CERN-TH/95–326

FISIST/14-95/CFIF

NTUTH-95-11

hep-ph/9512239

$R_b - R_c$ Crisis and New Physics

Gautam Bhattacharyya

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Gustavo C. Branco

Centro de Física das Interacções Fundamentais, Instituto Superior Técnico - Dep. de Física, Avenida Rovisco Pais P - 1096 Lisboa Codex - Portugal

Wei-Shu Hou

Department of Physics, National Taiwan University, Taipei, Taiwan 10764, R.O.C.

(September 25, 2013)

Abstract

The experimental values of R_b and R_c are the only data which do not seem to agree with Standard Model predictions. Although it is still premature to draw any definite conclusions, it is timely to look for new physics which could explain the excess in R_b and deficit in R_c. We investigate this problem in a simple extension of the Standard Model, where a charge $+2/3$ isosinglet quark is added to the standard spectrum. Upon the further introduction of an extra scalar doublet, one finds a solution with interesting consequences.

PACS numbers:

Typeset using REVTEX

Precision electroweak tests at the Z^0 resonance provide impressive confirmation of the Standard Model (SM), allowing for the extraction of m_t via global fits to electroweak data, which is in good agreement with direct measurements at the Fermilab Tevatron. Recently, however, the so-called "$R_b - R_c$" crisis has been reported [1], namely, an excess in $R_b \equiv \Gamma_b/\Gamma_{\rm had}$ and deficit in $R_c \equiv \Gamma_c/\Gamma_{\rm had}$, with respect to their SM predictions. From a multiparameter electroweak fit, the latest results are

$$R_b^{\rm exp} = 0.2219 \pm 0.0017, \qquad R_c^{\rm exp} = 0.1543 \pm 0.0074, \tag{1}$$

while, for $m_t = 180$ GeV, $R_b^{\rm SM} = 0.2156$, and $R_c^{\rm SM} = 0.172$. Thus, with an experimental accuracy of $\sim 0.8\%$ (5%), the SM expectation for R_b (R_c) lies 3.7σ (2.5σ) below (above) the experimental result. Of growing concern is that, while the discrepancy had existed previously [2], it became more acute after inclusion of 1994 data. It should be noted that the measurements of R_b and R_c are rather correlated (-0.35), therefore an improvement in the measurement of one will also reflect on the measurement of the other.

It may be premature to use these measurements to draw any definite conclusions. Indeed, more data or better analysis methods might bring R_b and R_c back at par with their SM predictions. On the other hand, there is also the more exciting possibility that, with time, R_b might remain above the SM prediction and R_c below it, thus hinting at physics beyond the SM. It should be kept in mind, however, that the measurement of the total hadronic width through the variable $R_\ell = \Gamma_{\rm had}/\Gamma_\ell$ is rather consistent with the SM. One may therefore ask: What sort of new physics can shift R_b and R_c in the *right directions*, while keeping other observables consistent with present experimental values?

In this paper we first explore the case where Γ_c is reduced while Γ_b is not changed. This shifts R_b and R_c in the right directions. A viable extension of the SM which can achieve this consists of adding a charge $+2/3$ quark Q whose left-handed and right-handed components are both singlets under $SU(2)_L$. The new quark Q mixes with the standard charge $+2/3$ quarks, and as a result Γ_c could be reduced [3]. Isosinglet charge $+2/3$ quarks have been considered in models where the supersymmetric gauge group is extended [4].

At the phenomenological level, it could lead to [5] a significant enhancement of $D^0 - \bar{D}^0$ mixing, detectable at the next generation of experiments. More drastically, the charge $+2/3$ isosinglet quark might itself be the 180 GeV quark observed at the Tevatron, while the actual top quark remains hidden below M_W via fast $t \to cH^0$ decay induced by large c-Q and t-Q mixings [6]. As we shall see later, the latter scenario provides us with a provocative possibility for *both* R_b and R_c to move in the right directions in a *substantial* way.

The minimal extension of adding only one charge $+2/3$ isosinglet quark Q leads to new gauge invariant mass terms of the type $\bar{Q}_L Q_R$ and $\bar{Q}_L u_{jR}$, as well as additional Yukawa coupling terms $\bar{u}_{iL} Q_R$, where u_i denotes standard up-type quarks. For the sake of simplicity, let us for now ignore the first generation and set the standard KM mixing matrix to unity [7]. One then has the charged current

$$(\bar{c}_L\ \bar{t}_L\ \bar{Q}_L) \begin{pmatrix} C_2 & 0 \\ -S_2 S_3 & C_3 \\ +S_2 C_3 & S_3 \end{pmatrix} \gamma_\mu \begin{pmatrix} s_L \\ b_L \end{pmatrix}, \tag{2}$$

where $S_i \equiv \sin\theta_i$, $C_i \equiv \cos\theta_i$. The isospin part of the neutral current becomes

$$(\bar{c}_L\ \bar{t}_L\ \bar{Q}_L) \begin{bmatrix} C_2^2 & -S_2 C_2 S_3 & +S_2 C_2 C_3 \\ -S_2 C_2 S_3 & C_3^2 + S_2^2 S_3^2 & C_2^2 S_3 C_3 \\ +S_2 C_2 C_3 & C_2^2 S_3 C_3 & S_2^2 C_3^2 + S_3^2 \end{bmatrix} \gamma_\mu \begin{pmatrix} c_L \\ t_L \\ Q_L \end{pmatrix}. \tag{3}$$

The only immediate change accessible in Z decay is in the $Zc\bar{c}$ coupling,

$$v_c = \sqrt{\rho}\ \left[t_3^c C_2^2 - 2Q_c \sin^2\bar{\theta}_W\right], \qquad a_c = \sqrt{\rho}\ t_3^c C_2^2, \tag{4}$$

where $\sqrt{\rho}$ represents the non-trivial wave function renormalization of the Z boson, and $\bar{\theta}_W$ is the effective weak angle at the Z-pole. One finds

$$R_l \simeq R_l^{\rm SM} \left(1 - 0.41 S_2^2 + 0.30 S_2^4\right), \tag{5}$$

$$R_b \simeq R_b^{\rm SM} / \left(1 - 0.41 S_2^2 + 0.30 S_2^4\right), \tag{6}$$

$$R_c \simeq R_c^{\rm SM} \left(1 - 2.41 S_2^2 + 1.75 S_2^4\right) / \left(1 - 0.41 S_2^2 + 0.30 S_2^4\right). \tag{7}$$

The SM expressions are given, to very good approximation, as

$$
\begin{aligned}
R_l^{\rm SM} &= (20.2 + 10.0\ \delta\rho + 6.3\ \ \delta V_b^t)(1 + \alpha_S(m_Z)/\pi + \cdots), \\
R_b^{\rm SM} &= 0.220 - 0.01\ \delta\rho + 0.25\ \delta V_b^t, \\
R_c^{\rm SM} &= 0.170 + 0.015\,\delta\rho - 0.055\,\delta V_b^t.
\end{aligned}
\tag{8}
$$

where $\delta\rho$ denotes the deviation of ρ from unity which is mainly due to the t–b splitting, and δV_b^t corresponds to the non-universal correction to the $Zb\bar{b}$ vertex. The leading Higgs dependence in $\delta\rho$ is logarithmic, whereas in δV_b^t the Higgs dependence is practically negligible. Within the framework of the SM, $\delta\rho$ and δV_b^t, then are given by ($x_i = m_i^2/m_Z^2$)

$$
\delta\rho \simeq (3\alpha/4\pi \sin^2 2\bar{\theta}_W)\ x_t, \qquad \delta V_b^t \simeq -(1.05\alpha/\pi)(x_t + 2.17\ {\rm ln}x_t). \tag{9}
$$

We now extract the bound on S_2^2 from $R_l^{\rm exp} = 20.788 \pm 0.032$, and examine the implications for R_b and R_c. To accommodate a large mixing angle we need a large value of α_S, as is evident from the expression of $R_l^{\rm SM}$ in eq. (8). R_b and R_c, on the other hand, are independent of α_S for all practical purposes. The combined average of LEP + SLD is $\alpha_S(m_Z) = 0.123 \pm 0.004 \pm 0.002$ [1]. Since we use R_l to extract S_2^2, we cannot use the value of $\alpha_S(m_Z)$ derived from R_l within the framework of SM. However, various other independent measurements of α_S at LEP (*e.g.* the comparison between 3-jet and 2-jet events, or, say, from τ-polarization measurement) are consistent with each other. We therefore choose two representative $\alpha_S(m_Z)$ values [8] as 0.123 and 0.126. Since R_l is almost flat with respect to variation of m_t, we fix $m_t = 180$ GeV. We take 70 GeV and 300 GeV as two representative values for m_{H^0}. A low m_{H^0} is slightly preferred to maximize the allowed S_2^2 and hence enhance the effects in R_b and R_c. The bounds on S_2^2 derived from the 2σ lower limit of R_l, and the consequent changes in δR_b and δR_c using those angles, are displayed in Table I.

It is clear from Table I that, although the shifts are in the right directions, the discrepancies in R_b and R_c are hard to make up in this minimal scenario. What one really needs is a scenario where Γ_b is increased while Γ_c is accordingly reduced, such that R_l remains consistent with experiment – a situation which could shift R_b and R_c in the right directions by significant amounts. However, *no minimal extension beyond the SM discussed so far in the literature can do this job satisfactorily.* In minimal supersymmetry, light superpartners ($\sim$ 50–70 GeV) could increase Γ_b and push up R_b by $\simeq 2\sigma$, but R_c remains practically untouched [10]. This results in a lower $\alpha_S(m_Z) \simeq 0.118$ which is in consonance with lower energy measurements, but not compatible with a simple supersymmetric Grand Unified Theory [11]. The distinctive feature of the isosinglet charge $+2/3$ quark scenario is that R_c, which in most scenarios is hard to move, can be brought down by $\simeq 0.4\sigma$ by directly affecting Γ_c [3], while the indirect effect on R_b is also non-negligible ($\simeq 0.5\sigma$ upward pull). Note, however, that the c-Q mixing angle S_2 has been singled out, while S_3 is tacitly assumed to be smaller. This is not particularly natural, for one might expect the t-Q mixing angle S_3 to be greater than S_2. Allowing for large S_3, one could consider an intriguing effect of the so called "light (hidden) top" scenario of ref. [6], which we now elaborate.

With both t and Q entering the $Zb\bar{b}$ vertex correction, the charged and neutral current couplings that appear in the loop are modified through eqs. (2) and (3). The impact can be summarized as an *effective* top mass,

$$m_t^2 \longrightarrow (m_t^{\text{eff.}})^2 = m_t^2 + 2S_3^2 m_t(m_Q - m_t) + S_3^2(S_2^2 + S_3^2 - S_2^2 S_3^2)(m_Q - m_t)^2. \qquad (10)$$

If one takes $m_t = 180$ GeV and $m_Q > m_t$, this relation then dictates that S_3^2 has to be very small to avoid aggravating the situation with R_b. In the scenario of ref. [6] (originally proposed in ref. [12]), however, it is proposed that $m_t < M_W$ is possible because of fast $t \to cH^0$ decay as compared to the standard $t \to bW^*$ mode, which allows the top quark to evade earlier searches by the CDF Collaboration. It is then natural to take $m_Q = 180$ GeV to be the heavy quark that is observed at the Tevatron. This could work *only if* both S_2^2 and S_3^2 are sizable [6]. If such is the case, then $m_t^{\text{eff.}}$ in the $Zb\bar{b}$ loop could be much smaller than 180 GeV. It has been known for a long time that *the larger R_b value favors a lighter m_t than suggested from the global electroweak fit* (and later, the Tevatron discovery). We now have a mechanism to fit both demands, hence it is worthwhile to redo our analysis. We will come back to the issue of R_l later, and for now just concentrate on R_b and R_c.

Let us illustrate how the mechanism would work. First, $R_b^{\rm SM}$ in eq. (6) should become $R_b^{\rm SM}(m_t^{\rm eff})$, with $m_t^{\rm eff}$ as given in eq. (10). Since R_c, in particular, may not be as far away from its SM value as in eq. (1), we assume that R_b is shifted by $+3.7\sigma$, while R_c is shifted by -1.4σ, such that $R_b + R_c$ is not drastically different from SM, *i.e.*

$$R_b \simeq 0.2219 \ \ (+3.7\sigma \text{ shift}), \quad R_c \simeq 0.1616 \ \ (-1.4\sigma \text{ shift}). \tag{11}$$

Thus, with $R_c/R_c^{\rm SM} \simeq 0.940$, from eq. (7) we find

$$S_2^2 = 0.0305, \tag{12}$$

which is larger than the values of 0.007 – 0.009 given in Table I. Substituting into eq. (6), we find that $R_b^{\rm SM}(m_t^{\rm eff.}) = 0.219$, which implies that $m_t^{\rm eff.} \simeq 100$ GeV. In the scenario of ref. [6], we could, for example, take $m_t = 70$ GeV and $m_Q = 180$ GeV. Solving eq. (10) we get

$$S_3^2 \simeq 0.27, \tag{13}$$

which is larger than S_2^2. Note that t is still dominantly the $SU(2)$ partner of the b quark, which justifies our flavor label. It may be noted , however, that with $C_2S_2S_3 \simeq 0.089$, the $\bar{c}_L t_R H^0$ Yukawa coupling is a factor of 3.5 weaker than in ref. [6], and if $m_{H^0} \gtrsim 60$ GeV, phase space suppression of $t \to cH^0$ is itself too severe to allow it to dominate over the standard $t \to bW^*$ mode. We turn, however, to the issue of R_l, the resolution of which results in a possible way out from this problem as well. Note that the present mechanism naturally does not affect Γ_d and Γ_s, and could be chosen not to affect Γ_u.

It should be emphasized that, within the present setup (minimal addition of Q), R_l cannot be accounted for. The reason is because something similar to eq. (10) would also enter into $\delta\rho$, making it smaller than the SM value for $m_t = 180$ GeV. To be more precise, defining $\delta\rho = (3\alpha/4\pi \sin^2 2\bar{\theta}_W)\ \hat{T}$, one finds [13]

$$\hat{T} = x_t + S_3^2 \left(-x_t + x_Q - C_3^2\ f_{tQ}\right) + S_2^2 \left(S_2^2 S_3^2 x_t + S_2^2 C_3^2 x_Q + (2 - S_2^2) S_3^2 C_3^2\ f_{tQ}\right), \tag{14}$$

where $f_{ab} = x_a + x_b + 2/(x_a^{-1} - x_b^{-1}) \ln x_a/x_b$. Using eqs. (12) and (13) and $m_t, m_Q = 70, 180$ GeV, one obtains $\hat{T} = 1.14$, which should be compared with $\hat{T}^{\rm SM}(m_t = 180) = 3.90$.

However, $\hat{T}$ is largely a measure of the accumulative effect of doublet splitting in Nature, which enters into the W and Z boson two-point functions (vacuum polarization). In contrast, the effects that we discuss are for the *flavor specific* $Zc\bar{c}$ (tree level) and $Zb\bar{b}$ (t and Q in loop) three-point functions [15]. Departing from the minimal addition of a singlet quark Q, it is easy to conceive other sources of doublet splitting that affect mainly the two-point functions and only marginally the flavor specific three-point functions. A convenient example is a second Higgs doublet with $m_{H^+} > v$ but $m_{h^0} < M_W$, where h^0 stands for lightest neutral (pseudo)scalar. This gives a *positive* contribution $\hat{T}^h = f_{+0}/3$, where '+' and '0' stand for m_{H^+} and m_{h^0}. Numerically, taking $m_{H^+}, m_{h^0} = 300, 60$ GeV, one obtains $\hat{T}^h = 2.78$. Hence, a sufficiently split second scalar doublet could mimic the effect of the SM top-contribution to $\delta\rho$, and help R_l maintain its near-perfect agreement with observation. As an extra bonus, $m_{h^0} < 60$ GeV becomes possible. In fact, no realistic limit exists on the lighter neutral Higgs in a two-doublet scenario. Thus, a relatively light h^0 boson (which is not directly produced in e^+e^- collisions) could help overcome the above mentioned phase space suppression in the decay mode $t \to ch^0$, and facilitate the hiding of the top below M_W [14]. Note that a heavy H^+ boson makes little impact on low energy observables such as $b \to s\gamma$ and B^0-$\bar{B}^0$ mixing.

We turn towards phenomenological consequences and check whether one runs into conflict with other data. In the conservative approach, because of the smallness of S_2 and the tacit assumption that S_3 is even smaller, there is practically no observable consequences, beyond the insufficient negative pull on R_c. However, for the more provocative case, because both S_2 and S_3 are quite sizable, there is considerable impact on phenomenology [6], especially those involving the top and singlet quarks. First, from eq. (2) one sees that V_{cs} gets modulated by $C_2 \simeq 0.985$, which is fully compatible with present errors. Second, one finds $V_{tb} \simeq C_3 \simeq 0.85$, which may appear to be a bit small. However, in this scenario, it is the (dominantly) singlet quark Q that is "faking" the SM top quark at the Tevatron. From eq. (2) one then finds that $|V_{Qb}| \simeq S_3 \simeq 0.52$, $|V_{Qs}| \simeq S_2 C_3 \simeq 0.15$, which is in apparent conflict with recent studies at the Tevatron that give $|V_{`t\text{'}b}| = 0.97 \pm 0.15 \pm 0.07$ [16]. On closer inspection, however, what is actually measured is the "b-content" of top events. If $m_Q \simeq 180$ GeV, the leading decays are $Q \to bW$, sW; tH, tZ; cH, cZ. Using eqs. (2), (3), (12) and (13), we find their relative weights 66.3%, 5.4%, 14.6%, 7.3%, 3.3%, 3.0%, respectively. Since $t \to cH^0$, bW^* and $H^0 \to b\bar{b}$, the final state contains b quarks whenever it contains t or H^0. Thus, the b quark content of Q decay is close to unity, and $|V_{t'b}| \simeq \sqrt{0.663 + 0.146 + 0.073 + 0.033} \simeq 0.96$, which is fully consistent with Tevatron results.

The implication for LEP-I is that, with our choices of S_2 and S_3, $\Gamma(Z \to t\bar{c} + \bar{t}c) \sim 1$ MeV [4,6], but this is no easy task to measure. We also note that the impact on A_{FB}^f and A_f are within errors. In contrast, the consequence at LEP-II is dramatic. The "light (hidden) top" scenario demands that $m_h \lesssim m_t \lesssim M_W < m_Q \simeq 180$ GeV. Thus, unless the Tevatron could rule out the scenario by detailed analysis below M_W [14,17] (without assuming SM decay), *toponium may show up soon at LEP-II.* One could also observe open $t\bar{t}$, and check that the decay rate is indeed faster than in SM. At the same time, one should be able to discover a relatively light Higgs boson in the decay products of $t\bar{t}$ events.

Turning our attention to D^0–$\bar{D}^0$ mixing, we note that it is expected to be small in the SM, while the present scenario can induce a substantial effect. The Z mediated contribution gives [5] $\Delta m_D \simeq \sqrt{2} G_F f_D^2 B_D m_D \eta_{\rm QCD} S_1^2 S_2^2/3 \sim 1 \times 10^{-7} S_1^2 S_2^2$ GeV, hence it depends crucially on the size of S_1. We have set $S_1 = 0$ from the outset, but it is in principle a free parameter, just like S_2 and S_3. Furthermore, it has been shown [5,6] that the hierarchy $S_1 : S_2 : S_3 \sim m_u : m_c : m_t$ does not necessarily hold. From the experimental limit $\Delta m_D < 1.3 \times 10^{-13}$ GeV [18], we obtain the limits $|S_1| \lesssim 0.012,\ 0.006$ for $S_2^2 = 0.008,\ 0.0305$, respectively. Note that with such an S_1 value, B^0–$\bar{B}^0$ mixing in the present scenario can have both t and Q (with $m_t \lesssim M_W$ and $m_Q \simeq 180$ GeV) quarks in the loop, but can still be accounted for.

In summary, we present the case of adding a charge $+2/3$ isosinglet quark as a possible solution to the so-called $R_b - R_c$ problem. In the conservative, minimal scenario where just one such quark is added and m_t is taken as ~ 180 GeV, the precisely measured quantity R_ℓ can tolerate only a -0.4σ pull on R_c, while generating a $+0.5\sigma$ pull on R_b. The direction is right, but the magnitude is insufficient. However, in the "light (hidden) top" scenario, one could take $m_t < M_W$ and identify the dominantly singlet quark as weighing 180 GeV. One could then in principle allow $\delta R_c \sim -1.4\sigma$ while inducing $\delta R_b \sim +3.7\sigma$. The push or pull comes about because of c-Q mixing, just like in the conservative case, but in addition, R_b is raised due to a lower effective top mass. The common, key ingredient is to have rather sizable c-Q and t-Q mixings. It is, however, necessary to add a sufficiently split scalar doublet to simulate the effect of a standard heavy top on the oblique parameters, as inferred by the global fit. At least one neutral Higgs boson should be rather light such that fast $t \to ch^0$ decay would not be hindered by phase space. The existence of toponium and light Higgs bosons are dramatic consequences that can be tested immediately at LEP-II, where the model could be fully confirmed or ruled out. Unlike MSSM solutions to R_b (but not R_c) problem, the present scenario is rather *ad hoc, i.e.* tailored to the R_b–R_c problem. But that is also an advantage, for its effects do not show up strongly elsewhere except when involving heavy charge $+2/3$ quarks. If new particles are found at LEP II, one should strive to distinguish between the light chargino/stop option of minimal supersymmetric Standard Model, *vs.* the light top/Higgs scenario with exotic charge $+2/3$ isosinglet quarks.

ACKNOWLEDGMENTS

GB thanks Suchandra Dutta for private communication regarding electroweak fit and D. Choudhury for discussions. The work of GCB was supported in part by Science Project No. SCI-CT91-0729 and E.C Contract No. CHRX-CT93-0132. WSH is supported in part by grant NSC 85-2112-M-002-011 of the Republic of China. He also wishes to thank the hospitality of the CERN Theory Division.

REFERENCES

[1] LEP Electroweak Working Group report, presented at the 1995 International Europhysics Conference on High Energy Physics, Brussels, Belgium; and the 17th International Symposium on Lepton-Photon Interactions, Beijing, China, 1995.

[2] In the Glasgow Conference (1994) a discrepancy of $+2\sigma$ in R_b and -1.5σ in R_c were reported, based on data accumulated until the end of 1993. See the reports from the LEP Collaborations ALEPH, DELPHI, L3 and OPAL, and the LEP electroweak working Group, preprint CERN–PPE/94-187 (1994).

[3] As we were preparing this manuscript, a paper by E. Ma, preprint UCRHEP-T153, hep-ph/9510289, appeared where a singlet charge $+2/3$ quark and the $I_3 = -1$ component of an isotriplet quark are employed to explain R_c and R_b, respectively.

[4] R. Barbieri and L. J. Hall, Nucl. Phys. **B 319**, 1 (1989); for a general review on singlet quarks, see, for example, V. Barger, M. S. Berger and R. J. N. Phillips, Phys. Rev. D **52**, 1663 (1995).

[5] G. C. Branco, P. A. Parada and M. N. Rebelo, Phys. Rev. D **52**, 4217 (1995).

[6] W. S. Hou and H. C. Huang, Phys. Rev. D **51**, 5285 (1995).

[7] To avoid confusion, let us clarify our notation as follows. We first diagonalize the standard u-quark mass matrix and relegate the 3×3 standard quark mixing matrix (consistently approximated as unity throughout the paper) to the down quark sector. We then add the singlet quark Q and follow the convention of L. Lavoura and J. P. Silva, Phys. Rev. D **47**, 2046 (1993).

[8] $\alpha_S(m_Z) = 0.126$ is within 1σ of the LEP + SLD average and within 2σ of the global average of 0.117 ± 0.005. See B. R. Webber, hep-ph/9410268, proceedings of the XXVII International Conference on High Energy Physics, Glasgow, Scotland, 20–27 July, 1994.

[9] S. Dutta (L3 Collaboration, Tata Institute), private communication.

[10] J. D. Wells, C. Kolda and G. L. Kane, Phys. Lett. **B 338**, 219 (1994); P. H. Chankowski and S. Pokorski, preprint IFT-UW-95/5, hep-ph/9505304; D. Garcia and J. Solà, Phys. Lett. **B 354**, 335 (1995). See, however, E. Ma and D. Ng, preprint TRI-PP-95-55, hep-ph/9508338 for critical remarks.

[11] Ignoring possible threshold effects and contribution from higher dimensional operators, $\alpha_S(m_Z)$ does not descend below 0.125 in such a theory.

[12] B. Mukhopadhyaya and S. Nandi, Phys. Rev. Lett. **66**, 285 (1991); Phys. Rev. D **46**, 5098, 1992.

[13] L. Lavoura and J. P. Silva, ref. [7].

[14] W. S. Hou, Phys. Rev. Lett. **72**, 3945 (1994).

[15] For a discussion of the point that new physics can emerge only in vacuum polarization, and separately in $Zb\bar{b}$ vertex, see G. Altarelli, plenary talk given at the II Rencontres du Vietnam, Ho Chih Minh City, October 1995.

[16] R. Stephens, plenary talk given at the II Rencontres du Vietnam.

[17] H. Haber, *Is $M_t \simeq M_W$ Ruled Out?*, CERN-TH/95-178, hep-ph/9506426, invited talk presented at the XXXth Rencontres de Moriond, Les Arcs, Savoie, France, 11-18 March, 1995; M. Carena, H. Haber and C.E.M. Wagner, preprint CERN-TH/95-311, November 1995.

[18] Review of Particle Properties, Phys. Rev. D **50**, 1173 (1994).

TABLES

TABLE I. Bounds on S_2^2 from 2σ lower limit of R_l for a fixed $m_t = 180$ GeV, but for different values of m_H and $\alpha_S(m_Z)$, are displayed. $R_l^{\rm SM}$ for various inputs have been calculated [9] using the ZFITTER version 4.9. Also shown are the corresponding δR_b and δR_c. For $\alpha_S(m_Z) = 0.123$ and $m_H = 300$ GeV, R_l lies below the 2σ lower limit of $R_l^{\rm SM}$.

m_H		$\alpha_S(m_Z) = 0.123$			$\alpha_S(m_Z) = 0.126$	
(GeV)	S_2^2	δR_b	δR_c	S_2^2	δR_b	δR_c
70	0.007	0.0006	−0.0024	0.009	0.0008	−0.0032
300	–	–	–	0.008	0.0007	−0.0026