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Constraints on the Standard Model and Two Higgs Models from B and K Physics

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ABSTRACT

We study the constraints that a joint fit to the CKM matrix and to inclusive quantities in B and K physics can place on the top quark and on the Higgs sector. We show that no significant bound on M_t can be obtained. We then determine the regions of parameter space that are allowed for the simplest extension of the minimal Standard Model, to the case of two Higgs doublets.

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Although the top quark was predicted a long time ago, and its existence is required both theoretically, through the cancellation of anomalies, and experimentally, because of the suppression of flavour changing neutral currents, this particle has eluded detection until now. The other missing ingredient in the Standard Model, the Higgs sector, is required to preserve renormalizability when breaking the $SU(2)_L \times U(1)$ gauge symmetry, but its precise structure is totally unknown: although in its minimal version the Standard Model requires only one neutral physical scalar, simple extensions are possible, or even attractive as they might result from unifying theories such as supersymmetry. Such extensions introduce new scalar particles, and we shall concentrate on the effect of an extra charged Higgs. Direct searches lead to model-independent bounds $M_t \geq 45$ GeV and $M_{H^+} \geq 35$ GeV from LEP,[1] and within the minimal Standard Model to $M_t \geq 89$ GeV from CDF.[2] Hadronic colliders are now starting to look at the top quark bounds that one can derive in the presence of a charged Higgs[3] : it is well known that the usual limit can then be avoided as a new decay channel is opened for the top quark (into $b[H^+ \rightarrow \tau\nu, c\bar{s}]$), which can totally modify the event signature for top quark decays. Any further information is indirect and can only be reached via radiative corrections. In the case of the top quark mass, electroweak radiative corrections to the Z^0 mass lead to an upper bound of the order of 200 GeV. More optimistic derivations[4] are being questioned as the inclusion of neutrino deep-inelastic data contains a hidden assumption on the charm quark mass.

One is then left with processes caused by loops containing the top and/or the Higgs. In the early days of the Standard Model, the analysis of K mixing and of rare K decays provided a very good prediction for the charm quark mass.[5] Nowadays the study of B meson mixing and decays is potentially an important source of information on the mass and mixing of the top (and bottom) quarks. In the case of a two-doublet extension of the Standard Model, it can provide constraints on the mass and coupling of the charged Higgs. The analysis of such constraints is the subject of the present letter.

One needs first to decide which observables to include in the analysis and then to pay special attention to the theoretical errors attached to their evaluation. Furthermore, the derivation of reliable bounds implies a well-defined statistical procedure, leading to a clear definition of the meaning of the proposed limits. We shall first examine these problems, and then turn to the results of our analysis, and discuss their consequences.

The first ingredient is of course the CKM matrix, for which we use Maiani representation.[6] The light quark mixings $|V_{ud}|$ and $|V_{us}|$ are well determined by data on neutron and hyperon and K_{e3} decays. As for $|V_{cd}|$ and $|V_{cs}|$, unitarity is enough to limit their values more stringently than the present experimental constraints (which in the case of $|V_{cs}|$ are either very loose or model-dependent). Finally, we include the recent ARGUS and CLEO bounds on $|V_{cb}|$ and $|V_{ub}/V_{cb}|$.[7] It is interesting to note that the present upper bound of 0.221 on $|V_{cs}|$ (derived from a combination of the Tevatron and the CDHS dilepton production data[8]) was already predicted in Ref. [9],* as well as the central value of $|V_{ub}/V_{cb}|$.

The other observables are related to B and K physics. The B semileptonic width should be reasonably well reproduced by perturbative QCD as the scale is big and the quantity inclusive. Note that our input value for $|V_{cb}|$ already uses an estimate of the B width. The procedure we use in our fit, which will be explained later, checks the consistency of a first-order QCD estimate[9] of this quantity with the quoted value of $|V_{cb}|$. We also take $B_d^0\bar{B}_d^0$ mixing and ϵ into account: for these data, the non-perturbative effects have been extensively studied on the lattice and are parametrized by bag and decay constants. Finally, we also consider the $K^0\bar{K}^0$ mass difference. We obtain that its value is always fitted within 10% of its perturbative estimate, well within the theoretical errors due to long-range effects.[10]

* However, we want to correct a mistake present in that reference: the error propagation was incorrectly done in the case of the Wolfenstein parametrization. For instance, the least constrained fit should limit the parameter 'A' between 0.85 and 1.69 at the 1σ level, and between 0.81 and 2.02 at the 2 σ level, the best fit being 0.92. These corrected values can be read off from the bounds on the CKM matrix elements.

We do not include ϵ'/ϵ in our fit as the constraints that one could get from the NA31 measurement have been considerably weakened by the E731 result.[11] Furthermore, the theoretical situation is unclear, both because of large M_t effects in QED and Z^0 penguin contributions and because of hadronic matrix elements and isospin breaking effects.[12] In principle, there are other experimental data which could further constrain the charged Higgs parameters, such as those on rare K decays[13] or those on rare B decays.[14] The exclusive character of these processes means that strong interactions are not under theoretical control: the perturbative corrections, the long-distance contributions and the transition from the partonic to the hadronic level involve enormous uncertainties. This makes it very difficult to relate realistically the experimental results to the theoretical parameters. For instance, in the case of the exclusive $B \to K^*\gamma$ process, the value of the ratio $\Gamma(B \to K^*\gamma)/\Gamma(b \to s\gamma)$ can be chosen among the 4.5-7%[15] from the constituent quark model and the 14% from a form-factor approach[16] to the 28% from QCD sum-rule predictions[17] or the 40% from Ref. [18]. We thus choose not to include such problematic quantities in our analysis.

The input parameter ranges, as well as the fitted data, are summarized in Table 1. We have chosen the most conservative estimates so that the limits we derive are as reliable as possible.

The originality of our paper resides in the inclusion of all the variables of the problem in a global fit. Many authors have already considered this problem, both in the Standard Model case[19] and in the charged Higgs case.[20] These studies, considering only the dependence of the predictions on a limited number of variables, and using various approximate expressions, are valuable in that they provide physical insight into the problem. However, the validity of the bounds derived is questionable, as these have no clear statistical meaning, and do not encompass the whole theoretical uncertainties. We shall also discuss in the following the difference of our fit with recent ones.

We use a χ^2 minimization method, the details and justification of which have been discussed elsewhere[9] . Let us simply mention that the quality of a fit is

measured in terms of a "minimum number of standard deviations" σ. This means that there is a parameter choice in the allowed ranges such that all data are fitted within σ standard deviations, and that any other choice will lead to a worse fit for at least one of the data. By calculating the value of σ for a parameter (or for an observable) fixed at a value P, we extract numerically a function $\sigma(P)$. The 1σ and 2σ ranges quoted in the following correspond to the values of P such that $\sigma(P) = 1$ or 2 respectively. This approach supposes that a fine tuning of the theoretical input is allowed, or equivalently that one cannot assign any statistical weight to theoretical guesses. Another point of view has been used[21] , where the probability that an observable be in a given interval is measured by the volume in parameter space corresponding to that interval. We think that such a definition is questionable as for instance a change of variables will modify the volume element but should not change the probability. We also want to stress that our χ^2 fit includes all the measured quantities instead of only two of them, as in Ref. [21].

We can now turn to the results of such an analysis in the case of the Standard Model. Let us briefly remind the reader of the main theoretical inputs. The formula for $x_d = \frac{\delta M}{\Gamma}|_{B^0_d \bar{B}^0_d}$ is well known:

$$x_d = 2\tau_B(\frac{G_F^2 M_W^2}{16\pi^2})(\frac{4}{3}f_B^2 M_B B_B)| \sum_{i,j=u,c,t} \eta_{ij}^B S_{ij} \mathrm{Re}(V_{id}^* V_{is} V_{jd}^* V_{js})| \qquad (1)$$

where $x_i = M_i^2/M_W^2$
and $S_{ij} = S_{ij}^{SM} = S_{ij}^{WW} = (1 + \frac{x_i x_j}{4}) I_2(x_i, x_j, 1) - 2x_i x_j I_1(x_i, x_j, 1)$. The loop integral factors I_1 and I_2 were reported in Ref. [22]. We have assumed that by fixing the QCD correction factors η_{ij}^B to the values of Table 1, we retain a good approximation. The dominant contribution to x_d comes from the terms involving top quark exchange. Their quadratic dependence on M_t for large top mass could in principle lead to restrictive bounds. Unfortunately, big uncertainties are involved in the analysis: x_d has to be corrected for long-range effects which enter in $B_B f_B^2$. Also, the coupling of the top quark is not known, as it involves $|V_{td}|^2$, and it must thus be deduced from the unitarity constraints. V_{td} is unfortunately one of the

very small CKM matrix elements, so that small errors in the adjacent mixings get translated into a huge one on $|V_{td}|$.

To constrain the CKM matrix, we include effects from K physics, namely

$$\Delta M_K = 2(\frac{G_F^2 M_W^2}{16\pi^2})(\frac{4}{3} f_K^2 M_K B_K)|\sum_{i,j=u,c,t} \eta_{ij}^K S_{ij} \mathrm{Re}(V_{id}^* V_{is} V_{jd}^* V_{js})| \qquad (2)$$

and

$$\epsilon = \frac{e^{i\pi/4}}{\sqrt{2}}(\frac{G_F^2 M_W^2}{16\pi^2})(\frac{4}{3} f_K^2 M_K B_K)\frac{1}{\Delta M_K}|\sum_{i,j=u,c,t} \eta_{ij}^K S_{ij} \mathrm{Im}(V_{id}^* V_{is} V_{jd}^* V_{js})| \qquad (3)$$

Both of these quantities have non-perturbative contributions, parametrized by $B_K f_K^2$, which bring some uncertainty (although much smaller than in the B case for which f_B is not measured, but can only be roughly estimated). As previously mentioned, long-range contributions influence further the understanding of ΔM_K but it turns out that it is automatically fitted within 10% so that, given the theoretical uncertainties, it does not constrain the fit strongly. Finally, we also include an estimate of the B semileptonic width, both from the experimental $|V_{cb}|$ and directly from the formula quoted in Ref. [9].

Once all these constraints are taken into account, the remaining uncertainty on $|V_{td}|$ is still of the order of a factor 5. This means that the theory has very little predictive power for x_d. From the above discussion, one would not expect the top quark mass to be predicted with a high precision. The result of the minimization is in total agreement: no bound on the top mass can be derived from the above constraints, the minimum number of standard deviations being totally flat as a function of M_t from 89 to 200 GeV, as can be seen from Fig. 1a. We also give in Fig. 1b our results for the phase δ of the Maiani representation. It has to be different from $n\pi$ as a real CKM matrix would forbid CP violation. Apart from this, δ is unconstrained at the 2σ level. The quantities we chose to fit are actually sensitive to $\cos\delta$, so that the curve is symmetric. This degeneracy can be broken

only by data sensitive to $\sin\delta$, such as ϵ'/ϵ. Fig. 1c shows that the bag parameter B_K has to be bigger than 0.66 at the 1.5 σ level, and that values from 0.9 to 1 are perfectly allowed. We want to stress that enlarging the allowed B_K interval cannot modify the fact that $B_K \approx 1$ fits all the data at the 0.6 σ level.

This seems to contradict the results of a recent fit.[23] We have tried to account for this discrepancy by comparing closely the two approaches. First of all, Maalampi and Roos include further experimental constraints. Some consist of additional estimates of the CKM matrix elements or of the top quark mass,[4] and we have checked that their inclusion in our fit does not modify our conclusions. Others are linked with model-dependent quantities, such as ϵ'/ϵ. Given the theoretical uncertainties these cannot change the result. We have also explicitly verified that the M_t dependence of the QCD corrections does not make any difference: we show in Fig. 1 the results of both procedures, using the exactly the same input as Maalampi and Roos. We thus cannot explain or confirm the surprising claims of Ref. [23].

We now consider the minimal extension of the Standard Model to the case of a second Higgs doublet. Many of our results could be easily generalized to a general theory with a charged scalar. We adopt the philosophy that in a model with extra Higgs doublets flavour changing neutral currents (FCNC) must be suppressed. The most general Yukawa coupling of the model will in general induce such FCNC. These can be avoided at tree level by the introduction of discrete K symmetries.[24] These in turn can be justified by unifying considerations[25] or as a symmetry breaking effect[26] and can be naturally implemented with minor restrictions on the quark mass matrices.[27] Several models are then possible, and we choose here to concentrate on the one most closely linked with supersymmetry and, by means of a small modification, with an eventual solution to the strong CP problem. This requires two SU(2) doublets with vacuum expectation values (v.e.v.) v_1 and v_2 which give masses to up and down quarks respectively.

Although this model contains at least six new free parameters (four Higgs masses, the ratio of the v.e.v. of the two doublets $\tan\beta = v_2/v_1$ and a mixing angle in the neutral Higgs sector), B and K physics are sensitive only to the presence of the extra charged scalar. This fact restricts the relevant extra parameters to two only: the charged Higgs mass M_H and the coupling strength $\tan\beta$. The mass is restricted by the new LEP bounds to be heavier than 35 GeV[1] . Due to this rather high value, the bounds on the ratio of the v.e.v. from lepton universality in μ and τ decay are of little use because these are suppressed by the Higgs propagator. A bound might be extracted only approximatively from a renormalization group analysis[28] or from perturbative considerations.[29] Furthermore it seems also difficult to derive useful limits from the effects of a charged boson on the ρ parameter[30] or from the analysis of several low energy processes like nuclear scattering, neutrino magnetic moment or semileptonic decays.[31] We argue that it will not be the controversial cosmological bounds[32] that can grasp the ultimate answer about this ratio. Since rare K and B decays cannot be clearly predicted, one is left with the tiny K_L-K_S mass difference (which we constrain to be fitted within the precision of the Standard Model, i.e. 10%), the CP impurity parameter ϵ and more importantly B meson mixings. It is the joint effect of these quantities which we shall study.

The extra Higgs doublet introduces new terms in formulae (1), (2)and (3): the S_{ij} now become[33]

$$S_{ij} = S_{ij}^{SM} + S_{ij}^{WH} + S_{ij}^{HH}$$

with the leading contributions

$$\begin{aligned} S_{ij}^{HH} &= \frac{\eta_H}{4}\left(\frac{v_2}{v_1}\right)^4 x_i x_j I_2(\eta_H x_i, \eta_H x_j; 1) \\ S_{ij}^{WH} &= \frac{\eta_H}{4}\left(\frac{v_2}{v_1}\right)^2 x_i x_j [-8 I_1(x_i, x_j, \eta_H) + 2 I_2(x_i, x_j; \eta_H)] \end{aligned} \tag{4}$$

where $\eta_H = M_H^2/M_W^2$.

As we have seen, the experimental data can be easily reproduced in the context of the Standard Model. So we already know that for large M_H, or small $\tan\beta$,

for which the Higgs decouples, we can get a good fit. Also, one knows that the effect of the Higgs sector will be magnified by large fermion masses, so that the parameter space will be more restricted in the case of a large top mass than for a light one. The leading constraint arises from the contribution to x_d where both W are replaced by charged Higgs bosons in the box diagram. We show our results in Fig. 2, in which the allowed regions of parameter space are given at the 1 and 2 σ level respectively. This is in good agreement with the results of Gunion[20] , and in rough agreement with the other papers of Ref. [20]. We want to point out that at the 2 σ level, the whole range of parameters is allowed for $M_t = 45$ GeV.

The main difference between the two-doublet scenario and the Standard Model is obviously the very existence of an extra charged boson. The only hope of direct detection, as has been extensively studied,[34] is in the case $M_H \le M_t + M_b$, for which the top quark could decay into a $b\tau\nu$ via a charged Higgs. There are two caveats to this: first, the decay width has to be sufficiently large compared to the more conventional $t \to bl\nu$ channel, and the branching fraction of the Higgs into $\tau\nu$ has to be large, the other channel cs being lost in the background. We can translate the allowed regions of Fig. 2 into Fig. 3, which shows the allowed regions for the product $B(t \to b\tau\nu)\,\frac{\Gamma(t\to H)}{\Gamma(t\to W)}$. The main result is that this quantity is hardly constrained irrespectively from the top quark mass. One only gets a very weak limit on the ratio of widths, which has to be smaller than 10 at the 2 σ level.

Finally, indirect evidence of the charged Higgs could be derived via the eventual observation of new quantities such as B_s mixing. The key observation is that the extra terms from the charged scalar always increase x_d. To compensate for this, one needs to decrease V_{td}. As this is very small, it is not too constrained by unitarity. On the other hand, when one calculates $x_s = \frac{\delta M}{\Gamma}|_{B_s^0 \bar{B}_s^0}$, the CKM matrix element is V_{ts}. This is much bigger than V_{td}, and so its value is much more constrained by unitarity. So the predicted value of x_s is always bigger than that from the minimal Standard Model. As can be seen from Fig. 4, we get, for the minimal Standard Model $x_s \le 41(1\sigma)$, $65(2\sigma)$ whereas the two-doublet model gives $x_s \le 115(1\sigma)$, $570(2\sigma)$. Both models predict $x_s \ge 4.2(1\sigma)$, $3.8(2\sigma)$. So a small B_s mixing would rule out both the Standard Model and its extension to two Higgs doublets whereas a large one would be an indication of a more complex Higgs structure.

To conclude, we have shown that new experimental results and theoretical estimates do not modify the status of the Standard Model. In particular, no substantial limit on the top quark mass can be derived from B and K physics. However, the same data can be used to constrain the parameter space of the minimal extension of the Higgs sector. Quantities sensitive to large CKM matrix elements, such as x_s, seem the best hope of improving substantially our knowledge of the minimal Standard Model, or equivalently, of limiting the degrees of freedom of the alternatives.

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TABLE CAPTIONS

[1.] Input data and parameter ranges for our fit. All quantities are in GeV units, except otherwise indicated.

FIGURE CAPTIONS

Fig. 1. Results of our fit for the top quark mass, the phase δ of the CKM matrix in the Maiani representation and for the bag parameter B_K, with fixed QCD radiative corrections (plain line) and using the parametrization of Ref. [23]. The vertical axis gives σ, the minimum number of standard deviations of the worst fitted observable, while the horizontal axis gives the value of the parameter kept fixed in the fit.

Fig. 2. Regions of the $\tan\beta - M_H$ parameter space allowed at the 1σ (a) and 2σ (b) level. Only the upper left corner of the plot is excluded in each case, that is the various bands are contained in each other.

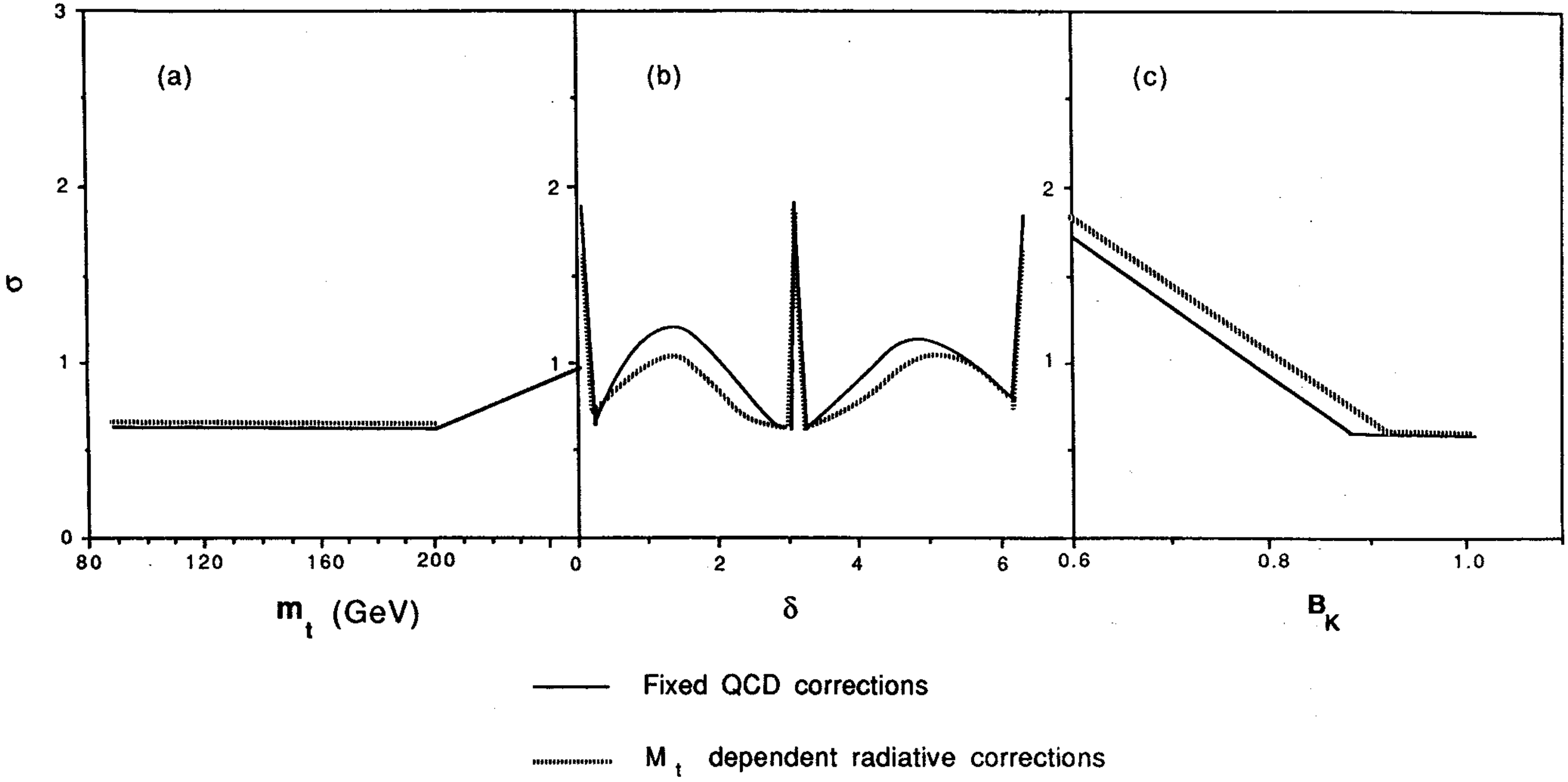
Fig. 3. Allowed regions at the 2 σ level for $B(t \to b\tau\nu)\ \frac{\Gamma(t\to H)}{\Gamma(t\to W)}$ as a function of $\tan\beta$

Fig. 4. Comparison of the best fits for x_s in the Standard Model and in the two-doublet case (a) and corresponding allowed values of x_s at the 2 σ level as a function of $\tan\beta$ (b). Only the lower right corner is excluded in each case: that is the bands are contained in each other.

fitted quantities		
experimental quantity	value	error
$\lvert V_{ud}\rvert$	0.9744	0.0010
$\lvert V_{us}\rvert$	0.2205	0.0023
$\lvert V_{cd}\rvert$	0.21	0.03
$\lvert V_{cb}\rvert$	0.046	0.010
$\frac{\lvert V_{ub}\rvert}{\lvert V_{cb}\rvert}$	0.10	0.04
$\varepsilon\ (10^{-3})$	2.259	0.018
$\Delta M(K_L K_S)\ (10^{-15})$	3.521	10%
x_d	0.70	0.13
τ_B (ps)	1.18	0.14
$B(B\to l\nu X)$	0.110	0.006
fixed quantities		
M_K	0.49772	
f_K	0.169	
M_W	80.11	
M_{B^0}	5.2752	
parameter ranges		
	minimum	maximum
B_K	0.5	1.0
$B_B f_B^2$	0.005	0.04
M_u	0.05	0.4
M_c	1.25	1.7
M_b	4.6	5.0
M_t	45 (2 H) 89 (s.m.)	200
tan(β)	0.1	10
M_H	35	1000

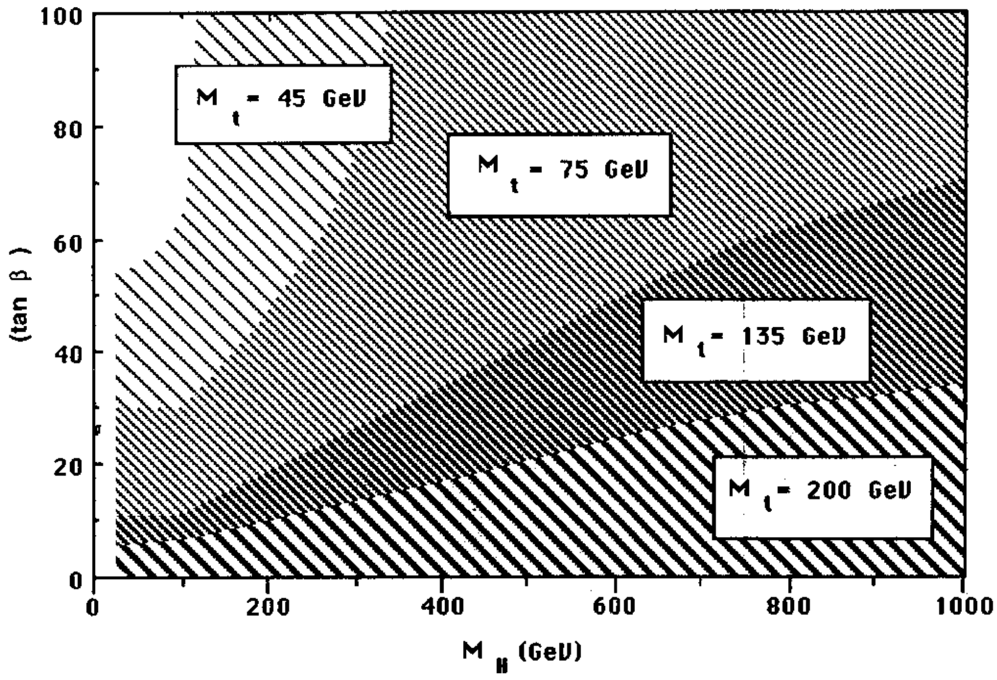
QCD corrections			
	η_{cc}	η_{tt}	η_{ct}
K	0.85	0.61	0.375
B	1.0	0.85	1.0

Table 1



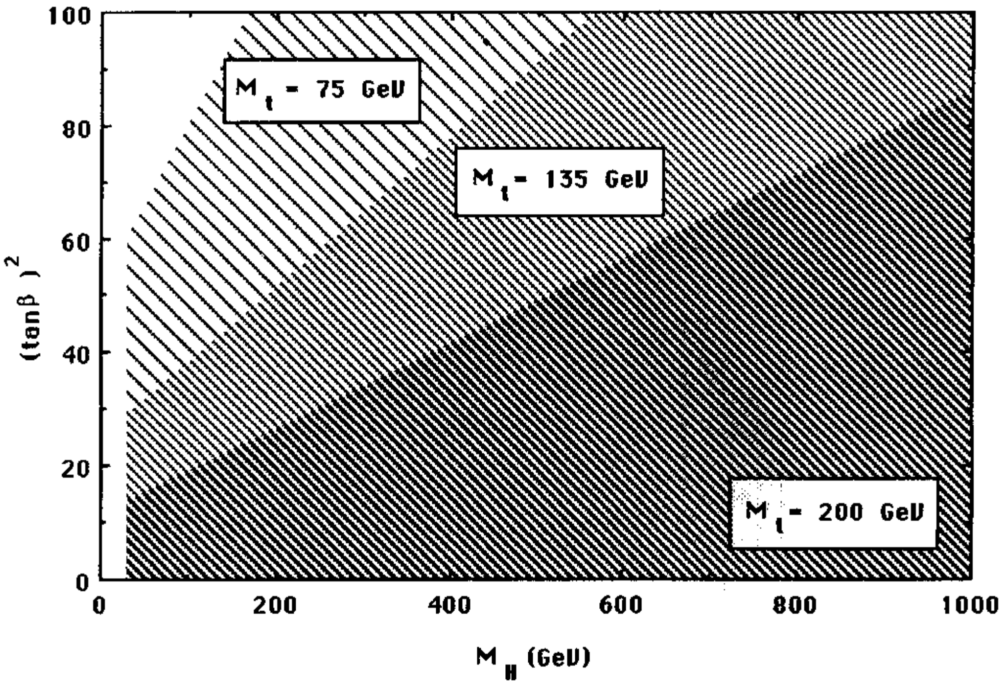
σ
(a)
(b)
(c)
0
1
2
3
80
120
160
200
0
2
4
6
0.6
0.8
1.0
m_t (GeV)
δ
B_K
Fixed QCD corrections
M_t dependent radiative corrections

Figure 1



100
80
60
40
20
0
(tan β^2)
M t = 45 GeV
M t = 75 GeV
M t = 135 GeV
M t = 200 GeV
0
200
400
600
800
1000
M H (GeV)

(a)



100
80
60
40
20
0
(tanβ)^2
M t = 75 GeV
M t = 135 GeV
M t = 200 GeV
0
200
400
600
800
1000
M H (GeV)

(b)

Figure 2

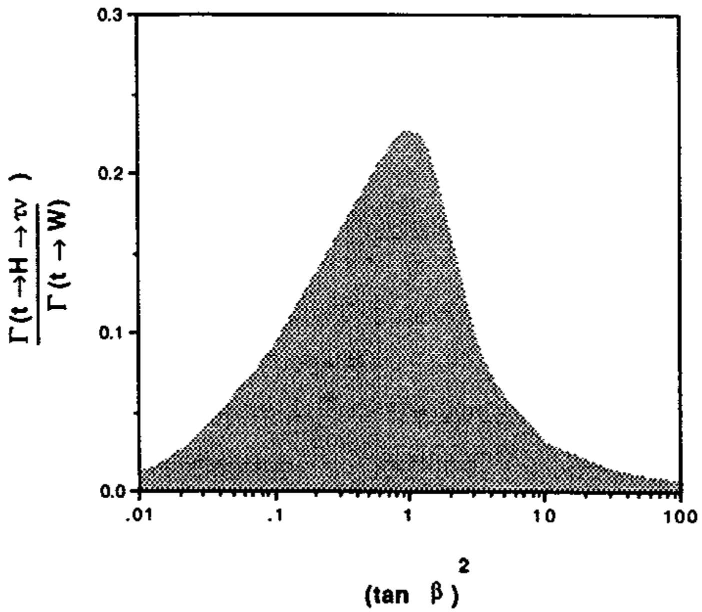


Figure 3

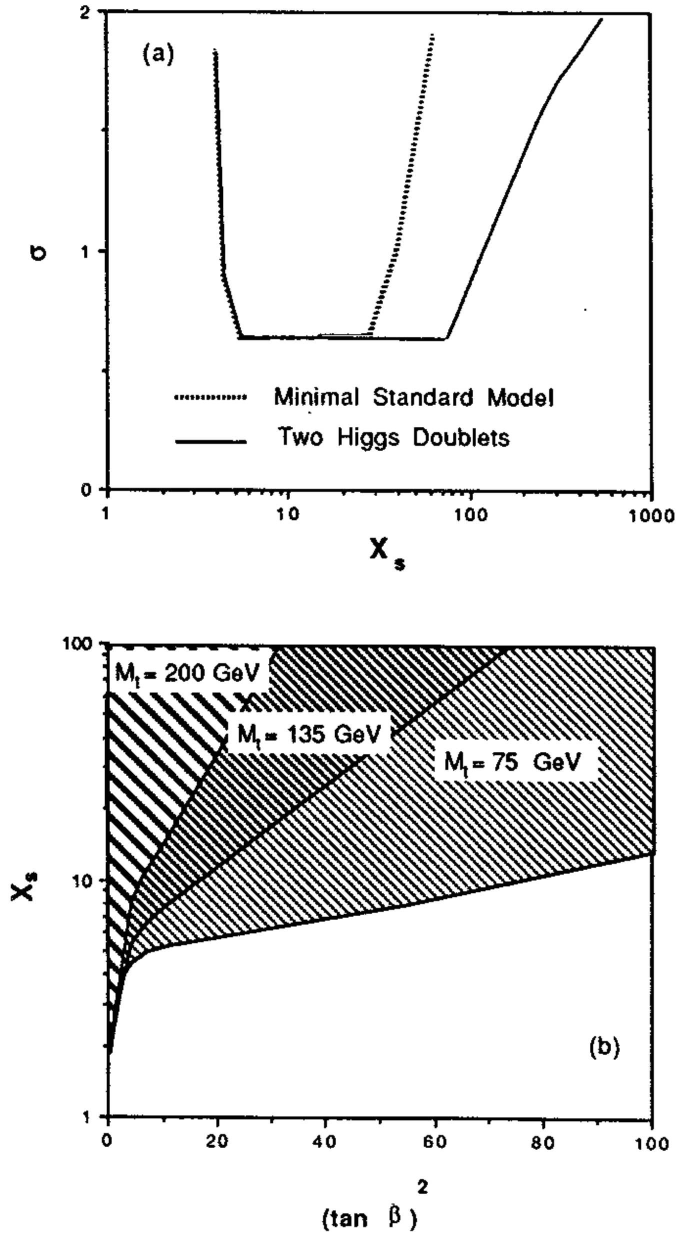


Figure 4