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$b\bar{b}$ -production on the Z resonance : a challenge to the standard model

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Abstract

We study the potentialities for exposing physics beyond the standard model that are offered by accurate measurements of the process $Z \rightarrow b\bar{b}$ in a high luminosity phase at LEP. In particular we propose a strategy by defining observables in such a way that they are separately sensitive to different kinds of New Physics. This approach enables us to show that with $10^7 - 10^8$ produced $b\bar{b}$ pairs one may either obtain very stringent bounds on the extra neutral gauge bosons sector, or identify it unambiguously. Also, it appears that $Z \rightarrow b\bar{b}$ provides under those circumstances a privileged tool to reveal clean virtual effects of supersymmetry.

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1 Introduction

The data provided by the first period of run at LEP1 do not show direct evidence for new spectacular phenomena but rather indicate that the Minimal Standard Model (MSM), if not the ultimate truth, is really a sensible scheme for describing physics at Z_0 energy. So the forthcoming high precision measurements at e^+e^- colliders appear as a nearly unique tool to uncover new physics via indirect effects, i.e. through definite deviations of the experimental results from the theoretical predictions at one-loop of the MSM. In fact, thanks to a remarkable combined experimental-theoretical effort [1,2], the latter predictions are now known to a sufficient accuracy, once the value of the Z_0 mass is given, to allow for a search of discrepancies at the one percent level (this will be achieved soon by the next run at LEP1).

On the theoretical side, the uncertainties are related to still unknown parameters, and mostly come from the top quark (in the MSM), the Higgs boson contribution being generally still marginal in this scheme. In the MSM, the top quark contributes in two quite different quantities that might have an effect on several observables. The first one is the oblique correction to the gauge boson propagators, usually called [3] $\Delta\rho(0)$

$$\Delta\rho(0) = \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2}, \quad (1.1)$$

that represents, in fact, the one-loop correction to the ρ parameter [4] and for sufficiently large m_t behaves like (a smaller, negative, Higgs contribution is also present)

$$\Delta\rho(0) \simeq \frac{\alpha}{\pi} \frac{m_t^2}{M_Z^2}, \quad (1.2)$$

becoming as large as one percent when $m_t \simeq 2M_Z$ ($m_H \leq 1TeV$). The second effect appears as a one-loop correction to the $Zb\bar{b}$ vertex, stemming from virtual $t - W$ exchange [5]. This enjoys the rather peculiar property of only being able to affect the theoretical prediction for the partial width of Z into $b\bar{b}$ couples and not that for the related forward-backward asymmetry A_{FB}^b (for $d\bar{d}, s\bar{s}$ final states the virtual $t - W$ exchange is highly suppressed by KM matrix elements). To quantify the relevance of this effect, it is sufficient to write the expression of the $Zb\bar{b}$ partial width in the MSM as [6] :

$$\Gamma_b = \Gamma_b^{(0)} \left[1 + \frac{19}{13} (\Delta\rho(0) + \Delta_{bV}^{(t)}) \right], \quad (1.3)$$

where $\Gamma_b^{(0)}$ is computed for $m_t = 90 GeV$ and the vertex correction $\Delta_{bV}^{(t)}$ behaves for large m_t as :

$$\Delta_{bV}^{(t)} \simeq -\frac{20}{19} \frac{\alpha}{\pi} \left[\frac{m_t^2}{M_Z^2} + \frac{13}{6} \ln \frac{m_t^2}{M_Z^2} \right]. \quad (1.4)$$

Note that, contrary to what happens in $\Delta\rho(0)$, the Higgs does not contribute to $\Delta_{bV}^{(t)}$.

From eqs. (1.3, 1.4) one realizes that the vertex correction $\Delta_{bV}^{(t)}$ has the opposite sign of $\Delta\rho(0)$, and owing to the non negligible logarithmic term, is of larger size than that of

the oblique correction $\Delta\rho(0)$. In fact, for $m_t \simeq 2M_Z$, $|\Delta_{bV}^{(t)}|$ is almost equal to two percent, i.e. nearly twice as large as $\Delta\rho(0)$. This suggests already that isolating the full vertex component (eq. 1.4) would be an interesting alternative way in the MSM of searching for virtual top effects in measurable quantities, compared with the more "conventional" way of isolating the $\Delta\rho(0)$ effect, as pointed out in previous papers [6,7].

As soon as one considers extensions of the MSM, the differentiation between $\Delta\rho(0)$ and $\Delta_{bV}^{(t)}$ becomes deeper. Models with extra families, "non canonical" extra Higgses, extra vector boson(s), might all contribute (both at one loop and at tree level) to a single "effective" measurable quantity [8] :

$$\nabla\rho \equiv \Delta\rho(0) + \Delta\rho^{NewPhysics}. \quad (1.5)$$

In general, if one discards e.g. the cases of extra Higgses or of charged W' , the new contributions to $\nabla\rho$ are positive [8,9], i.e. they enhance the pure top contribution of the MSM. However, such additional terms are completely m_t independent. Thus, a substantial value of $\nabla\rho$ does not necessarily imply a corresponding large value of m_t , in models with New Physics. Conversely if the top mass were known, one might try to derive, from a measurement of $\nabla\rho$, information on its possible New Physics content. The copiousness of possible contributing models would make, though, this task a not easy one, unless some extra, complementary information is added.

In the case of $\Delta_{bV}^{(t)}$, extra families, non canonical neutral Higgses, extra Z would not contribute whereas charged Higgses would be important [10]. Thus, models like SUSY which naturally contain charged Higgses might modify the MSM expectations. If no other extensions of the MSM are considered, one can conclude that the possible effect of New Physics will be that of defining an effective observable quantity :

$$\nabla_{bV} = \Delta_{bV}^{(t)} + \Delta_{bV}^{(SUSY)}. \quad (1.6)$$

If the considered SUSY model is the so called "minimal" one $\equiv$ MSSM [11], the extra contributions have two interesting features [7] :

a) they are negative, i.e. they enhance the pure top contribution of the MSM

b) they are still dominantly proportional to m_t^2 . In this sense, ∇_{bV} represents a more genuine "top indicator" than $\Delta\rho(0)$. Also, if m_t were known, the possible New Physics content of ∇_{bV} would be much simpler to examine than for $\Delta\rho(0)$, because of the aforementioned properties.

The previous discussion indicates the reasons why we believe that a measurement of ∇_{bV} represents an interesting and unconventional way of obtaining information on electroweak Physics, both within the MSM and within the MSSM. An obvious statement is that the proper quantity to achieve this goal is the partial width of Z into $b\bar{b}$ quarks, or other quantities containing this width, provided that measurements of sufficient accuracy are achievable. This, however, does not represent a sufficient condition for the previous program, unless it is possible at the same time to isolate the vertex correction from other contributions coming e.g. from other kinds of New Physics, that confuse the ∇_{bV} effect.

In particular, models with one extra Z of either extended gauge origin [12,13,14], or composite Z origin [15], might introduce a "mixing" effect that would act in this sense and make the situation confuse.

The aim of this paper is to show that, if a next phase of "high luminosity", corresponding to $\sim 10^7 - 10^8$ produced Z , were available at LEP1 [16], a full and self consistent strategy might be developed that would allow to isolate unambiguously, from a measurement of the $Zb\bar{b}$ width and forward-backward asymmetry, the ∇_{bV} effect from the mixing effect of a Z' and to measure them both to a typical $\sim$ one percent accuracy. Moreover, it would also be possible to obtain an independent measurement of the oblique block $\nabla\rho$, to an accuracy of few per mille, comparable to that which can be provided by a determination of $M_{H^\pm}$ with a precision of $\sim 100\text{MeV}$.

Thus, at the end of the game, a drastic picture would emerge, either in favour or against the MSM, that should orient future experiments.

Technically speaking, this paper is organized as follows. In section 2 we explicitly derive the MSSM contribution to $\nabla_{bV}^{(t)}$, that was not previously known. In section 3 we sketch our strategy and begin to isolate the Z' mixing effects in various "high luminosity" observables. In section 4, we then show how to build observables that would only measure the vertex effect $\nabla_{bV}^{(t)}$. Section 5 contains an analysis of future high luminosity measurements of the remaining quantity $\nabla\rho$, together with a final discussion and some conclusions. Appendix A contains the details of the computation of ∇_{bV} in the MSSM. Finally, in Appendix B, we give the definitions of some of the quantities that we use and the QCD corrections to those that involve hadrons.

2 Effects of Supersymmetry on the $Zb\bar{b}$ vertex

The theoretical prejudice that in a supersymmetric model like the one that we are considering here, sizeable corrections to the $Zb\bar{b}$ vertex might appear, stems from the known [10] fact that this happens in a non supersymmetric model with one extra doublet of Higgses characterized by two independent vacuum expectation values v_1 and v_2 providing masses to up and down quarks respectively. In particular, the contribution to the vertex is proportional to $m_t^2/\tan^2\beta$, where

$$\tan\beta = v_2/v_1, \quad (2.1)$$

and is weakly dependent on the charged Higgs mass. This contribution has the same sign as that of the MSM top quark and thus enhances the sensitivity of the vertex to large m_t values.

In the MSSM, the scalar Higgs sector has essentially the same features (with much less freedom for the parameters) as in the previous model and thus its contribution to the $Zb\bar{b}$ vertex will be formally identical. One has to compute, though, the contribution of the "genuinely" supersymmetric particles, and add it to the previous one. This implies an evaluation of both the neutralino and of the chargino exchange diagrams. The first ones have actually been already computed in the literature [17]. Their effect seems completely

negligible in the MSSM, and we shall accept this result. The explicit contribution from the chargino sector, corresponding to the diagrams represented in Fig.(1) is not available. We have therefore carried out its computation, to be completely self-contained, and we give here a discussion of the results.

The numerical outcome of our analysis depends on a number of parameters. The non genuinely supersymmetric part, Fig.(1a), contains the top, the charged Higgs masses and $\tan \beta$, defined by eq. (2.1). For the latter quantity, the model favours the range

$$1 \leq \tan \beta \leq 10. \quad (2.2)$$

The genuine SUSY contribution Fig.(1b) depends also on $\tan \beta$. Moreover, it contains the stop mass and the parameters M, μ that enter the chargino mass matrix. The actual situation is, luckily, less complicated since several theoretical or experimental bounds can be used, that make our task relatively simpler.

To start with, we shall adopt the criterion of "naturalness" [18], that implies the limits :

$$0 \leq M \leq 200 \text{ GeV}, \quad (2.3)$$

$$|\mu| \leq 250 \text{ GeV}. \quad (2.4)$$

Within this reduced region, there are the existing experimental bounds provided by the absence of observation of supersymmetry at LEP1 and at other machines. A very recent analysis [19] gives the limits shown in Fig.(2) for the typical value $\tan \beta = 4$. Similar figures can be drawn for other values of $\tan \beta$, like the ones that we shall consider [20]. Thus, for every value of $\tan \beta$, we have considered in the (M, μ) plane the area enclosed between the experimental boundaries of ref.[19] and the extreme new boundaries given by eqs. (2.3, 2.4). All our numerical results, for simplicity, will be presented for two values $\tan \beta = 1, 10$, but the prescription to extrapolate to different $\tan \beta$ is very simple and will be indicated. We shall also give our predictions for a stop and a charged Higgs mass of hundred GeV, that would make these objects, in principle, visible at LEP2. The results are rather smooth with the latter masses, and reasonable variations around 100 GeV would not affect our conclusions appreciably.

With the described limitations on the parameters, our analysis becomes relatively simpler. In particular, the following general features emerge :

1) In all the considered range, the contribution to the $Zb\bar{b}$ vertex coming from the chargino sector is always of the same sign as that of the charged Higgs sector (this would not be true for values of (M, μ) beyond the naturalness bounds, eqs.(2.3, 2.4)). Thus, the full MSSM contribution to the vertex adds coherently to that of the MSM top and enhances it. Note that the dominant part of the chargino contribution is proportional to m_t^2 ; this is also true of the full charged Higgs contribution . In this more general sense, the $Zb\bar{b}$ vertex acts as a "genuine" top mass indicator : a large value of the ∇_{b1} vertex correction can never be obtained with a light top quark, contrary to the case of the oblique correction $\nabla\rho$.

2) The maximum chargino contribution in the considered range is higher than the contribution of the charged Higgses. When these two terms are added to the MSM one,

one obtains a maximum contribution to ∇_{bV} that is $\sim$ three times larger than that of the MSM alone, for $\tan \beta \sim 1$.

In table 1, we present separately the contributions to ∇_{bV} from the different sources for $m_t = 150 \text{ GeV}$. The SUSY contributions for other values of m_t can be obtained by simply rescaling our results by a factor $(\frac{m_t}{150})^2$, the charged Higgs contribution also scales as $(\cotan \beta)^2$ and the chargino one as $1 + (\cotan \beta)^2$, thus remaining practically constant as soon as $\tan \beta \geq 3$.

Although still qualitative, the previous discussion shows, we believe, the great interest of a determination of the $Zb\bar{b}$ vertex via a high precision measurement of Γ_b (or of $\frac{\Gamma_b}{\Gamma_t}$). To achieve such a goal, one has, though, to isolate the ∇_{bV} term from other possible competitor effects that generally enter the previous observables. One such quantity would be the $\nabla\rho$ block, as eq.(1.3) shows. Another, and in principle even more dangerous, effect may come from the class of models with one extra Z described in refs.[12,15] (that such models can give sizeable contributions to the various widths has been already discussed in previous references [21,22]).

Thus, one has to separate (at least) three kinds of possible New Physics effects, that are of quite different origin ; this requires a well defined and self-contained strategy. In the next section, we shall show how this strategy can actually be built and used in a high luminosity program like that of ref[16].

3 A strategy for disentangling the Z' mixing effect

In order to work out a self-consistent scheme to isolate the effects of a certain type of New Physics, it is oportune to recall what are the possible manifestations of models with one extra Z . As it has already been exhaustively discussed in the literature [8], on top of Z resonance two kinds of effects may arise. The first one simply redefines the ρ parameter by adding a term

$$\delta\rho^{(Z')} = \sin^2\theta_M \left[\frac{1}{\epsilon} - 1 \right] \sim \frac{\theta_M^2}{\epsilon}, \quad (3.1)$$

where $\epsilon = \frac{M_Z^2}{M_{Z'}^2}$, and Z, Z' are the two physical mass eigenstates. The second one ($\equiv \delta_M$) is a pure mixing effect, $\delta_M \simeq \theta_M$. Analogous properties characterize the effect of a Z' generated by a strongly interacting electroweak sector [14], or by a composite Z [15], as fully discussed in previous papers [23]. The mixing effect δ_M is a tree level effect that modifies the Z couplings to fermions and cannot be reabsorbed into either $\nabla\rho$ or ∇_{bV} . As such, it is a "genuine" Z' manifestation on Z resonance, that for certain models can be sizeable (say, up to a relative ten percent [23]).

From this short preliminary discussion, a possible identification strategy has now become reasonably clear. It consists in generating special combinations of observables to isolate contributions that are specific of the various proposed MSM extensions, so that a minimum number of unknown parameters contribute that may be reliably fixed or severely constrained. More precisely, we shall first define observables that are both $\nabla\rho$ - and ∇_{bV} -free, and are therefore ideal tools to measure the Z' mixing (δ_M) effect. Once the latter will be either understood, or under control, we shall consider observables that are either

$\nabla\rho$ - free and ∇_{bV} - dependent, or vice versa ∇_{bV} -free and $\nabla\rho$ - dependent. In this way, at the end of a sequential chain of measurements, all performable on Z resonance via a high luminosity program, one can get independent estimates of the three separate quantities, to a precision that will be specified in the following. This would lead to firm, unbiased conclusions on the investigated models, that we shall analyse in a systematic way.

To proceed with our program, we first show how to isolate the mixing ($\equiv \delta_M$) effect. This can actually be done, in principle, in the first phase ($\sim 10^6$ produced Z 's) at LEP1 by considering the following two $\nabla\rho$ and ∇_{bV} - free observables [24] :

$$\gamma - \frac{1}{3} A_\tau \equiv \left[\gamma - \frac{1}{3} A_\tau \right]^{MSM} + \zeta, \quad (3.2)$$

$$\xi - \frac{1}{2} A_\tau \equiv \left[\xi - \frac{1}{2} A_\tau \right]^{MSM} + w. \quad (3.3)$$

Here $\gamma = \frac{9}{\alpha(M_Z)} \frac{\Gamma(Z \rightarrow \mu\bar{\mu})}{M_Z}$, A_τ is the final τ - polarization [25] and ξ is the ratio :

$$\xi = \frac{M_W^2}{M_Z^2 c_0^2}, \quad c_0^2 = \frac{1}{2} \left(1 + \sqrt{1 - \frac{4\mu^2}{M_Z^2}} \right), \quad \mu = 38.45 \text{ GeV}, \quad (3.4)$$

to be measured with high accuracy at $p\bar{p}$ colliders and, later, at LEP2.

In the MSM, the theoretical predictions for the two quantities eqs. (3.2, 3.3) are the following (we allowed $90 \text{ GeV} \leq m_t \leq 250 \text{ GeV}$)

$$\left[\gamma - \frac{1}{3} A_\tau \right]^{MSM} = 1.018 \pm 0.003, \quad (3.5)$$

$$\left[\xi - \frac{1}{2} A_\tau \right]^{MSM} = 0.939 \pm 0.004. \quad (3.6)$$

The smallness of the theoretical uncertainty is related to the absence of the $\nabla\rho$ and ∇_{bV} terms, which leaves an almost negligible residual m_t, m_H dependence, to be added to the uncertainty coming from the redefinition of the electric charge $\alpha(M_Z^2)$ [26]. Thus, the only possibly sizeable source of error will be the experimental one that in a conventional LEP1 phase should be, approximately, ± 0.020 for eq.(3.5) and 0.015 for eq.(3.6) assuming $\delta M_W \simeq 300 \text{ MeV}$.

The mixing effects on eqs. (3.2, 3.3) in the different models with one extra Z' have been thoroughly investigated in ref.[24], and we do not insist on them here. In the plane of the (ζ, w) variables, that represent deviations from the (known) MSM predictions, the "genuine" Z' effects are shown in Fig.3 together with the expected experimental error. Note that, indeed, effects induced by different types of models are rather well distinguished by the choice of variables ; in particular, gauge models and models without Higgses [14,15] are almost completely separated.

With a high luminosity phase, it will become possible to also measure with high accuracy Γ_b and A_{FB}^b . We shall assume, in what follows, that these observables can be measured with the following accuracies :

$$\frac{\delta(\Gamma_b/\Gamma_l)}{\Gamma_b/\Gamma_l} = \pm 0.02(0.01), \quad \delta A_{FB}^b = \pm 0.003, \quad (3.7)$$

and we consider the second error in parentheses on Γ_b/Γ_l as a final goal, whose consequences we shall illustrate.

As an immediate first consequence of these assumptions, we can introduce ($\Gamma_4 \equiv \Gamma_{had} - \Gamma_b$) a new $\nabla\rho, \nabla_{bV}$ -free variable :

$$D \equiv \frac{6}{23} \left[\frac{1}{4} \frac{\Gamma_4}{\Gamma_l} - \frac{26}{27} A_{FB}^b \right] \equiv D^{MSM} + \delta D, \quad (3.8)$$

for which :

$$D^{MSM} = 1.039 \pm 0.001. \quad (3.9)$$

With a precision in the measurement of $R'_Z \equiv \frac{3}{59}(\Gamma_{had}/\Gamma_l)$ of ± 0.005 [16], the experimental error on D would be :

$$\delta D^{(exp)} \simeq \pm 0.008(0.006), \quad (3.10)$$

much larger than the theoretical uncertainty in the MSM.

Also, in a high luminosity phase, it will be possible to use the variable w_b , instead of w (eq. 3.3), simply replacing A_τ by the (theoretically equivalent) $\frac{13}{9} A_{FB}^b$:

$$\xi - \frac{13}{18} A_{FB}^b = \left[\xi - \frac{13}{18} A_{FB}^b \right]^{MSM} + w_b. \quad (3.11)$$

This would be meaningful since one of the final goals of the high luminosity program is to improve the accuracy, leading to a final $\sim 70 MeV$ error on the W mass determination at LEP2 [16] and, consequently, to a precision $\delta w_b \simeq 0.004$, comparable with the theoretical error.

In the $(w_b, \delta D)$ plane, the various models with one extra Z correspond to the regions depicted in Fig.4. In addition to the property of largely separating the various models, the use of these two variables leads to a much better test of the predictions. This can be seen by comparing in each case the limits on the "mixing" parameters (in the case of models without Higgs, these would actually be mass ratios) that one can derive from a negative search in the "conventional" LEP1 phase (ζ, w) variables and in a "high luminosity" phase $(w_b, \delta D)$ variables.

As one sees from Figs.(5) and (6) in the case of extra gauge models, the gain is impressive, leading to a severe final bound, $|\theta_M| \leq 0.01$ in case of negative searches. Analogous improved results are obtainable for the models without Higgses, as table 2 shows. In general, for all the models with one extra Z , the bounds obtained in the high luminosity phase would be a factor two stricter with respect to the ones derived in the "conventional" LEP1 phase.

In the next section, we shall show that this is sufficient to carry on our subsequent program of measuring ∇_{bV} without introducing any appreciable theoretical uncertainty.

4 An unbiased measurement of the $Zb\bar{b}$ vertex

With the Z' mixing effect under control, isolating the ∇_{bV} term is relatively simple. One has to choose observables that are $\nabla\rho$ -free and ∇_{bV} dependent and impose on the residual

δ_M effect the constraints derived in the previous section and represented in Figs. (5), (6) and Table 2. The choice of the proper observable is mainly dictated by convenience. In ref.[6] it was shown that the $\nabla\rho$ -free combination

$$M = \frac{3}{13}[\Gamma_b/\Gamma_l - \frac{26}{27}A_{FB}^b], \quad (4.1)$$

(the numerical coefficient $\frac{3}{13}$ is chosen to normalize M to one) enjoys several interesting features that make it rather special. We briefly review here the main properties of eq.(4.1) adding the presentation of the explicit calculation of the full supersymmetric vertex, which did not appear in ref. [6].

Consider the mixing contribution from a Z' of extended gauge origin first. In the most general case of a E_6 generated extra $U(1)$ [12], this can be written as :

$$\delta M^{(E6)} \simeq +\theta_M(\cos 2\beta_{E_6} + \frac{\sin 2\beta_{E_6}}{3}), \quad (4.2)$$

where $\cos 2\beta_{E_6}$ parametrizes the symmetry breaking pattern to the final $SU(2)_L \times U(1)_Y \times U(1)_{Y'}$ situation.

This mixing contribution is severely bounded by the previous analysis summarized in Fig.(5), from which it is possible to set the rigorous bound (or uncertainty) :

$$|\delta M^{(E6)}| \leq 0.005. \quad (4.3)$$

For a Z' of left-right symmetry origin, an analogous estimate can be performed. The theoretical contribution is :

$$\delta M^{(LR)} \simeq \theta_M \frac{8}{13}[\frac{1}{\alpha_{LR}} + \alpha_{LR}], \quad (4.4)$$

where

$$\sqrt{\frac{2}{3}} \leq \alpha_{LR} \leq \sqrt{2}. \quad (4.5)$$

A glance at Fig.(6) shows that, within this range, the unpredictable shift eq.(4.4) remains always limited

$$|\delta M^{LR}| \leq 0.01. \quad (4.6)$$

The bound is saturated for values of $\alpha_{LR} \geq 1$, while for α_{LR} values at the edge, $\alpha_{LR} \simeq \sqrt{\frac{2}{3}}$, it decreases to about 0.005.

In conclusion, the residual theoretical uncertainty due to the possible existence of one extra Z of the considered extended gauge origin would be, at most, of one percent, i.e. smaller than (or equal to) the realistically expected experimental error on M , that one estimates from eq.(3.7) to be :

$$\delta M^{(exp)} \simeq 0.02(0.01). \quad (4.7)$$

Similar, even more optimistic conclusions, apply to the case of a Z' either due to a strongly interacting electroweak sector [14], or to a composite Z [15]. In fact, in most of these cases,

the Z' contribution vanishes exactly owing to the properties of the quantity M , that is $\nabla\rho$ -free and built out of ratios of observables, as already discussed in ref. [6]. Thus, for our next purposes, we shall consider from now on the Z' contribution to M as known, with an uncertainty of, at most, one percent, and include it as a $\delta Z'$ correction in the theoretical expression of eq.(4.1). With this convention, we shall consequently write :

$$M = M^{(0)}[1 + \frac{19}{13}\nabla_{bV}], \quad (4.8)$$

where

$$M^{(0)} = [1.036 \pm 0.004 + O(\alpha_s) + \delta Z'], \quad (4.9)$$

and the $O(\alpha_s)$ term is given in Appendix B.

From the discussion given in this section, it turns out that the determination of the $Zb\bar{b}$ vertex given by eqs.(4.8, 4.9), is of a rather general nature. It is valid in a class of theoretical models that include either non canonical neutral Higgses or new families (besides Z' , whose contribution can always be controlled). The only possible source of enhancement to the MSM effect eq.(1.4) would therefore come from SUSY diagrams, that we have estimated in section 2 for the particularly appealing case of the MSSM. We now give a quantitative discussion of the possible size of such an effect (technical details are exposed in Appendix A), keeping in mind that the limit for observability is placed by eq.(4.7) at the two percent (one percent) "threshold".

Table 3 shows the effect on M in the MSM and the possible maximum effect on M in the MSSM, for the representative value $\tan \beta = 1$, of a variation of the top mass between 90 GeV and higher values. From inspection of this table, one draws the following conclusions :

1) In the MSM, values of m_t beyond 150 GeV could produce visible effects. For $m_t = 200$ GeV the shift from M (90 GeV) would be of two percent. Note that this effect would measure the top mass in the (not minimal) Standard Model independently of the value of the ρ parameter, owing to the property of the chosen observable M . Therefore, the possibility of a top mass equal to (or even slightly larger than) ~ 200 GeV cannot be a priori discarded, as stressed in a recent analysis where the top mass effect and the ρ parameter were independently fitted [27]. If we accept the "extreme" bound $m_t \leq 230$ GeV , which is probably a pessimistic one, we see that the SM top effect cannot be, anyway, larger than three percent.

2) For values of $\tan \beta = v_2/v_1$ not far from one, the maximum effect of the MSSM can be much larger than that of the SM alone. For instance, for a top mass of 150 GeV , the negative shift from M (90 GeV) could be of four percent for $\tan \beta \simeq 1$, and for $m_t = 200$ GeV , the same shift would be of eight percent, much beyond the tolerable values in the SM. This value becomes larger for smaller m_t values (for $m_t = 50$ GeV , $m_t = 200$ GeV , it would be of ~ 10 percent). Thus, for conceivable values of the parameters, one would obtain an impressive, characteristic and, to our knowledge, unique virtual signal of minimal supersymmetry in a "standard" $e^+e^- \rightarrow f\bar{f}$ reaction.

The previous discussion has shown more quantitatively than in Section 2 the reasons why we believe that a high luminosity program at LEP like that illustrated in ref [16]

would be interesting and efficient to uncover New Physics. To conclude in a self consistent way our paper we shall devote the last and final section to the discussion of the appealing possibility of an extremely accurate measurement of $\nabla\rho$ offered by the high luminosity program which would also provide an increase in luminosity of a factor $\sim$ two at the WW production threshold at LEP2 [16].

5 An accurate measurement of the oblique correction $\nabla\rho$.

In principle, in a High Luminosity phase, and with the Z' mixing effect under control, a measurement of the full block $\nabla\rho$ might be provided by the ∇_{bV} -free observable A_{FB}^b , whose theoretical expression in the general class of models that we have considered reads :

$$A_{FB}^b = [A_{FB}^b]^{(0)} + \frac{27}{13} \nabla\rho, \quad (5.1)$$

where

$$[A_{FB}^b]^{(0)} = [0.084 \pm 0.002] + O(\alpha_s) + \delta Z', \quad (5.2)$$

where $\delta Z'$ is known to $\sim \pm 0.005$ [6], and the $O(\alpha_s)$ correction is fully controlled, as discussed in Appendix B.

As pointed out in Section 1, several models of New Physics can contribute to $\nabla\rho$, with both signs, thus, it is important to separate in what follows the topic of a precise determination of $\nabla\rho$ from that of the consequent theoretical interpretation. One sees from eq.(5.1) that $A_{FB}^{(b)}$, with an overall uncertainty of ~ 0.006 would lead to a determination in $\nabla\rho$ with a precision :

$$\delta(\nabla\rho) = \pm 0.003. \quad (5.3)$$

In making this estimate, we have assumed an experimental error of 0.003 and we have combined it with the theoretical error from the renormalization of the electric charge [26] and from $\delta Z'$.

This precision on $\nabla\rho$ should be compared with the corresponding value obtained from a measurement of the W mass. The theoretical expression of the M_W/M_Z ratio can be written as :

$$\frac{M_Z^2}{M_Z^2 c_0^2} = [0.998 \pm 0.003] + \frac{3}{2} \nabla\rho^{(W)}, \quad (5.4)$$

where, if extra charged W are absent, $\nabla\rho^{(W)}$ is the same quantity as the one that appears in eq.(5.1), and c_0 is defined by eq.(3.4).

Eq.(5.4) implies an experimental error on $\nabla\rho^{(W)}$:

$$\delta\nabla\rho^{(W)} \simeq \frac{4}{3} \frac{\delta M_W}{M_W}. \quad (5.5)$$

Note that, in this case, no other source of theoretical error ($\delta Z', \alpha_s, \Delta\alpha, \dots$) is present in the determination of $\nabla\rho$ via ξ .

To be better than A_{FB}^b at ± 0.006 (overall) M_W should be thus measured to better than $\sim 150 \text{ MeV}$ accuracy. This would be achievable at LEP2 with a High Luminosity phase that would reduce the experimental error on M_W to a value of $\leq 70 \text{ MeV}$ [16], and thus would lead to a determination of $\nabla\rho$ to ± 0.002 !

Therefore, within this program, two independent and extremely accurate determinations of $\nabla\rho$ will be available. A meaningful theoretical interpretation of these measurements requires a thorough investigation, to be given elsewhere. Here we shall only give a summary of the salient features of several models that would contribute to $\nabla\rho$ namely :

1) SUSY. The supersymmetric contribution to $\nabla\rho$ has been computed [17], not always with a discussion of the complete $\tilde{t}, \tilde{b}$ doublet with physical (mixed) stop states. For sake of completeness, we have computed this effect, and we give here the result in the MSSM. All the other possible contributions in this model are known to be negligible [17], and we shall omit them. Thus, we can write in practice :

$$\nabla\rho^{(MSSM)} \simeq \nabla\rho^{(i,\tilde{b})}. \quad (5.6)$$

Varying the parameters of the model within their allowed range and taking into account the existing experimental constraint [28] :

$$m_{\tilde{b}} \gtrsim 100 - 150 \text{ GeV}, \quad (5.7)$$

we were able to set a conservative limit :

$$0 \leq \nabla\rho^{(MSSM)} \leq 0.004. \quad (5.8)$$

Thus, the (positive) MSSM contribution to $\nabla\rho$ would not produce spectacular effects in any case.

2) Models with one extra neutral gauge boson. In general (eq.(3.1)), these models contribute positively to $\nabla\rho$ in a model dependent way, since one can write :

$$\theta_M = P\epsilon ; \quad \epsilon = M_Z^2/M_{Z'}^2, \quad (5.9)$$

so that

$$\nabla\rho^{(Z')} \simeq P^2\epsilon, \quad (5.10)$$

where P , that depends on the Higgs sector of the model, is of $O(1)$.

3) Models with Z' of alternative origin. These can contribute to $\nabla\rho$ with both signs, the contribution still being of $O(\epsilon)$.

4) Non SUSY models with extra Higgses. These can contribute to $\nabla\rho$ with both signs, either at tree level (non "canonical" Higgses) or at one loop (extra doublets). They are not always simply or directly related to observable quantities, nor deeply motivated by theoretical arguments. Still, a negative shift in $\nabla\rho$ might lead to a reconsideration of their role, particularly if independent analyses ruled out possible alternative Z' .

5) As a final example, we consider the effect of one extra charged W . This would only affect the $\nabla\rho^{(W)}$ derived from the W mass, and not the $\nabla\rho$ which appears in A_{FB}^b . Thus, a sizeable difference between two quantities might be an interesting alternative way to reveal such extra charged sector.

6 Concluding remarks

We have examined in this paper some of the Physics possibilities of a project of High Luminosity at LEP1, illustrated in ref.[16].

Via a systematic procedure, that isolates and constraints different effects in succession, we have been able to prove that experiments in this phase would not miss :

- a) a top of at least 150 GeV
- b) an extra gauge Z mixing angle of at least 0.01
- c) anomalous contributions to $\nabla\rho$ of the order of a few per mille.

Moreover, we have seen that the virtual effects of Supersymmetry might be spectacular and of rather specific signature. We believe, therefore, to have shown that such a program looks quite promising and, to some extent, unique for challenging the Minimal Standard Model and several of its candidate extensions.

Acknowledgments

We benefitted from several discussions on experimental aspects with participants of the working group for High Luminosities at LEP.

Appendix A Non-standard $Zb\bar{b}$ vertex corrections

In this appendix, we specify those vertex corrections to the $Zb\bar{b}$ vertex which carry the factor $\sim m_t^2/M_Z^2$ from the Yukawa couplings. These contributions can be summarized in terms of a left-handed form factor $F_L(q^2)$ entering the $Zb\bar{b}$ vertex as follows :

$$\Gamma_\mu^{Zb\bar{b}} = i \frac{e}{4s_0c_0} \gamma_\mu (v_b - a_b \gamma_5) + ie \gamma_\mu (1 - \gamma_5) \frac{\alpha}{4\pi} F_L(q^2) \quad (\text{A.1})$$

with the fermionic coupling constants

$$v_f = I_f^3 - 2s_0^2 Q_f, \quad a_f = I_f^3. \quad (\text{A.2})$$

The form factor F_L can be written as a sum

$$F_L(q^2) = F_L^{(H)}(q^2) + F_L^{(C)}(q^2). \quad (\text{A.3})$$

$F_L^{(H)}$ thereby denotes the contributions from the virtual charged Higgs states (which would be present also in a non-SUSY 2-Higgs doublet model), and $F_L^{(C)}$ the contributions from virtual charginos involving large Yukawa couplings via their Higgsino component.

(i) Higgs contributions

Besides the top mass m_t , the ratio $\cot\beta = v_1/v_2$ of the Higgs vacua and the mass $M_{H^\pm}$ of the charged Higgs bosons are required as additional free parameters. $F_L^{(H)}$ is the sum of the vertex diagrams (a1), (a2) and of the b-quark self-energy diagram (a3) :

$$F_L^{(H)} = F_{a1} + F_{a2} + \frac{2s_0^2 - 3}{12s_0c_0} \delta Z_L^{(H)} \quad (\text{A.4})$$

The expressions given below correspond to the finite parts which remain after cancellation of the singular parts in the vertex and external self-energy diagrams :

$$\delta Z_L^{(H)} \cong \frac{1}{2s_0^2 c_0^2} \frac{m_t^2}{M_Z^2} (\cotan\beta)^2 \bar{B}_1(m_b^2, m_t, M_{H^+}), \quad (\text{A.5})$$

$$\begin{aligned} F_{a1} = & \frac{v_t - a_t}{8s_0^3 c_0^3} \frac{m_t^2}{M_Z^2} (\cotan\beta)^2 \times \\ & \left\{ 2C_2^0(q^2, m_t, m_t, M_{H^+}) - \frac{3}{4} + \log\left(\frac{M_{H^+}}{m_t}\right) \right. \\ & \left. - q^2 \left[C_2^+(q^2, m_t, m_t, M_{H^+}) - C_2^-(q^2, m_t, m_t, M_{H^+}) \right] \right\} \\ & - \frac{v_t + a_t}{8s_0^3 c_0^3} \frac{m_t^2}{M_Z^2} (\cotan\beta)^2 m_t^2 C_0(q^2, m_t, m_t, M_{H^+}) \end{aligned} \quad (\text{A.6})$$

$$F_{a2} = \frac{s_0^2 - c_0^2}{8s_0^3 c_0^3} \frac{m_t^2}{M_Z^2} (\cotan\beta)^2 \left\{ 2C_2^0(q^2, M_{H^+}, M_{H^+}, m_t) - \frac{1}{4} \right\} \quad (\text{A.7})$$

The functions $C_2^0, C_2^\pm, C_0, \bar{B}_1$ can be found in [29]

(ii) The chargino contributions

In analogy to (i), we write $F_L^{(C)}$ as the sum of the vertex diagrams (b1), (b2) and the external b-quark self-energy (b3) due to the charginos :

$$F_L^{(C)} = F_{b1} + F_{b2} + \frac{2s_0^2 - 3}{12s_0 c_0} \delta Z_L^{(C)} \quad (\text{A.8})$$

Denoting the masses of the charginos by $\tilde{M}_i$ $i = 1, 2$ (following the convention of Haber and Kane [30], we choose $\tilde{M}_1 > \tilde{M}_2$) and the scalar top mass by m_t , we have the following expressions :

$$\begin{aligned} F_{b1} = & \frac{1}{4s_0^3 c_0^3} \frac{m_t^2}{M_Z^2 \sin^2 \beta} \frac{2}{3} s_0^2 \times \\ & \sum_{i=1,2} |V_{i2}|^2 \left\{ 2C_2^0(q^2, m_t, m_t, \tilde{M}_i) - \frac{1}{4} \right\} \end{aligned} \quad (\text{A.9})$$

$$\begin{aligned} F_{b2} = & -\frac{1}{4s_0^3 c_0^3} \frac{m_t^2}{M_Z^2 \sin^2 \beta} \sum_{i,j} V_{j2} V_{i2}^* \times \\ & \left\{ O_{ij}^L \left\{ 2C_2^0(q^2, \tilde{M}_i, \tilde{M}_j, m_t) - \frac{3}{4} + \frac{1}{2} \log\left(\frac{m_t^2}{\tilde{M}_i \tilde{M}_j}\right) \right. \right. \\ & \left. \left. - q^2 \left[C_2^+(q^2, \tilde{M}_i, \tilde{M}_j, m_t) - C_2^-(q^2, \tilde{M}_i, \tilde{M}_j, m_t) \right] \right\} \right. \\ & \left. - O_{ij}^R \tilde{M}_i \tilde{M}_j C_0(q^2, \tilde{M}_i, \tilde{M}_j, m_t) \right\}, \end{aligned} \quad (\text{A.10})$$

$$\delta Z_L^{(C)} = \frac{1}{2s_0^2 c_0^2} \frac{m_t^2}{M_Z^2 \sin^2 \beta} \sum_i |V_{i2}|^2 \bar{B}_1(m_b^2, \tilde{M}_i, m_t), \quad (\text{A.11})$$

with

$$O_{ij}^L = -V_{i1}V_{j1}^* - \frac{1}{2}V_{i2}V_{j2}^* + \delta_{ij}s_0^2 \quad (\text{A.12})$$

$$O_{ij}^R = -U_{i1}U_{j1}^* - \frac{1}{2}U_{i2}U_{j2}^* + \delta_{ij}s_0^2 \quad (\text{A.13})$$

The quantities V_{ij}, U_{ij} are the elements of the transformation matrices V and U which diagonalize the chargino mass matrix

$$X = \begin{pmatrix} M & M_W\sqrt{2}\sin\beta \\ M_W\sqrt{2}\cos\beta & \mu \end{pmatrix} \quad (\text{A.14})$$

according to

$$U^*XV^{-1} = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} \quad (\text{A.15})$$

M and μ in are the usual soft SUSY-breaking parameters.

Appendix B Remarks on QCD corrections

In this Appendix, we give the definitions of some of the measurable quantities that we have used in our analysis as well as the QCD corrections to the ones involving hadrons.

Using α, G_μ and M_Z as input parameters and taking into account the running of the electric charge, the partial decay width of the Z into a massive fermion pair is given by:

$$\Gamma_f \equiv \Gamma_{Z \rightarrow f\bar{f}} = N_c \frac{\alpha(M_Z^2)}{48} \frac{M_Z}{c_0^2 s_0^2} \times \left[\frac{\beta(3-\beta^2)}{2} v_f^2 + \beta^3 a_f^2 \right] \quad (\text{B.1})$$

where

$$a_f = 2I_f^{3L} \quad v_f = 2I_f^{3L} - 4Q_f s_0^2 \quad (\text{B.2})$$

with I_f^{3L} the weak isospin ($\pm 1/2$ for up/down fermions), Q_f the electric charge, N_c a color factor and β the usual threshold factor given by $\beta = \sqrt{1-\mu^2}$, $\mu = 2m_f/M_Z$. The electroweak mixing angle $s_0^2 = 1 - c_0^2$ is defined by:

$$s_0^2 = \frac{1}{2} \left[1 - \sqrt{1 - \frac{4\pi\alpha(M_Z^2)}{\sqrt{2}G_\mu M_Z^2}} \right] \quad (\text{B.3})$$

For the light fermions ($f \neq b$), the QCD corrections can be incorporated by multiplying the partial widths by a factor $(1 + \frac{\alpha_s}{\pi})$. For the b quark a very good approximation is to replace the vectorial and the axial parts of Γ_b by [31]:

$$v_b^2 \longrightarrow v_b^2 \times \left[1 + \frac{\alpha_s}{\pi} (1 + 3\mu^2) \right] \quad (\text{B.4})$$

$$a_b^2 \longrightarrow a_b^2 \times \left[1 + \frac{\alpha_s}{\pi} (1 + 3\mu^2 \ln(\frac{4}{\mu^2})) \right] \quad (\text{B.5})$$

The forward-backward asymmetry for b quarks is, on top of Z resonance, given by:

$$A_{FB}^b = \frac{3}{4} \frac{2a_e v_e}{a_e^2 + v_e^2} \frac{2a_b v_b}{a_b^2 + v_b^2} \quad (\text{B.6})$$

where, due an accidental cancellation among the couplings ($v_b^2 \simeq a_b^2/2$), the mass correction is strongly suppressed to $O(10^{-4})$.

The QCD correction is implemented by multiplying the asymmetry by a factor $(1 - \frac{\alpha_s}{\pi} \delta_{QCD}^{FB})$ where, to a very good approximation

$$\delta_{QCD}^{FB} \simeq 1 - \frac{2}{3} \pi \mu \simeq 0.8 \quad (\text{B.7})$$

This coefficient can be drastically reduced by considering "two-jet" events [31,32] (in which e.g. the invariant mass of one jet is less than a fraction $\sqrt{y}$ of the total energy). For instance for the two values $y = 0.02$ and $y = 0.04$ one gets respectively $\delta_{QCD}^{FB} = 0.18$ and $\delta_{QCD}^{FB} = 0.30$.

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Table captions

Table 1 :

Contributions to $(-\nabla_{b1})$ from the Standard Model, Charged Higgses and Charginos sectors of the MSSM (for the charginos, the maximum allowed contribution $\equiv M$ is given) for $m_t = 150 \text{ GeV}$, $m_{\tilde{t}} = m_{H^\pm} = 100 \text{ GeV}$, $m_{\chi^\pm} \geq 45 \text{ GeV}$.

Table 2 :

Limits on the parameters of models with one Z' of alternative (composite Z) origin from "standard" and high luminosity LEP1 experiments. The notations are those of ref. [23].

Table 3 :

Effect of the variation of the top mass on M in the Standard Model and maximum allowed effect in the MSSM. For simplicity we neglected the (constant) contributions from α_s, θ_M . The values of the MSSM parameters are fixed as in table 1.

Table 1

$\tan\beta$	$-\nabla_{bV}^{SM}$	$-\nabla_{bV}^{(H^+)}$	$-\nabla_{bV(M)}^{(\chi^+)}$	$-\nabla_{bV(M)}^{MSSM}$
1	0.012	0.005	0.015	0.032
10	0.012	$5 \cdot 10^{-5}$	0.006	0.018

Table 2

	Y	Y_L	Z^*
LEP1	$M_Y > 500 \text{ GeV}$	$M_{Y_L} > 700 \text{ GeV}$	$M_{Z^*} > 600 \text{ GeV}$
HLEP 1	$M_Y > 900 \text{ GeV}$	$M_{Y_L} > 900 \text{ GeV}$	$M_{Z^*} > 1500 \text{ GeV}$

Table 3

m_t	$M_{(\alpha_s=\theta_M=0)}^{SM}$	$M_{(\alpha_s=\theta_M=0)}^{MSSM}$
90	1.03	1.02
150	1.02	0.99
200	1.01	0.95
230	1.00	0.93

Figure captions

Fig. 1 :

The set of considered diagrams (1a),(1b) contributes to the $Zb\bar{b}$ vertex. The subset (1a) gives the result of one extra doublet of charged Higgses, ref.[10].

Fig. 2 :

Allowed region in the (M, μ) parameter space, taken from ref.[19]. The dotted and point-dotted lines delimit the region already excluded by negative searches at LEP1.

Fig. 3 :

Mixing effects on the (w, ζ) variables of several models with one extra Z . Three different experimental errors on w , corresponding to $\delta M_W = \pm 600, 300, 100 MeV$ are shown.

Fig. 4 :

Same as in Fig.(3), in the plane of the $(w_b, \delta D)$ variables.

Fig. 5 :

Bounds on the mixing angle for a general E_6 model obtainable from a conventional (LEP 1) and a High luminosity (HLEP) LEP phase, assuming three different determinations of M_W as in Figs (3) and (4). The same full line in the left corner corresponds both to (LEP1, $\delta M_W = 100 MeV$) and to (HLEP, $\delta M_W = 300 MeV$).

Fig. 6 :

Same as in Fig. 5, for a general left-right symmetric model.

Fig 1 a

Fig 1 b

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6