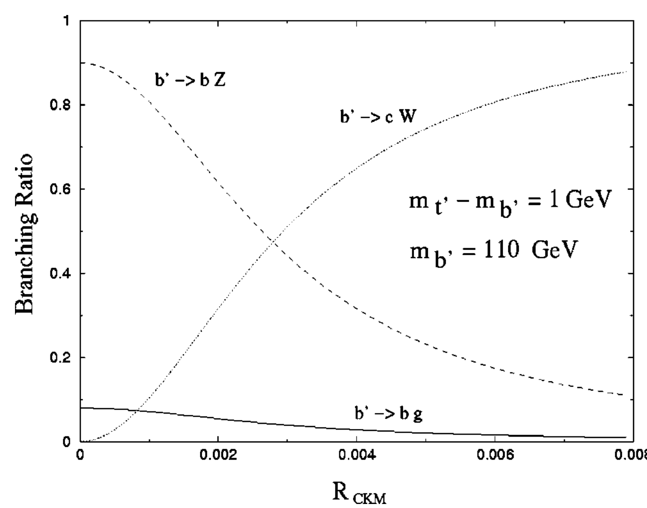

FIG. 2. Branching ratios as a function of the R_{CKM} with $m_{b'}=110$ GeV and $m_{t'}=m_{b'}+1$ GeV. The dashed line is $b'\to bZ$; the full line is $b'\to bg$ and the dotted line is $b'\to cW$. The Higgs boson channel is closed.

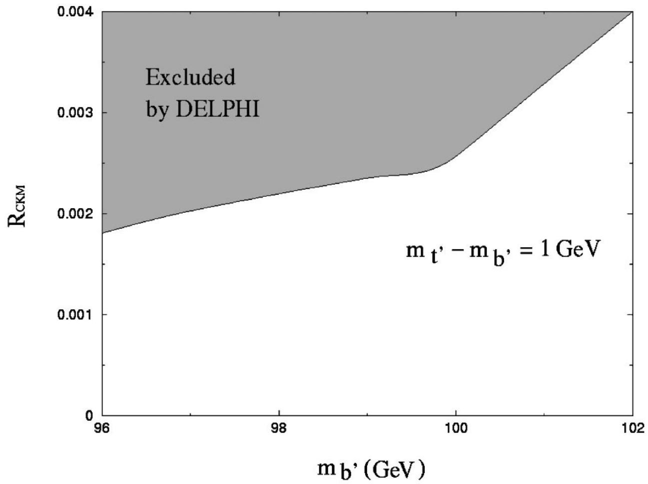

FIG. 3. 95% C.L. excluded region in the plane $(R_{CKM}, m_{b'})$ with $m_{t'} - m_{b'} = 1$ GeV, obtained from limits on $\mathrm{Br}_{b' \to bZ}$ and $\mathrm{Br}_{b' \to cW}$ (top).

experimental data from the DELPHI Collaboration and the data from the CDF and D0 Collaborations together with the theoretical values of the cross sections and the branching ratios we have drawn the exclusion plots shown in the figures below. The upper regions are excluded by the limits on $\mathrm{Br}_{b' \to cW}$ and the lower regions by the limits on $\mathrm{Br}_{b' \to bZ}$.

The results based on the DELPHI data are shown in Figs. 3 and 4. The only difference between the two plots is in the value of $m_{t'}$. It can be seen that as $m_{t'} - m_{b'}$ grows, the allowed region gets smaller. This is because $\mathrm{Br}_{b' \to bZ}$ decreases with $m_{t'}$ due to a GIM suppression as long as $m_{t'}$ is smaller than m_t and $(m_{t'} - m_t) \to 0$. On the contrary, $\mathrm{Br}_{b' \to cW}$ does not depend on the t' mass. Hence, as $m_{t'}$ grows, $\mathrm{Br}_{b' \to cW}$ becomes dominant and the upper excluded region increases.

The reason why there is not a lower bound close to 96 GeV in both figures is because of the competing neutral currents. Close to the Zb threshold (≈ 96 GeV), $b' \to bg$ dominates over $b' \to bZ$ and the experimental bound on $\mathrm{Br}_{b' \to bZ}$ becomes useless. As one moves away from the Zb threshold, $b' \to bZ$ becomes the dominant neutral current. $\mathrm{Br}_{b' \to bZ}$ falls less sharply with $m_{t'}$ than the other neutral currents and that explains why there is a lower bound for, e.g., at $m_{b'} = 100$ GeV in Fig. 4 but not in Fig. 3. After 102 GeV almost all values are allowed because the experiments are not sensitive to those mass values.

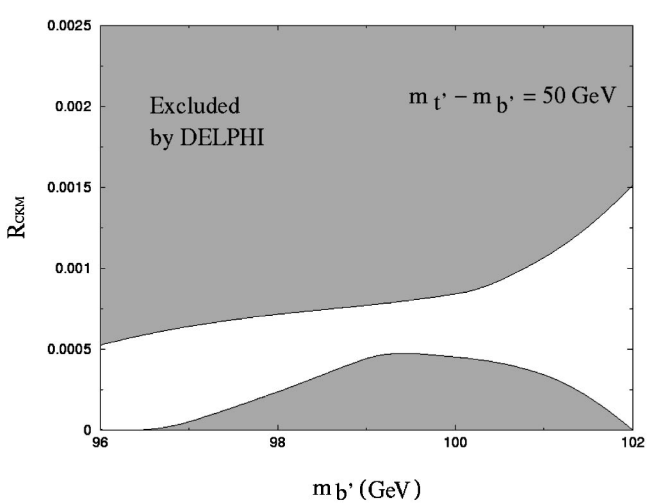

FIG. 4. 95% C.L. excluded region in the plane $(R_{CKM}, m_{b'})$ with $m_{t'} - m_{b'} = 50$ GeV, obtained from limits on $\mathrm{Br}_{b' \to bZ}$ (bottom) and $\mathrm{Br}_{b' \to cW}$ (top).

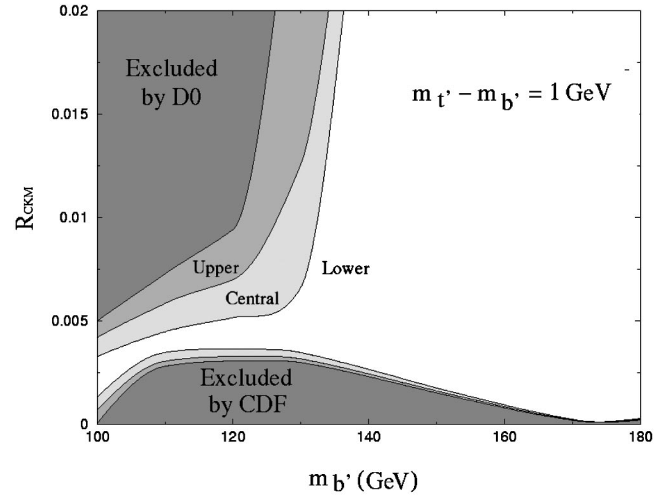

FIG. 5. 95% C.L. excluded region in the plane $(R_{CKM}, m_{b'})$ with $m_{t'} - m_{b'} = 1$ GeV, obtained from limits on $\mathrm{Br}_{b' \to bZ}$ by the CDF Collaboration (bottom) and $\mathrm{Br}_{b' \to cW}$ by the D0 Collaboration (top). Upper, central, and lower curves correspond to the values used for the b' production cross section.

In Figs. 5 and 6 we show similar plots but using the CDF and the D0 data. The D0 data are responsible for excluding the upper regions because they deal with CC's as the CDF excludes the lower regions due to the bounds on NC's. The three curves marked upper, central, and lower are related to the theoretical error bars in the b' production cross section.

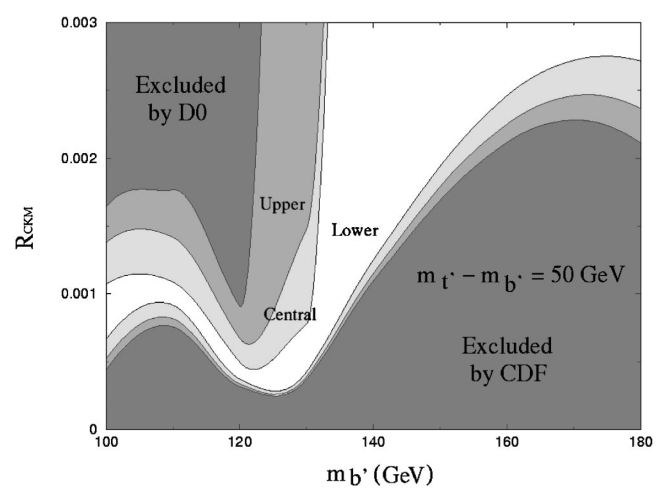

FIG. 6. 95% C.L. excluded region in the plane $(R_{CKM}, m_{b'})$ with $m_{t'} - m_{b'} = 50$ GeV, obtained from limits on $\mathrm{Br}_{b' \to bZ}$ by the CDF Collbaboration. (bottom) and $\mathrm{Br}_{b' \to cW}$ by the D0 Collaboration. (top). Upper, central and lower curves correspond to the values used for the b' production cross section.

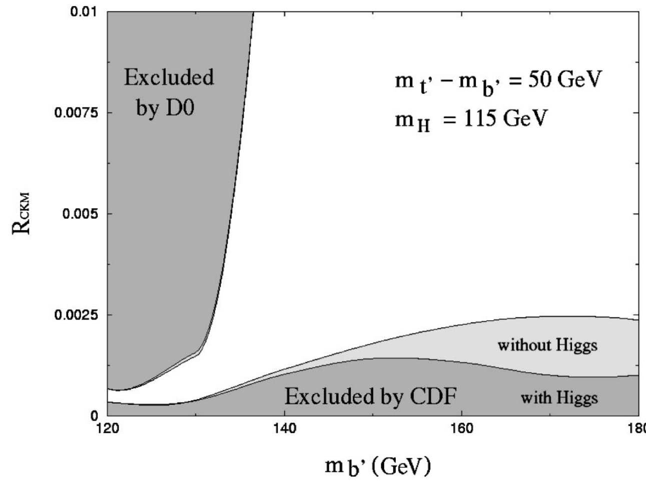

FIG. 7. 95% C.L. excluded region in the plane (R_{CKM}, $m_{b'}$) with $m_{t'}-m_{b'}=50$ GeV, obtained from limits on $\mathrm{Br}_{b'\to bZ}$ by the CDF Collaboration (bottom) and $\mathrm{Br}_{b'\to cW}$ by the D0 Collobration (top). The darker region is the excluded region with a Higgs boson of 115 GeV. Central values were taken for the b' production cross section.

Again and for the same reason the excluded region grows with $m_{t'}-m_{b'}$. This means that like the constraints from precision electroweak data, the experimental data also disfavor a fourth family with a large mass difference between the two quarks.

In some cases the allowed regions in the CDF/D0 and DELPHI plots overlap and the excluded region grows. For instance, considering $m_{b'}=100$ GeV and $m_{t'}-m_{b'}=50$ GeV we get for DELPHI $4.5\times10^{-4}<R_{CKM}<8.4\times10^{-4}$ and for CDF/D0 (lower) $6.7\times10^{-4}<R_{CKM}<1.1\times10^{-3}$. Hence, the resulting excluded region is $6.7\times10^{-4}<R_{CKM}<8.4\times10^{-4}$.

With the bound $|V_{tb}|^2+0.75|V_{t'b}|^2\leqslant1.14$ [6] and assuming $|V_{tb}|\approx1$ it is possible to limit the value of the matrix element $V_{cb'}$. For the same value of the b' mass, $m_{b'}=100$ GeV, we know that $R_{CKM}<8.4\times10^{-4}$ and so

$$V_{cb'}<8.4\times10^{-4}\sqrt{0.14/0.75}\approx3.6\times10^{-4}$$

with $m_{t'}=m_{b'}+50=150$ GeV. The bound gets weaker for smaller $m_{t'}$ [7].

Finally we show an exclusion plot with the Higgs boson channel opened and a Higgs boson mass of 115 GeV (Fig. 7). As we expected, the inclusion of the Higgs boson makes the excluded region to shrink. By itself, the inclusion of one more channel always diminishes the branching ratios and consequently less values will be excluded. Like $b'\to bZ$, $b'\to bh$ is larger for small R_{CKM} and large $m_{b'}$. Hence in this region of parameter space it competes with $b'\to bZ$ and $b'\to cW$ making the allowed region larger. For a detailed analysis of the so-called cocktail solution see [4].

IV. CONCLUSION

In this work we have found the allowed b' mass as a function of the CKM elements of a four generation sequential model. Using all available experimental data for $m_{b'}>96$ GeV we have shown that there is still plenty of room for a b' with a mass larger than 96 GeV. We have also shown that the allowed region decreases as $m_{t'}$ increases. In fact, as the gap between the fourth generation quark masses increases the allowed region shrinks. Notice that this is in full agreement with the tendency of a small mass gap, if not completely degenerated, favored by the electroweak precision measurements.

All plots show that R_{CKM} is for sure smaller than $\approx10^{-2}$ and it can be as small as $\approx10^{-4}$. This is not surprising because this region is exactly where we expected it to be. In fact, the CKM values we know so far suggest that $V_{cb'}\approx10^{-4}$–10^{-3}. If $V_{tb'}\approx10^{-1}$ then a value of R_{CKM} between 10^{-2} and 10^{-4} is absolutely natural. Moreover, the limit we have obtained for $V_{cb'}$ in the last section makes it even more natural.

We know that the DELPHI analysis [12] is being improved. In the near future we hope to reduce very much the allowed region in Figs. 3 and 4. As far as we know there are no new results from the CDF and the D0 Collaborations improving their bounds. For large $m_{t'}-m_{b'}$ and for some values of $m_{b'}$, the CDF/D0 limits almost shrink the allowed region to zero. Hence, a small improvement in the analysis could disallow a large region of the parameter space.

As for the future, searches in hadron colliders will have to wait for the RunII of the Tevatron and for the Large Hadron Collider (LHC). The $b'\overline{b'}$ production cross section increases by roughly two orders of magnitude at the LHC compared to the Tevatron. Thus LHC will be a copious source of b' pairs. With high values for cross section and luminosity, if background is suppressed exclusion plots can be drawn for a very wide range of b' masses. However, we have to worry about two problems in future searches. From the theoretical point of view we have to take into account all the possible hierarchies in mass, for instance one could have $m_{t'}<m_t<m_{b'}$ or $m_t<m_{t'}<m_{b'}$. A careful study, including also the possibility of finding a Higgs boson, has to be done. From the experimental point of view we have to know how the detectors will perform.

Nobody knows yet if there is going to be a Next Linear Collider (NLC) with energies of $\sqrt{s}=500$ GeV or $\sqrt{s}=1$ TeV. NLC would allow us to go up $m_{b'}=250$ GeV or $m_{b'}=500$ GeV which is close to the perturbative limit. Depending on the available luminosity, and because a small background is expected, we believe that the excluded region would be very large, probably allowing the exclusion of some values of $m_{b'}$ regardless of the values of the mixing angles. However, if a Higgs boson is found the excluded region will surely be smaller and will depend on the mass and type of Higgs boson found. For a detailed discussion on future searches see [2].

In summary we believe that there is still experimental and theoretical work to be done to find or definitely to exclude a sequential fourth generation of quarks at the electroweak scale.

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