

NEW BOUNDS ON THE MASS OF A  $b'$  QUARK\*

S.M. OLIVEIRA

Centro de Física Teórica e Computacional  
Faculdade de Ciências, Universidade de Lisboa  
Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal

AND R. SANTOS

Centro de Física Teórica e Computacional  
Faculdade de Ciências, Universidade de Lisboa  
Av. Prof. Gama Pinto 2, 1649-003 Lisboa, Portugal  
and  
Instituto Superior de Transportes e Comunicações  
Campus Universitário R.D. Afonso Henriques  
2330-519 Entroncamento, Portugal

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In this work we present limits on a sequential down-type quark,  $b'$ , based on the most recent DELPHI data. Using all available experimental data for  $m_{b'} > 96$  GeV we conclude that a sequential four generations model is far from being experimentally excluded.

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## 1. Introduction

The Standard Model (SM) of the electroweak interactions start to show some difficulties in explaining recent experimental data especially in the fermionic sector. What about a fourth family of fermions? Is it experimentally ruled out? Cancellation of gauge anomalies require the addition of a family of leptons for each family of quarks added to the SM. Since the number of light neutrinos ( $m_\nu < M_Z/2$ ) is definitely equal to three [1] the new lepton family has to accommodate a neutrino with a mass larger than around 45 GeV. Hence, if a sequential fourth family exists it certainly has to show a much different structure in the leptonic sector.

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Despite the strength of the previous argument 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 [2] allow a sequential fourth generation if the quark masses are not too far apart. 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, it was shown in [3] that even if one takes a degenerate fourth family of quarks with 150 GeV masses, it is enough to choose a non-degenerate family of leptons with masses of 100 GeV and 200 GeV and a Higgs mass of 180 GeV for the discrepancy with experimental data to fall from roughly three to two standard deviations. Moreover, it is clear that any new physics will also influence these results.

It was shown in Refs. [3, 4] that the mass range  $|m_{t'} - m_{b'}| \leq 60$  GeV, where  $t'$  and  $b'$  are the fourth generation quarks, is consistent with the precision electroweak data on the  $\rho$  parameter. This range enables us to say that even if  $m_{b'} > m_{t'}$ , the decay  $b' \rightarrow t' W$  is forbidden. The decay  $b' \rightarrow t' W^*$  although allowed, is phase space suppressed 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 190 GeV. Hence, the  $b'$  cannot decay to a top quark. Furthermore, while some recent studies (see [5]) 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  $2\sigma$  bound  $|V_{tb}|^2 + 0.75|V_{t'b}|^2 \leq 1.14$  [6] coming from  $Z \rightarrow b\bar{b}$  to constrain the CKM element  $V_{cb'}$ .

There are presently three bounds on the  $b'$  mass for  $m_{b'} > 96$  GeV and all of them suffer from the drawback of assuming a 100 % branching ratio for a specific decay channel. The first one [7],  $m_{b'} > 199$  GeV, assumes that  $\text{BR}(b' \rightarrow bZ) = 100\%$ . We will drop this condition and use instead their plot of  $\sigma(p\bar{p} \rightarrow b'\bar{b}' + X) \times \text{BR}^2(b' \rightarrow bZ)$  as a function of the  $b'$  mass. The second one [8]  $m_{b'} > 128$  GeV, is based on the data collected in the top quark search. Because the D0 collaboration looked for  $t \rightarrow bW$ , the analysis can be used to set a limit on  $\sigma(p\bar{p} \rightarrow b'\bar{b}' + X) \times \text{BR}^2(b' \rightarrow cW)$ . By doing so we assume that the  $b$  and  $c$  quark masses are negligible and that  $\sigma(p\bar{p} \rightarrow b'\bar{b}') \approx \sigma(p\bar{p} \rightarrow t\bar{t})$ . The obtained limit  $m_{b'} > 128$  GeV assumes  $\text{BR}(b' \rightarrow cW) = 100\%$ . The third bound is from CDF [9] and is based on the decay  $b' \rightarrow bZ$  followed by the search for  $Z \rightarrow e^+e^-$  with displaced vertices. They also assume  $\text{BR}(b' \rightarrow bZ) = 100\%$  and their excluded region depends heavily on the  $b'$  lifetime. This means we cannot use this limit in our analysis (for a discussion see [5]).

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 [10], is all that is available for  $m_{b'} > 96$  GeV. We will draw exclusion

plots in the planes  $(R_{\text{CKM}}, m_{b'})$  and  $(m_{t'}, m_{b'})$ , where  $R_{\text{CKM}} = \left| \frac{V_{cb'}}{V_{tb'} V_{tb}} \right|$ , from 96 GeV to 190 GeV without assuming a definite value for the branching ratios of specific channels. Notice that the use of the  $R_{\text{CKM}}$  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.

## 2. $b'$ production and decay

At LEP, a pair of  $b' \bar{b}'$  quarks is produced via  $e^+ e^- \rightarrow b' \bar{b}'$ . The corresponding cross section was calculated using PYTHIA [11] with initial state radiation (ISR), final state radiation and QCD corrections turned on. The results were cross checked in [5] and agree very well with the PYTHIA results.

The equivalent process at the Tevatron is  $p \bar{p} \rightarrow b' \bar{b}' + X$  with the relevant processes being  $gg (q \bar{q}) \rightarrow b' \bar{b}'$ . Due to its hadronic nature, this cross section is equal to the top quark production one, and it is known to order  $\alpha_s^3$  [12]. This approximation is used both by the CDF and the D0 collaborations in their studies on  $b'$  production and decay.

Two body  $b'$  decays occur either through neutral currents (NC) or through charged currents (CC). Although NC proceed only via loops, it was shown in [13] that depending on the values of the CKM matrix elements and on the values of the quark masses, they can be comparable to CC decays. The reason is simple: if  $b' \rightarrow W t$  and  $b' \rightarrow W t'$  are not allowed, the dominant CC decay is  $b' \rightarrow W c$  which is doubly Cabibbo suppressed.

As long as the Higgs channel is closed the dominant neutral decay is  $b' \rightarrow b Z$ . Other neutral decays like  $b' \rightarrow b g$  and  $b' \rightarrow b \gamma$  give smaller contributions but can sometimes be relevant. As soon as the Higgs channel opens the decay  $b' \rightarrow b H$  can be as large as  $b' \rightarrow b Z$ .

The three body decays  $b' \rightarrow b e^+ e^-$ ,  $b' \rightarrow b \nu \bar{\nu}$  and  $b' \rightarrow b q \bar{q}$ , including box diagrams were calculated in [14]. Using the results in [14] we estimate [5] that all three body decays plus the decay  $b' \rightarrow b \gamma$  are smaller than  $b' \rightarrow b g$ . Nevertheless, because we want to make a conservative estimate we will take it to be as large as  $b' \rightarrow b g$ .

Taking  $V_{ub'} V_{ub} \approx 0$  and  $V_{cb} \approx 10^{-2}$  and using the unitarity of the CKM matrix we obtain  $V_{t'b'} V_{t'b} \approx -V_{tb} V_{tb'}$ . Thus, we can write all branching fractions as a function of three quantities alone:  $R_{\text{CKM}}$ ,  $m_{t'}$  and  $m_{b'}$ .

One-loop calculations of the NC  $b'$  decays were performed using the FeynArts, FeynCalc [15] and the LoopTools/FF [16] packages. We have carried out several checks in the four generations model following [4, 13, 14] and we have found full agreement. To decide on the relevant values of  $R_{\text{CKM}}$

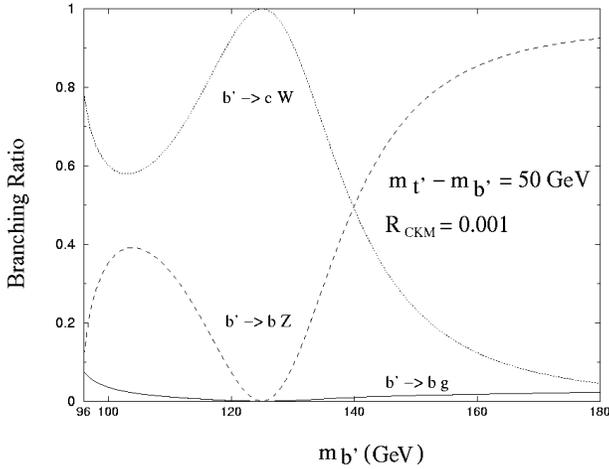


Fig. 1. Branching ratios as a function of the  $b'$  mass. The Higgs channel is closed. The dashed line is  $b' \rightarrow b Z$ ; the full line is  $b' \rightarrow b g$  and the dotted line is  $b' \rightarrow c W$ .

and  $m_{t'}$  to use, we present in Fig. 1 the branching ratios as a function of the  $b'$  mass with  $R_{\text{CKM}} = 0.001$  and  $m_{t'} - m_{b'} = 50$  GeV. The closer to  $m_{b'} = 96$  GeV we are the larger  $b' \rightarrow b g$  gets due to phase space suppression of the competing NC  $b' \rightarrow b Z$ . In fact, for an almost degenerate fourth family and small values of  $R_{\text{CKM}}$ ,  $b' \rightarrow b g$  can be the dominant NC for  $m_{b'} = 96$  GeV. As soon as one moves away from this value,  $b' \rightarrow b Z$  becomes the dominant NC. If the Higgs channel is closed, for  $m_{b'} \geq 97$  GeV, the competition is always between  $b' \rightarrow c W$  and  $b' \rightarrow b Z$ . As  $m_{b'}$  rises so does the NC except if the Glashow–Iliopoulos–Maiani (GIM) mechanism gets in the way. It can be clearly seen in the figure that the GIM mechanism is 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  $R_{\text{CKM}}$  grows so does  $b' \rightarrow c W$  and the crossing point is shifted to the left. As the mass difference tends to zero the GIM effect is shifted to  $m_{b'} \approx m_t$ .

### 3. Results and discussion

Using the latest 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 results based on the DELPHI data, are shown in Figs. 2 and 3. The excluded regions in the two plots due to the limits on  $\text{BR}_{b' \rightarrow c W}$  are the stripe centered in  $m_{t'}$  in Fig. 2 and the upper excluded region in Fig. 3. The remaining excluded regions are due to limits on  $\text{BR}_{b' \rightarrow b Z}$ . When  $(m_{t'} -$

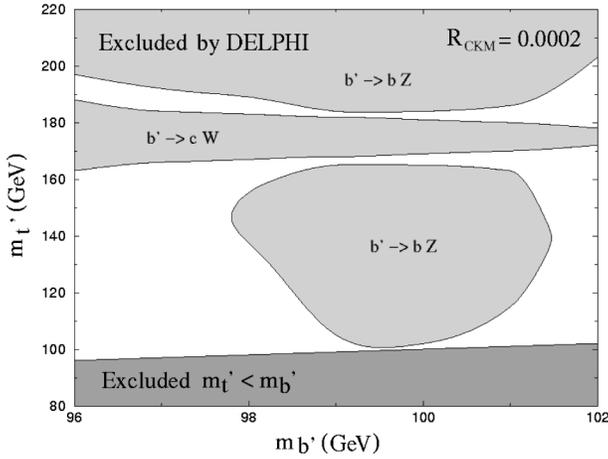


Fig. 2. 95% confidence level (CL) excluded region in the plane  $(m_{t'}, m_{b'})$  with  $R_{CKM} = 0.0002$ , obtained from limits on  $BR_{b' \rightarrow bZ}$  and  $BR_{b' \rightarrow cW}$ .

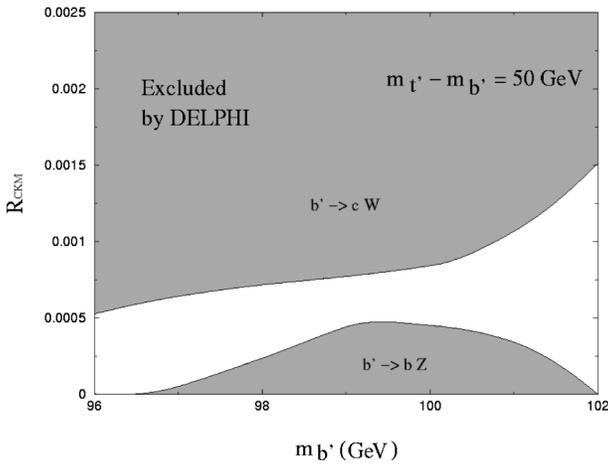


Fig. 3. 95% CL excluded region in the plane  $(R_{CKM}, m_{b'})$  with  $m_{t'} - m_{b'} = 50$  GeV, obtained from limits on  $BR_{b' \rightarrow bZ}$  (bottom) and  $BR_{b' \rightarrow cW}$  (top).

$m_t) \rightarrow 0$ ,  $BR_{b' \rightarrow bZ}$  decreases as a consequence of a GIM suppression and  $BR_{b' \rightarrow cW}$  becomes dominant. In fact, when  $m_{t'} - m_t = 0$ ,  $BR_{b' \rightarrow cW} \approx 100\%$ . Thus, there is always an excluded stripe around  $m_t$ . As  $R_{CKM}$  grows, *i.e.*, CC dominates, the stripe gets larger and the other two regions in Fig. 2 get smaller. This can also be seen in Fig. 3 where for  $R_{CKM} > 0.0015$  everything is excluded. Obviously this will change if we change the mass difference.

The reason why there is not a lower bound close to 96 GeV in Fig. 3 is because of the competing NC. Close to the  $Zb$  threshold ( $\approx 96$  GeV),  $b' \rightarrow bg$  dominates over  $b' \rightarrow bZ$  and the experimental bound on  $\text{BR}_{b' \rightarrow bZ}$  becomes useless. As one moves away from the  $Zb$  threshold,  $b' \rightarrow bZ$  becomes the dominant NC. After 102 GeV almost all values are allowed because the experiments are not sensitive to those mass values.

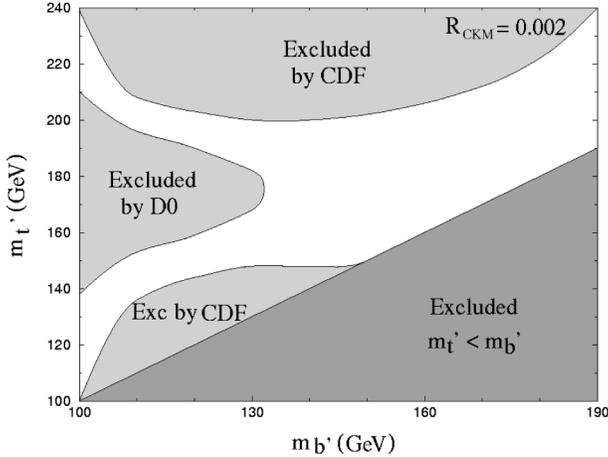


Fig. 4. 95% CL excluded region in the plane  $(m_{t'}, m_{b'})$  with  $R_{\text{CKM}} = 0.002$ , obtained from limits on  $\text{BR}_{b' \rightarrow bZ}$  by the CDF coll. and  $\text{BR}_{b' \rightarrow cW}$  by the D0 coll.

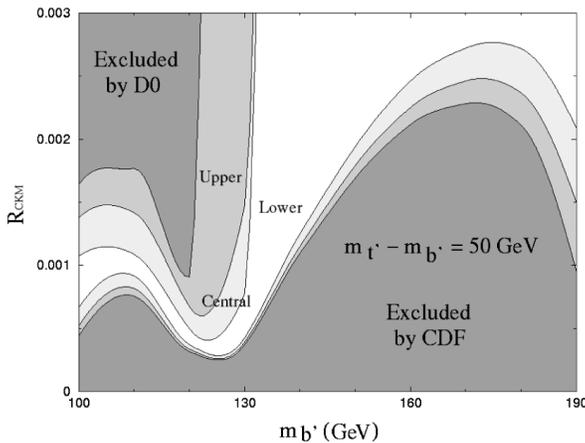


Fig. 5. 95 % CL excluded region in the plane  $(R_{\text{CKM}}, m_{b'})$  with  $m_{t'} - m_{b'} = 50$  GeV, obtained from limits on  $\text{BR}_{b' \rightarrow bZ}$  by the CDF coll. (bottom) and  $\text{BR}_{b' \rightarrow cW}$  by the D0 coll. (top). Upper, Central and Lower curves correspond to the values used for the  $b'$  production cross-section.

In Figs. 4 and 5 we show similar plots but using the CDF and the D0 data. The behavior follows the general trend explained for the DELPHI data. The D0 deals with the CC and the CDF deals with the NC. The three curves marked Upper, Central and Lower in Fig. 5 are related with the theoretical error bars in the  $b'$  production cross section. In Fig. 4 we have used central values for the cross sections. Again and for the same reason we see a stripe around  $m_t$  in Fig. 4. The stripe ends, as it should, for  $m_{b'}$  close to 130 GeV which is approximately the D0 bound on  $m_{b'}$ . Notice that whatever the value of  $m_{b'}$  is, one can always find an allowed  $m_{t'}$  if  $R_{\text{CKM}}$  is not too large. As  $R_{\text{CKM}} \rightarrow 0$ ,  $\text{BR}_{b' \rightarrow bZ} \approx 100\%$  and we recover the CDF bound [7].

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  $4.5 \times 10^{-4} < R_{\text{CKM}} < 8.4 \times 10^{-4}$  and for CDF/D0 (lower)  $6.7 \times 10^{-4} < R_{\text{CKM}} < 1.1 \times 10^{-3}$ . Hence, the resulting excluded region is  $6.7 \times 10^{-4} < R_{\text{CKM}} < 8.4 \times 10^{-4}$ .

With the bound  $|V_{tb}|^2 + 0.75|V_{t'b}|^2 \leq 1.14$  [6] and assuming  $|V_{tb}| \approx 1$  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  $R_{\text{CKM}} < 8.4 \times 10^{-4}$  and so

$$V_{cb'} < 8.4 \times 10^{-4} \sqrt{0.14/0.75} \approx 3.6 \times 10^{-4}$$

with  $m_{t'} = m_{b'} + 50 = 150$  GeV. The bound gets weaker for smaller  $m_{t'}$  [6].

Finally we mention that if new particles are added and the  $b'$  gets a new decay channel the excluded region will always shrink. This can be seen in [5] where an exclusion plot with the Higgs channel opened and a Higgs mass of 115 GeV is shown (see also [4]).

#### 4. Conclusion

Using all available experimental data for  $m_{b'} > 96$  GeV we have shown that there is still plenty of room for a sequential  $b'$  with a mass larger than 96 GeV. This is our main conclusion. We have also shown that the allowed region depends heavily on the values of  $R_{\text{CKM}}$  and  $m_{t'}$ . The region where  $m_{t'} \approx m_t$  is always excluded due to a 100% CC. All plots show that  $R_{\text{CKM}}$  is somewhere between  $10^{-4}$  and  $10^{-2}$  which is a reasonable value regarding the CKM elements known so far. In fact, those CKM values suggest that  $V_{cb'} \approx 10^{-4} - 10^{-3}$ . If  $V_{t'b} \approx 10^{-1}$  then a value of  $R_{\text{CKM}}$  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 and also the CDF analysis are being improved and we hope to shrink the allowed region with this new data.

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  $b'\bar{b}'$

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. For a detailed discussion on future searches see [3].

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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