PHYSICAL REVIEW D VOLUME 50, NUMBER 5 1 SEPTEMBER 1994

Information and discrimination from b quark production on the Z resonance

D. Comelli and C. Verzegnassi
Dipartimento di Fisica Teorica, Università di Trieste Strada Costiera, 11 Miramare, I-34014 Trieste, and INFN, Sezione di Trieste, Italy

F. M. Renard
Physique Mathématique et Théorique, CNRS-URA 768, Université Montpellier II F-34095 Montpellier Cedex 5, France
(Received 25 February 1994)

We introduce and define operatively, in a model-independent way, a new "heavy" b-vertex parameter η_b that can be derived from the measurement of a special polarization asymmetry for production of b quarks on the Z resonance. We show that the combination of the measurement of η_b with that of a second and previously defined "heavy" b-vertex parameter δ_{bV} can discriminate a number of models of new physics that are associated with different "trajectories" in the plane of the variations of the two parameters. This is shown in particular for some popular SUSY and technicolor-type models. In general, this discrimination is possible if a measurement of *both* parameters is performed.

PACS number(s): 12.60.−i, 13.10.+q, 14.65.Fy, 14.70.Hp

I. INTRODUCTION

In the first four years of running at the CERN e^+e^- LEP collider 1, remarkable experimental effort has allowed the collection of a number of events that begins to approach the 10^7 limit, that was once considered nothing more than an optimistic dream. This is the result of a number of machines' modifications or improvements, whose main features can be found in several recent publications or in the proceedings of dedicated workshops.

Meanwhile, on the other side, the theoretical approach to the interpretation of this huge amount of data has also been adapted and improved. In fact, in very recent years it has become clear that, to a certain extent, the comparison of the various results with the minimal standard model (MSM) predictions, and the consequent search for possible signals of new physics through small deviations due to one-loop effects, can be performed in a rigorously model-independent way. In particular, it has been stressed [1] that the *leptonic* charged processes can be "read" in terms of two parameters, originally called $\epsilon_{1,3}$ in the first of Ref. [1], in a totally unbiased way, that is, for models of new physics that are able to modify any of the three classes (self-energies, vertices, boxes) of one-loop radiative effects (in practice, owing to their intrinsic irrelevance of LEP 1 physics at the starting MSM level, boxes are usually neglected for this kind of search).

The generalization of the previous philosophy to *hadron* production requires some more care. In fact, the extra vertex corrections that enter the theoretical expressions are not universal and introduce new unwanted degrees of freedom of both "light" (in practice, massless) and "heavy" quark type. The latter effect is, for the specific case of e^+e^- physics on the Z resonance, entirely due, in the MSM, to that component of the $Zb\bar{b}$ vertex due to the charged would-be Goldstone boson exchange that behaves as m_t^2 for large top masses, as has been exhaustively shown in the literature [2]. Since various models of new physics generally contribute either to the light quark and lepton or to the heavy quark degrees of freedom but not to both, it becomes necessary to develop an appropriate strategy to perform a satisfactory search for new physics effects.

A first possible attitude is that of only considering those models that would *not* contribute to the lepton and light quark vertices. Then, one only has to add to the "canonical" quantities $\epsilon_{1,3}$ one extra parameter. For the latter, an operational definition should now be provided. The original proposal [3,4], to which we shall stick in this paper, was to define the vertex correction δ_{bV} from the ratio of the $Zb\bar{b}$ and $Zs\bar{s}$ partial widths: i.e.,

$$\frac{\Gamma_b}{\Gamma_s} \equiv 1 + \delta_{bV} \qquad (1)$$

where the physical b width (we follow in fact the slightly modified version given in Ref. [4]) should be taken.

Once the definition of Eq. (1) is chosen, a systematic analysis of all LEP 1 data that includes both leptonic and hadronic channels can be performed in terms of three parameters: e.g., $\epsilon_1, \epsilon_3, \delta_{bV}$ or $\Delta\rho, \Delta_{3Q}, \delta_{bV}$ in the notation of Ref. [4], for the previously selected set of models of new physics. This was proposed in Ref. [4] and also in another series of papers [5], where an essentially similar $Zb\bar{b}$ vertex parameter was introduced (and defined ϵ_b).

The full details can be found in Refs. [4] and [5]; the point that we want to stress here is that, after the most recent LEP 1 data [6], this type of investigation leads to the conclusion that ϵ_1, ϵ_3 (or $\Delta\rho, \Delta_{3Q}$ in the notation of Ref. [4]) are now perfectly consistent with the MSM predictions. This means that the small discrepancy that might have been present in the previous determinations of $\epsilon_3(\Delta_{3Q})$ has now been (almost) completely washed out. On the contrary, the possibility of a *small* deviation is still allowed in the heavy vertex parameter δ_{bV}, since one has now [7]

$$\delta_{bV} = (-12 \pm 10) \times 10^{-3} \qquad (2)$$

0556-2821/94/50(5)/3076(9)/$06.00

and the MSM tolerance region (corresponding to the last bound $m_t \geq 131$ GeV [8]) is

$$\delta_{bV}^{\rm MSM} \leq -0.021. \quad (3)$$

If one believes that a small discrepancy is still present in R_b, one possible attitude is that of placing the full responsibility to the heavy b-vertex parameter δ_{bV}. We shall first concentrate on this solution, in which new physics only affects δ_{bV} as a direct consequence of the fact that the b quark is, for a certain type of effect, to be considered as a member of a "heavy" doublet. We shall return to the alternative solution in which new physics can modify the light fermion vertices, at the end of the paper.

In terms of shifts in the (conventionally defined) vector and axial vector $Zb\bar{b}$ couplings, the effect of new physics on δ_{bV} can be parametrized as [3,4]

$$\delta_{bV}^{\rm NP} = -\frac{4}{1+b^2}[b\delta g_{Vb}^H + \delta g_{Ab}^H] \quad (4)$$

where

$$b = 1 - \frac{4}{3}s^2 \quad (5)$$

and $s^2 \simeq 0.231$. The subscript H denotes the fact that we are now considering "heavy"-quark-type effects.

From the previous discussion it appears, we believe, that for the purposes of this search it would be extremely important to be able to define and to measure a certain experimental quantity where a *different* combination of shifts in g_{Vb}, g_{Ab} enters. In fact, such a quantity exists and has been proposed a few years ago [9]. It was defined as the "longitudinally polarized forward-backward $b\bar{b}$ asymmetry" and usually called A_b,

$$A_b = \frac{\sigma(e_L^- \to b_F) - \sigma(e_R^- \to b_F) - \sigma(e_L^- \to b_B) + \sigma(e_R^- \to b_B)}{\sigma(e_L^- \to b_F) + \sigma(e_R^- \to b_F) + \sigma(e_L^- \to b_B) + \sigma(e_R^- \to b_B)}, \quad (6)$$

and, as one sees, it requires the availability of longitudinally polarized electron beams. The remarkable feature of A_b is that of only depending on the couplings of Z to b, as was stressed in Ref. [9]. This explains the great potential interest of its measurement that will be performed in the very near future at the SLC if the very encouraging trend of recent progress in machine performance (hopefully) continues [10], and might also be performed in the near (distant) future at LEP if a phase with polarized beams became operative [11]. If this were the case, an extremely fruitful combination with the results on R_b obtained by unpolarized measurements at LEP 1 would become possible, which could allow one to draw unexpected conclusions on this fascinating and still existing possibility of small MSM failures.

The aim of this paper is that of showing that, indeed, the combination of the two independent sources of information coming from R_b and A_b is not only useful, but almost necessary if a complete analysis of possible new physics effects has to be performed. With this aim, in Sec. II we shall very briefly recall the needed definitions and the relevant theoretical expressions. In Sec. III, an investigation of the possible *combined* effects on the two heavy vertex measurable combinations of some models of new physics will be performed, showing that there would be distinct "trajectories" in the $(\delta R_b, \delta A_b)$ plane corresponding to different models, and also a brief discussion of some "unnatural" possibility of light vertex-type effects will be given, before we draw the final conclusions. A short Appendix will be devoted to the derivation of some mass relationships in one of the considered models, where one extra U(1) is involved.

II. DEFINITION OF THE SECOND HEAVY QUARK VERTEX PARAMETER

An immediate and natural way of defining a new heavy b-vertex parameter is to follow the philosophy that led to Eq. (1) in the case of δ_{bV} and to introduce the quantity η_b as

$$A_b = A_s(1+\eta_b) \quad (7)$$

i.e., as the ratios of the longitudinal polarization forward-backward asymmetries for b- and s-type quarks. The asymmetry A_s (which corresponds mathematically to that of practically massless b quarks) can be written in the form

$$A_s = 0.703\left(1 - 0.158(\Delta\kappa' + \delta_s') - \Delta_{\rm QCD}\frac{\alpha_s}{\pi} + \text{“negligible”}\right) \quad (8)$$

where $\Delta\kappa'$ is a radiative correction entirely fixed by the measurements at LEP 1 (SLC) of the effective angle $s_{\rm eff}^2(M_Z^2)$ defined as [12]

$$s_{\rm eff}^2(M_Z^2) = s^2(1+\Delta\kappa'), \quad s^2 \simeq 0.231. \quad (9)$$

The quantity δ_s' is a vertex correction [13] defined as

$$\delta_s' = -\frac{1}{2s^2}[\delta g_{Vl} - 3\delta g_{Vs} - v\delta g_{Al} + (3-4s^2)\delta g_{As}] \quad (10)$$

where $v \equiv 1 - 4s^2$ and $\Delta_{\rm QCD}$ is a QCD factor of order 1. With this choice, one can easily see that the expression of η_b becomes

$$\eta_b = -\frac{2(1-b^2)}{b(1+b^2)}[\delta g_{Vb}^H - b\delta g_{Ab}^H]. \quad (11)$$

The shifts $\delta g_{Vb,Ab}^H$ in Eq. (11) take into account in the MSM the effect of the would-be Goldstone boson exchange in the $Zb\bar{b}$ vertex and also QCD effects due to the non-negligible b mass, whose complete calculation has been given elsewhere [14] and that are, as such, supposedly known. The important feature is that, *in the MSM* (but not *a priori* in the models of new physics that we shall consider), the effect on η_b of the charged would-be Goldstone boson (that is proportional to m_t^2 in δ_{bV}) is practically negligible, owing to the fact that it gives the same contributions to δg_{Vb} and to δg_{Ab} that are nearly canceling in the combination of Eq. (11). Thus, in the MSM prediction for A_b, the "heavy" b-vertex component $\sim m_t^2$ can be ignored and the relevant expression does only contain universal self-energies and light vertices (and known QCD corrections). Obviously, this property is *a priori* no longer verified as soon as one considers models of new physics, for which the relative role of η_b could be much more relevant or fundamental.

To make the previous statement more illustrative, it is convenient to reexpress the shifts of δ_{bV} and η_b, rather than in the (g_V, g_A)basis, in that provided by the (conventionally defined) (g_L, g_R) parameters. In that case, one can write

$$\delta_{bV} = -\frac{4(1+b)}{(1+b^2)}\left[\delta g_{bL}^H - \frac{1-b}{1+b}\delta g_{bR}^H\right], \quad (12)$$

$$\eta_b = -\frac{2(1-b)}{b}\left[\frac{(1+b)^2}{1+b^2}\delta g_{bR}^H + \frac{1-b^2}{1+b^2}\delta g_{bL}^H\right]. \quad (13)$$

As one sees, in the (L,R) basis the two shifts are orthogonal, which means that effects that would not contribute to one observable will be revealed by the other one, and conversely.

To the previous remarks one can still add a property of η_b that is a direct consequence of our chosen definition Eq. (11). In fact, if one eliminates δg_{bL}^H in Eq. (12), one obtains

$$\eta_b = -\frac{2(1-b)}{b}\left[2\delta g_{bR}^H - \frac{(1-b)}{4}\delta_{bV}\right] \quad (14)$$

and, to a very good approximation, this becomes

$$\eta_b = -2\left[\delta g_{bR}^H - \frac{1}{25}\delta_{bV}\right] \quad (15)$$

showing that, once δ_{bV} is experimentally known, the measurement of η_b fixes unambiguously the pure right-handed contributions from various models to the "heavy" $Zb\bar{b}$ vertex.

After these preliminary definitions, all the necessary ingredients to formulate an unbiased search of new physics effects in the "heavy" quark vertex sector are at our disposal. One only has to take Eqs. (12) and (13) and calculate the various shifts for a set of interesting models to be examined. This will be done in the forthcoming Sec. III.

III. SURVEY OF MODELS AFFECTING THE HEAVY B VERTEX

The simplest known example of a model that contributes to the heavy b vertex is that with just one extra Higgs doublet. In this case both the charged and the neutral Higgs bosons will have to be considered. The charged contribution can be decomposed into two terms. The first one essentially reproduces that of the MSM (i.e., $\sim \delta g_{bL}$) with the same kind of m_t dependence [weighted by a factor $\sim \cot^2\beta$ where $\tan\beta$ is the ratio of the two vacuum expectation values (VEV's)]; the second one is proportional to the product of m_b^2 and $\tan^2\beta$. As such, it can only be relevant for very large values of $\tan\beta \approx m_t/m_b$. since it only modifies the right-handed $Zb\bar{b}$ coupling, it will generate a suppressed effect in δ_{bV} (again, of the same sign as that of the MSM). More interestingly, it will also be able to affect η_b. The neutral Higgs sector is described by a larger set of parameters, and is therefore more model dependent than the charged one. In general, it will affect both δg_{bL} and δg_{bR} with terms proportional to m_b^2 and will consequently be only relevant if some enhancement factor can be adjusted. In particular, this can be achieved when the value of $\tan\beta$ becomes very large. In this case, its contribution to δ_{bV} can be of opposite sign to that of the MSM [15].

These features of the simplest model with one extra Higgs doublet remain essentially unchanged if one embeds it in a supersymmetric picture, with the additional constraints between the various couplings and the existence of other types of contributions to be taken into account. This has been done in great detail in a number of previous papers [16] for the specific case of the so-called "minimal" supersymmetric standard model (MSSM) [17] for both small and large values of $\tan\beta$. The results of all analyses indicate that in some cases the effects of the Higgs sector and of the genuine "soft" supersymmetric sector can add up constructively, leading to possible effects of a few percent that should be visible at future measurements of δ_{bV}, η_b.

Among the special situations examined in Ref. [16], that corresponding to large $\tan\beta$ values was considered as a particularly interesting one. The main motivation is that, while for small $\tan\beta$ values the model essentially contributes to δg_{gL} but not to δg_{bR}, in the large $\tan\beta$ case it can affect both δg_{bL} and δg_{bR}. As a consequence of this, two independent experimental tests would become available. In particular, one would be able to draw certain "trajectories" in the (η_b, δ_{bV}) plane that would correspond to, or identify, a certain model and could be experimentally "seen," at least in a certain part of the plane.

In the analyses of Ref. [16], the contribution of the Higgs sector was calculated using the supersymmetry (SUSY) mass relationships valid at the tree level in the MSSM. Since it has become known [18] that these relationships are appreciably modified at one loop, one might be interested in evaluating the eventual modification of the relevant trajectories (that are certain functions of the various Higgs boson masses). Also, one might consider the effect of adding an extra neutral Higgs boson to the model since this seems to be a reasonable extension of the "minimal" picture.

In this paper, we have examined the two possibilities and considered as a toy model with one extra Higgs boson the so-called η model [19], whose mass relationships at the tree level, which have been already examined in the literature [20], show several interesting differences from those of the MSSM. The results of our calculation will be only shown for the Higgs sector and for the related trajectories. The remaining contributions should be identical with those computed in Ref. [16] in the MSSM case. For the η model, a separate calculation of non-Higgs effects should be performed. We believe, though, that the already large existing limits on the mass of the extra Z of this model ($M_{Z'} > 500$ GeV [13]), that also push the involved soft masses to large values, limit somehow in this model their potential effect (that should not differ drastically, in any case, form the corresponding MSSM one).

The relevant diagrams containing the various Higgs boson contributions are shown in Fig. 1; from these one derives compact expressions that have already been provided in the literature. Here we shall follow the notation of Ref. [15] that, in the large $\tan\beta$ limit chosen by us, produces the relatively simple formulas

$$\delta g_{bR}^{H} = \frac{\alpha m_b^2 \tan^2\beta}{16\pi s^2 M_W^2}\Bigg[\left(1-\frac{4}{3}s^2\right)\rho_3[m_t, M_{H^+}, m_t, M_Z] - m_t^2 C_0[m_t, M_{H^+}, m_t, M_Z] + (s^2-c^2)\rho_4[M_{H^+}, m_t, M_{H^+}, M_Z] \\ +(-1/2+1/3s^2)(\rho_3[m_b, M_A, m_b, M_Z] + \rho_3[m_b, M_h, m_b, M_Z]) \\ -\frac{1}{2}\rho_4[M_h, m_b, M_A, M_Z] - \frac{1}{2}\rho_4[M_A, m_b, M_h, M_Z]\Bigg], \tag{16}$$

$$\delta g_{bL}^{H} = \frac{\alpha m_b^2 \tan^2\beta}{16\pi s^2 M_W^2}\Bigg[+1/3s^2(\rho_3[m_b, M_A, m_b, M_Z] + \rho_3[m_b, M_h, m_b, M_Z]) \\ -\frac{1}{2}\rho_4[M_h, m_b, M_A, M_Z] - \frac{1}{2}\rho_4[M_A, m_b, M_h, M_Z]\Bigg]. \tag{17}$$

Here $\rho_{3,4}[m_1, m_2, m_3, M_Z]$ and $C_0[m_1, m_2, m_3, M_Z]$ are the functions introduced in the appendix of Ref. [15]. The masses that appear in the previous expressions are those of the charged Higgs boson (M_{H^+}), of the CP-odd neutral Higgs boson (M_A), and of that CP-even neutral Higgs boson (M_h) whose mass is nearly degenerate with M_A in the MSSM and in the η model. Starting from the given expressions, one only has to insert, at a certain level of accuracy, the mass relationships of the various models that are, in general, not the same. In particular, the famous tree-level formulas of the MSSM and the corresponding ones of the η model [20] can be substantially different. For example, one finds in the first case the equality

$$M_{H^+}^2 = M_A^2 + M_W^2 \tag{18}$$

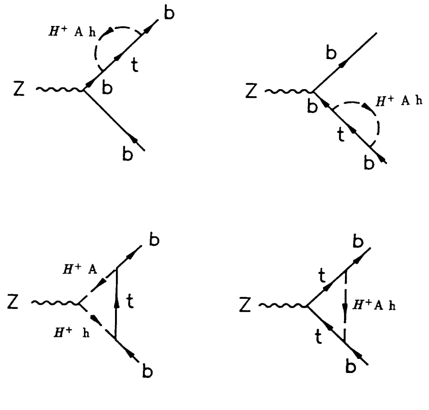

FIG. 1. Self-energy and vertex corrections to the $Zb\bar{b}$ vertex.

whereas in the second model one has

$$M_{H^+}^2 = M_A^2 + M_W^2\left[1 - \frac{2\lambda^2}{g^2}\right] \tag{19}$$

where λ is a free parameter. Also, one finds a bound for the lightest neutral in the MSSM, that becomes sensibly larger in the other case [20]. At one loop, extra non-negligible differences can arise in both models, which could in principle give rise to observable effects.

Motivated by the previous argument, we have calculated Eqs. (16) and (17) inserting the one-loop mass relationships of the two models. For the MSSM, these are known and can be found in the literature [18]. For the η model, in the chosen configuration, they are given in the short Appendix. The numerical values of δ_{bV} and η_b are shown in the following figures. They will depend on m_t (from the charged sector), on $m_b\tan\beta$ (from both sectors), and on *one* residual neutral mass chosen to be $M_A \approx M_h$. The value of M_{H+} remains fixed by the choice of the parameters, as shown in the Appendix, for the MSSM. In the case of the η model, for which extra parameters exist, we have chosen the situation that optimizes the effect and thus the related figures are actually showing the maximal deviations that the model can produce. All the numerical results are given for $m_b = 5$ GeV, $\tan\beta = 70$, following the approach of Ref. [16].

To get a qualitative feeling of the differences obtained by using the modified mass relationships, we show in Figs. 2 and 3 the trajectories corresponding to the MSSM with mass constraints at the tree level, Eq. (18), and at one loop. One sees that one effect is that of "smoothing" the m_t dependence, particularly in the heavy mass region, say, between 150 and 200 GeV (intermediate and

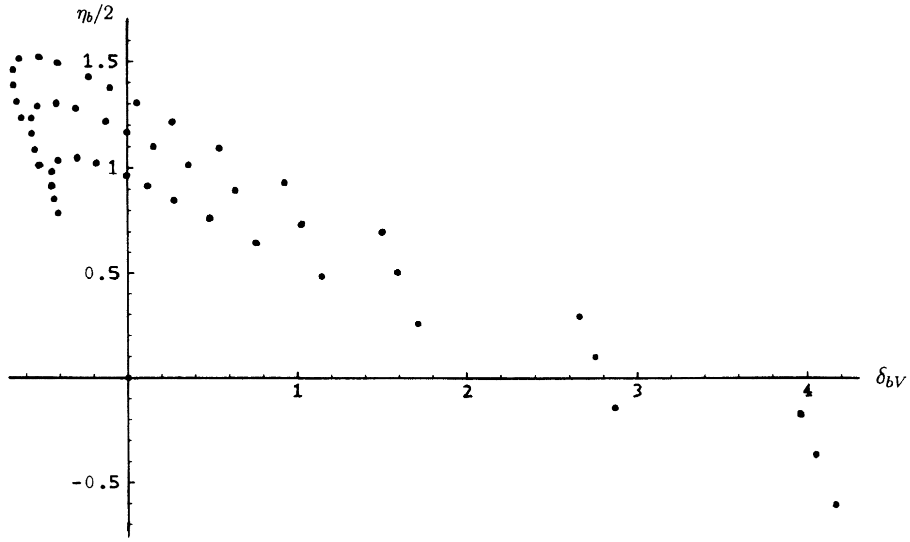

FIG. 2. Plot in the $(\delta_{bV}, \eta_b/2)$ plane of the corrections (in percent) in the MSSM case with the relationships $M_{H^+} - M_A$ at the tree level [see Eq. (18)]. There are 16 point for each "curve," each one corresponding to a given value of M_A, in particular (starting from the right to the left): M_A = 40, 45, 50, 55, 60, 65, 70, 75, 80, 90, 100, 120, 140, 160, 180, 200 GeV. The upper line corresponds to m_t = 200 GeV, the intermediate one to m_t = 150 GeV, and the lowest one to m_t = 110 GeV.

upper lines) (this is a consequence of the fact that in the charged Higgs boson contribution this dependence is now weakened in the relevant ratio between the top and the Higgs boson masses). Also, one notices a systematic (small) decrease in η_b, compensated by a corresponding (small) increase in δ_{bV}.

In fact, the compensation between η_b and δ_{bV} is quite general, in the sense that for small M_A values the full (positive) effect is on the second parameter, while for large M_A only the first one is modified. This is related to the fact that η_b is dominated by right-handed effects that are peculiar to the charged Higgs boson contribution whose decoupling is slower than that of the neutral ones (that give the important effect on δ_{bV}).

If we accept the experimental available indication [6] that seem to prefer *positive* (or, at least, not too negative) δ_{bV} shifts, we conclude that the most relevant part of the Higgs sector trajectory of this model lies in the positive η_b region of the plane (with the exception of the fraction that would correspond to substantial δ_{bV} effects (larger than, say, two percent), i.e., to very small M_A values, where the shift on η_b could be negative). Since the same feature seems to be valid for the remaining genuinely supersymmetric contributions of the model [16], we conclude that the observation of (small) positive deviations in either δ_{bV} or η_b, or possibly in both, could be interpreted as the experimental evidence for this model in the considered region of its parameter space. This would require a precision of the two measurements of the order of one percent, although in certain favorable cases the shifts could be larger than that, particularly if the effects form the Higgs boson and the genuine SUSY sector added in a substantial way as they seem to be willing to do.

The previous analysis was performed at the "extreme" value $\tan\beta = 70$ considered in Ref. [16]. For lower $\tan\beta$ values it is rather easy to draw the corresponding trajectories since, to very good approximation, one simply has to multiply the shifts of both δ_{bV} and η_b by the factor $(\tan\beta/70)$ squared. For large ($\geq$ 150 GeV) m_t values this

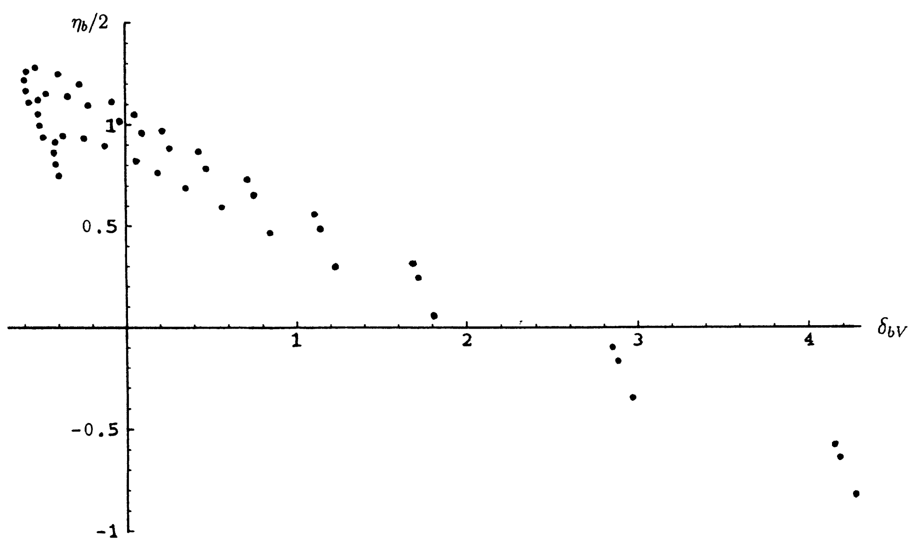

FIG. 3. The same as before for the MSSM but with the mass relationships at one loop [see Eq. (22)].

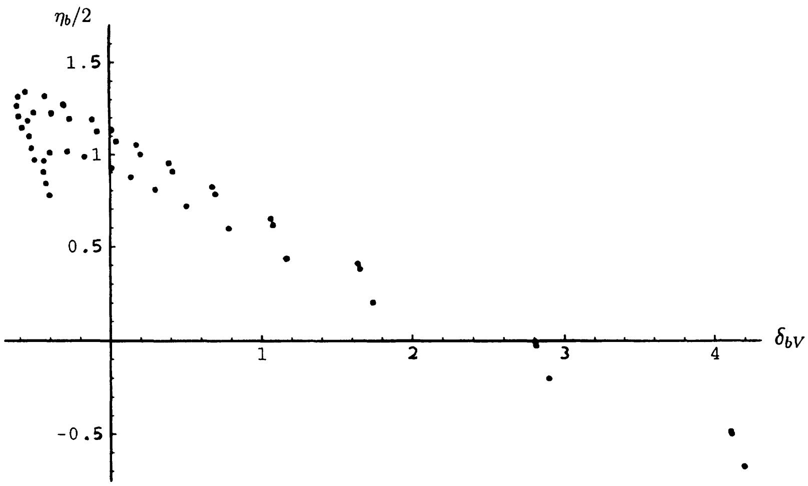

FIG. 4. The same as before but for the η model and with the mass relationships at one loop [see Eq. (24)].

leads to the conclusion that values of $\tan\beta \leq 50$ would still be revealed by a measurement of δ_{bV} with a one percent precision for $M_A \leq 50$ GeV, while a corresponding signal in η_b would be seen for $\tan\beta \geq 60$ and M_A ranging between, say, 100 and 180 GeV. Note that, as we already said, the effect on η_b could in principle survive for fairly large values of M_A (this remarkable feature was already stressed in the literature [16]).

The case of the η model is illustrated in Fig. 4, only showing the situation where the mass constraints are used at one loop. As one sees, the results for the Higgs sector are very similar to those of the previous example, with a small general increase of η_b and practically no change in δ_{bV}. Since we expect that other contributions are depressed in this case, we would conclude that the trajectories of this model are qualitatively similar to those of the MSSM (with possibly smaller overall effects); in other words, the presence of one more neutral scalar does not affect the trajectory in this case. Whether this is a general feature of SUSY models with one extra (singlet) scalar remains to be investigated; we postpone the discussion of this point to a forthcoming paper.

It can be interesting to remark that in the "orthogonal" case of technicolor-type modifications of the MSM, the associated trajectories would be completely different for a wide class of models. This can be deduced from the analysis presented in Ref. [21] where the contributions to δ_{bV} were computed. In fact, for a broad class of extended technicolor models the effect on δ_{bV} was negative and of purely left-handed type, leading in any case to negative corrections to η_b as one can easily verify from the defining Eqs. (12) and (13). The exception to this statement would be represented by a class of special models where fermion masses are due to the presence and mixing of technibaryons [22], that produce positive shifts in δ_{bV}. But for these models, the shift in η_b can be written to a good approximation, using again Eqs. (12) and (13) as

$$\eta_b \simeq \delta_{bV}\frac{1-5c^2}{5(5+c^2)}, \tag{20}$$

where $c^2 = \sin^2\alpha/\sin^2\beta'$ and α, β' are the two mixing angles of the model. Varying this ratio from zero to infinity fixes η_b in a region between, practically, zero and $-\delta_{bV}$ as shown in Fig. 5. Thus, the observation of two small effects of opposite sign with a negative η_b would provide evidence for this special model.

To conclude our investigation, we have considered the (less attractive, in our opinion) possibility that the origin of small discrepancies in $\delta R_b/R_b$ and $\delta A_b/A_b$ is due to effects of light-fermion type. Using Eqs. (7) and (8) for A_b and expressing R_b in the form [13]

$$\frac{\Gamma_b}{\Gamma_h} \equiv R_b = \frac{13}{59}\left[1+\frac{46}{59}\delta_{bV} - \frac{23}{59}(\delta_1-\delta_2) + \frac{2}{65}\Delta\kappa' + 0.1\frac{\alpha_s(M_Z^2)}{\pi} + \text{“negligible”}\right] \tag{21}$$

with $\delta_{1,2}$ given by the expressions [13]

$$\delta_1 = \delta_u^{(1)} - \frac{16s^2a}{3(1+a^2)}\delta'_u, \tag{22}$$

$$\delta_2 = \delta_d^{(1)} - \frac{8s^2b}{3(1+b^2)}\delta'_d, \tag{23}$$

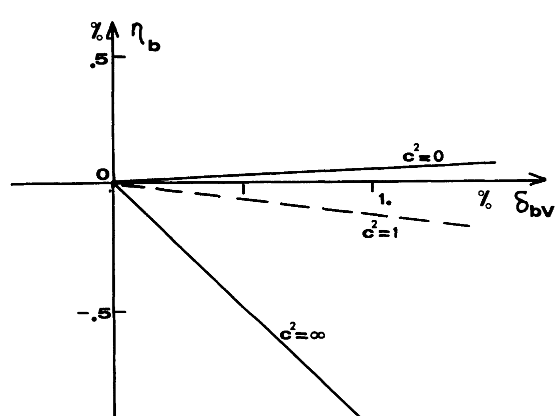

FIG. 5. The set of allowed trajectories for the Kaplan model discussed in Refs. [21,22] at variable ratio c^2 of the two mixing angles.

in which

$$\delta^{(1)}_{u,d} \equiv 4(\delta g_{Al} - \delta_{Au,d}), \quad (24)$$

$$\delta'_u \equiv -\frac{1}{2s^2}\left[\delta g_{Vl} + \frac{3}{2}\delta g_{Vu} - v\delta g_{Al} - \left(\frac{3}{2} - 4s^2\right)\delta g_{Au}\right], \quad (25)$$

$$\delta'_d = -\frac{1}{2s^2}[\delta g_{Vl} - 3\delta g_{Vd} - v\delta g_{Al} + (3 - 4s^2)\delta g_{Ad}], \quad (26)$$

$$a = 1 - \frac{8}{3}s^2, \quad (27)$$

$$b = 1 - \frac{4}{3}s^2. \quad (28)$$

We have first considered the class of models with one extra Z' of E_6 origin that has often been considered in the literature [19]. For these models, strong experimental constraints on the mixing angle exist [13] that limit its modulus to be less than, say, one percent. Using this extreme value as the tolerated limit for every single model (which is somehow optimistic) we obtain the effects shown in Fig. 6. As expected, the possible effects of this kind are always below the one percent level and are spread in the $(\delta R_b/R_b, \delta A_b/A_b)$ plane. In other words, the existing limits on the mixing angle seem to rule out visible effects in these models. Note, accidentally, that the contribution coming from the η model (that would belong in the chosen configuration of large $\tan\beta$ values to positive mixing angles) goes in the opposite direction to that of the Higgs sector, which represents a negative feature of the model. We have repeated our analysis for an extra Z' predicted by left-right symmetry models and for higher vector bosons predicted by various types of different models, in particular compositeness inspired models (Y, Y_L, Z^*) [24] and alternative symmetry-breaking models (Z_V) [25]. As in the first case, the limits imposed by precision tests in the light fermion sector prevent from getting large effect on R_b and A_b as one can see in Fig. 6.

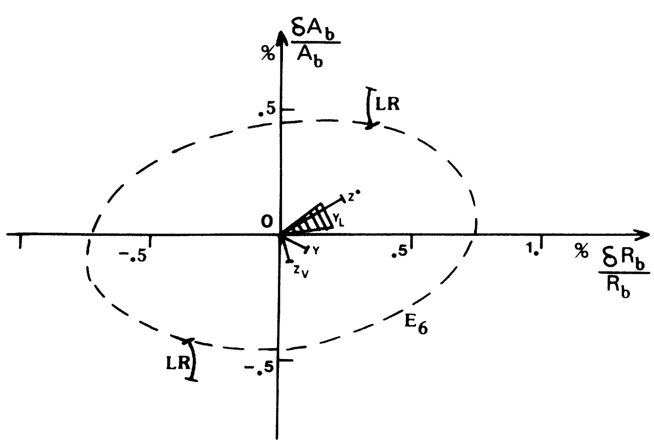

FIG. 6. Maximal allowed Z-Z' mixing effects in the $(\delta R_b/R_b, \delta A_b/A_b)$ plane, from E_6 based models with $-1 \leq \cos(\beta) \leq +1$ (dashed), from L-R symmetry based models with $\sqrt{\frac{2}{3}} \leq \alpha_{LR} \leq \sqrt{2}$ (full), in both cases with $|\theta_M| = 0.01$. We have also indicated the trajectories or small domains allowed for various alternative models of higher vector bosons (Y, Y_L, Y^*, Z_V) taking into account the constraints established in Ref. [7].

We can summarize the results of this preliminary investigation as follows. Assuming as a realistic goal a final experimental accuracy on the measurements of both A_b and R_b of a relative one percent, the best chances of providing visible signals seem to belong to models of new physics that can affect the "heavy" b-vertex component. Among these, we have seen that those of SUSY type are associated with trajectories in the plane of the variations of δ_{bV} and η_b that differ substantially from those of technicolor type. We stress the fact that this differentiation is made possible by the *combined* measurements of the two observables; for instance, the discovery of a positive effect in δ_{bV} could not discriminate the models of Figs. 2, 3, and 4 from that of Fig. 5. Should this effect (that is apparently not disallowed by the existing data) survive in the future, the role of a high precision measurement of η_b would become, to say the least, fundamental.

Before concluding this paper we would like to make a rather speculative remark concerning the possibility that a positive shift of R_b is observed with no effect on A_b. From a purely technical point of view, it might be possible to explain this effect in a picture where the MSM calculation is still valid, but where the *effective* axial vector coupling of Z to the *top* is slightly decreased. In fact, in the large m_t limit, the dominant contribution to δg_{bL} can be expressed in the form

$$\delta g_{bL} \simeq \frac{\alpha m_t^2}{8\pi s^2 M_W^2} g_{t,A} \quad (29)$$

and values of $g_{t,A}$ slightly smaller than one-half (with no effect on the corresponding b vertex) could provide this possible deviation, thus motivating searches of reasonable models where the axial "form factors" of heavy quarks can be possibly modified [23].

ACKNOWLEDGMENTS

One of us (C.V.) acknowledges some useful discussions with B.W. Lynn and H. Schwarz during a stay at UCLA. The work of C.V. was partially supported by NATO.

APPENDIX

In this Appendix we give the expressions of the relevant radiative corrections (RC's) to Eq. (18) in the MSSM and to Eq. (19) in the η model. The Higgs sector of the MSSM at the tree level is described by two parameters $\tan\beta$ and M_A; when we include the radiative corrections all the parameters which describe the spectrum of the theory enter in the mass formulas. The most important contributions to the RC's come from the top-squark–bottom-squark sector, so we must fix the soft squark masses ($m_{\tilde{t}_{L,R}} = m_{\tilde{b}_{L,R}} = m_{\tilde{q}} \simeq 1$ TeV), the trilinear SUSY-breaking parameters ($A_t = A_b = 100$ GeV), the SUSY H_1H_2 coupling μ, and of course the top mass. In the large $\tan\beta$ limit the one loop mass relationships read [18]

$$M_{H^+}^2 = M_A^2 + M_W^2 + \Delta M_{H^+}^2 \tag{A1}$$

where

$$\Delta M_{H^+}^2 = \frac{3g^2}{32\pi^2 M_W^2}\left(2m_t^2 m_b^2 \tan^2\beta - M_W^2(m_t^2 + m_b^2\tan^2\beta) + \frac{2}{3}M_W^4\right)\ln\frac{m_{\tilde{q}}^2}{m_t^2} + \frac{3g^2}{96\pi^2}\left[m_t^2\left(\frac{\mu^2 - 2A_t^2}{m_{\tilde{q}}^2}\right)\right.$$
$$\left. + m_b^2\tan^2\beta\left(\frac{\mu^2 - 2A_b^2}{m_{\tilde{q}}^2}\right)\right] + \frac{3g^2}{64\pi^2}M_W^2\left[\frac{m_t^2 m_b^2 \tan^2\beta}{M_W^2}\left(\frac{A_t + A_b}{m_{\tilde{q}}^2}\right)^2\right.$$
$$\left. - \frac{\mu^2}{m_{\tilde{q}}^2}\left(\frac{m_t^2 + m_b^2\tan^2\beta}{M_W^2}\right)^2\right] - \frac{3g^2 m_t^2 m_b^2 \tan^2\beta}{192\pi^2 M_W^2}\left(\frac{A_t A_b - \mu^2}{m_{\tilde{q}}^2}\right)^2 . \tag{A2}$$

The radiatively corrected mass M_h of the CP-even neutral Higgs boson which runs into the loop of Fig. 1 is always nearly equal to M_A.

In the η model the tree level Higgs sector is defined by four parameters: $\tan\beta, M_A, x, \lambda$. The new parameter x is the VEV of the extra complex Higgs field N and fixes the scale of the breaking of the extra U(1) gauge group, so naturally $x \gg v_1, v_2$. In this large x limit the Higgs sector, that is described by three CP-even, one CP-odd, and one charged-state, effectively reduces, at the M_Z scale, to that of the MSSM with the following identifications: $\mu = \lambda x, m_3^2 = \lambda A_\lambda x$ (m_3^2 is the soft SUSY-breaking term of the operators H_1H_2 in the MSSM, A_λ is the trilinear soft term which multiplies the product NH_1H_2 in the potential). When RC's are evaluated, in addition to the parameters of the MSSM there is another Yukawa coupling h_E of the exotic quark sector ($m_{\tilde{E}} = m_{\tilde{q}}, A_E = A_t$). So finally the extra new parameters are λ, x, and h_E. We fix x via the mass of the extra Z' boson: $M_{Z'} = 25/18 g_1^2 x^2 \sim 1$ TeV. The exotic Yukawa coupling gives very little contributions (some GeV) to the "standard" Higgs sector and can be safely fixed to 1. The Higgs spectrum is at the contrary very sensitive to the λ parameter: this strong dependence is exhibited by the charged Higgs sector [see Eq. (19)] and by the lightest CP-even mass. As shown in Ref. [20] (for values of $M_A < M_{Z'}$) the lightest Higgs boson mass (M_l) is a convex parabola in the λ^2-M_l plain. The imposition of the experimental bound $M_l \geq 60$ GeV gives a very strong upper limit on λ (typically $\lambda < 0.4$); therefore the difference between the charged Higgs boson mass (for fixed M_A) in the two models cannot be arbitrarily large. The mass M_h is again nearly equal to M_A. So, the only effective difference between the η model and the MSSM, in this region of the space parameters, is contained in the relation $M_{H^+} - M_A$,

$$M_{H^+}^2 = M_A^2 + M_W^2\left(1 - \frac{2\lambda^2}{g^2}\right) + \Delta M_{H^+}^2 + \Delta' M_{H^+}^2 \tag{A3}$$

where $\Delta M_{H^+}^2$ is the same as in Eq. (20) with the suitable identifications and $\Delta' M_{H^+}^2$ is the small contribution of the exotic sector:

$$\Delta' M_{H^+}^2 = -\frac{3}{8\pi^2}M_W^2\frac{\lambda^2}{g^2}h_E^2\left[\ln\frac{m_{\tilde{q}}^2 + m_E^2}{M_Z^2} - \left(\frac{1}{6}\right)\frac{A_E^2 m_E^2}{m_{\tilde{q}}^2 + m_E^2}\right]. \tag{A4}$$

In general when $\lambda \to 0$ we have the same relationships $M_{H^+} - M_A$ as in the MSSM and the trajectories in the plane (δ_{bV}, η_b) are the same. What we have shown in Fig. 4 are the trajectories with the maximum value of λ such that the neutral Higgs sector is beyond the present experimental bound.

[1] G. Altarelli and R. Barbieri, Phys. Lett. B **253**, 161 (1990); see also M. Golden and L. Randall, Nucl. Phys. **B361**, 3 (1991); B. Holdom and J. Terning, Phys. Lett. B **247**, 88 (1990); M. Peskin and T. Takeuchi, Phys. Rev. Lett. **65**, 964 (1990); A. Dobado, D. Espriu, and M. Herrero, Phys. Lett. B **255**, 405 (1991); M. Peskin and T. Takeuchi, Phys. Rev. D **46**, 381 (1992); D. Kennedy, Fermilab Report No. FERMILAB-CONF-93/023-T (unpublished).

[2] A. Akhundov, D. Bardin, and T. Riemann, Nucl. Phys. **B276**, 1 (1986); W. Beenakker and W. Hollik, Z. Phys. C **40**, 141 (1988); B. W. Lynn and R. G. Stuart, Phys. Lett. B **252**, 676 (1990); J. Bernabeu, A. Pich, and A. Santamaria, Nucl. Phys. **B363**, 326 (1991).

[3] A. Blondel, A. Djouadi, and C. Verzegnassi, Phys. Lett. B **293**, 253 (1992).

[4] A. Blondel and C. Verzegnassi, Phys. Lett. B **311**, 346 (1993).

[5] G. Altarelli, R. Barbieri, and F. Caravaglios, Phys. Lett. B **314**, 357 (1993).

[6] We use the data communicated by the various LEP Col-

laborations, in *Proceedings of the International Europhysics Conference on High Energy Physics*, Marseille, France, 1993, edited by J. Carr and M. Perottet (Editions Frontières, Gif-sur-Yvette, 1993).

[7] A. Blondel and C. Verzegnassi, in *Proceedings of the International Europhysics Conference on High Energy Physics* [6].

[8] D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **72**, 2138 (1994).

[9] A. Blondel, B. W. Lynn, F. M. Renard, and C. Verzegnassi, Nucl. Phys. **B304**, 438 (1988).

[10] For a recent review of the machine's status, see, e.g., C. Prescott, in *Neutral Currents Twenty Year Later*, Proceedings of the International Conference, Paris, France, 1993, edited by U. Nguyen-Khac (World Scientific, Singapore, 1994).

[11] For a recent review on the subject, see, e.g., A. Blondel, in *Precision Tests of the Standard Electroweak Model*, edited by P. Langacker (World Scientific, Singapore, in press).

[12] D. C. Kennedy and B. W. Lynn, Nucl. Phys. **B253**, 216 (1985); A. Sirlin, Phys. Lett. B **232**, 971 (1989); M. Consoli and W. Hollik, in *Z Physics at LEP I*, Proceedings of the Workshop, Geneva, Switzerland, 1989, edited by G. Altarelli, R. Kleiss, and C. Verzegnassi (CERN Report No 89-08, Geneva, 1989).

[13] J. Layssac, F. M. Renard, and C. Verzegnassi, Phys. Rev. D **49**, 3650 (1994).

[14] A. Djouadi, J. H. Kuhn, and P. Zerwas, Z. Phys. C **46**, 411 (1990).

[15] A. Denner, R. J. Guth, W. Hollik, and J. H. Kuhn, Z. Phys. C **51**, 695 (1991).

[16] A. Djouadi, J. L. Kneur, and G. Moultaka, Phys. Lett. B **242**, 265 (1990); A. Djouadi, G. Girardi, W. Hollik, F. M. Renard, and C. Verzegnassi, Nucl. Phys. **B349**, 48 (1991); M. Boulware and D. Finnel, Phys. Rev. D **44**, 2054 (1991); C. Sheng Li, J. Min Yang, B. Quan Hu, and Y. Sheng Wei, Report No. CQU-TH-92-17, 1992 (unpublished).

[17] L. E. Ibanez, Phys. Lett. **118B**, 73 (1982); Nucl. Phys. **B218**, 514 (1983); R. Barbieri, S. Ferrara, and C. Savoy, Phys. Lett **119B**, 343 (1982); P. Nath, A. Arnowitt, and A. Chamseddine, *ibid.* **49B**, 970 (1982).

[18] J. F. Gunion and A. Turski, Phys. Rev. D **40**, 2325 (1989); M. A. Diaz and H. E. Haber, *ibid.* **45**, 4246 (1992).

[19] For a full discussion of this model (and similar ones) see, e.g., L. Hewett and T. G. Rizzo, Phys. Rep. **C183**, 193 (1989).

[20] H. E. Haber and M. Sher, Phys. Rev. D **35**, 2206 (1987); M. Drees, *ibid.* **35**, 2910 (1987); D. Comelli and C. Verzegnassi, Phys. Lett. B **303**, 277 (1992).

[21] R. S. Chivukula, S. B. Selipsky, and E. H. Simmons, Phys. Rev. Lett. **69**, 575 (1992); E. H. Simmons, R. S. Chivukula, and S. B. Selipsky, in proceedings of *Beyond the Standard Model III*, edited by S. Godfrey and P. Kalyniak (World Scientific, Singapore, 1993); N. Kitazawa, Phys. Lett. B **313**, 395 (1993); R. S. Chivukula, E. Gates, E. H. Simmons, and J. Terning, *ibid.* **311**, 157 (1993).

[22] D. B. Kaplan, Nucl. Phys. **B365**, 259 (1991).

[23] The possibility that the axial form factors of the *constituent* quarks are modified in a rather different context has been already discussed in several papers. See, e.g. S. Peris, Phys. Lett. B **268**, 415 (1991); S. Weinberg, Phys. Rev. Lett. **67**, 3473 (1991); E. de Rafael and S. Peris, Phys. Lett. B **309**, 389 (1993). The effects of anomalous top quark couplings on precision electroweak measurements have also been considered by R. D. Peccei and X. Zhang, Nucl. Phys. **B337**, 269 (1990); R. D. Peccei, S. Peris, and X. Zhang, *ibid.* **B349**, 305 (1991); M. Frigeni and R. Rattazzi, Phys. Lett. B **269**, 412 (1991).

[24] M. Kuroda, D. Schildknecht, and K. H. Schwarzer, Nucl. Phys. **B261**, 432 (1985); U. Baur, D. Schildknecht, and K. H. Schwarzer, Phys. Rev. D **37**, 297 (1987).

[25] R. Casalbuoni, S. De Curtis, D. Dominici, and R. Gatto, Nucl. Phys. **B282**, 234 (1987); J. L. Kneur and D. Schildknecht, *ibid.* **B357**, 357 (1991); J. L. Kneur, M. Kuroda, and D. Schildknecht, Phys. Lett. B **262**, 93 (1991).