On the possibility of a very light $A^0$ at low $\tan \beta$

in the MSSM

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The searches at LEP II for the processes $e^+e^- \rightarrow h^0Z$ and $e^+e^- \rightarrow h^0A^0$ in the Minimal Supersymmetric Standard Model (MSSM) fail to exclude regions of the $m_h, m_A$ plane where $\tan \beta < 1$, thus allowing a very light $A^0$ ($m_A < 20$ GeV). Such a parameter choice would predict a light $H^\pm$ with $m_{H^\pm} < m_W$. Although the potentially large branching ratio for $H^\pm \rightarrow A^0W^*$ would ensure that $H^\pm$ also escaped detection in direct searches at LEP II and the Tevatron Run I, we show that this elusive parameter space is overwhelmingly disfavoured by electroweak precision measurements through its large contribution to the $Zb\bar{b}$ vertex.
I. INTRODUCTION

The Minimal Supersymmetric Standard Model (MSSM) is currently the leading candidate for physics beyond the Standard Model (SM). The MSSM predicts five physical Higgs bosons: a charged pair \( (H^+, H^-) \), two CP–even scalars \( (h^0, H^0) \), and a CP–odd pseudoscalar \( A^0 \). To date their detection remains elusive despite intense searches at past and present colliders. Lower limits on their masses have been derived, which assume certain decay modes and apply to specific regions of the MSSM parameter space [1]. LEP II has the strongest lower limits on the masses of all the above Higgs bosons. In the case of \( H^{\pm} \), limits from the Tevatron run I can be competitive in specific regions of parameter space (small and large \( \tan \beta \)) [2,3]. LEP carries out searches in the channels \( e^+e^- \rightarrow h^0Z, h^0A^0 \) and obtains the mass limits \( m_A > 91 \text{ GeV}, m_h > 91 \text{ GeV}, \) for \( \tan \beta > 1 \) [4]. In the framework of the MSSM, these mass limits enable indirect bounds on \( m_{H^\pm} \) and \( m_{H^0} \) to be derived which are stronger than the direct search limits for these particles [3]. For example, \( m_A > 90 \text{ GeV} \) implies \( m_{H^\pm} > 120 \text{ GeV} \), which is stronger than the direct bound \( m_{H^\pm} > 78 \text{ GeV} \).

The above mass bounds are obtained for \( \tan \beta > 1 \). In this paper we concentrate on the region of \( \tan \beta < 1 \) in which the mass bounds are considerably weakened. In particular, a very light \( A^0 \) (\( m_A < 20 \text{ GeV} \)) has not been excluded by direct searches [3]. The MSSM with \( \tan \beta < 1 \) is not strictly the minimal model since it calls for a new physics scale below the GUT scale where the top–quark Yukawa coupling becomes strongly interacting. We nevertheless advocate consideration of the \( \tan \beta < 1 \) parameter space for the following reasons:

(i) Theoretical studies and searches for the Higgs bosons of the general two–Higgs doublet model consider \( \tan \beta < 1 \) [4]. In such models one usually imposes the milder requirement that the top–quark Yukawa coupling is perturbative at the weak scale, corresponding to \( \tan \beta > 0.4 \) [4].

(ii) A very light pseudoscalar is a necessary condition for spontaneous CP violation in the MSSM [8–11] i.e. the existence of a relative phase between the vacuum expectation values of the two Higgs doublets.

Point (ii) is of particular interest since spontaneous CP violation has been considered ruled out in the MSSM for years due to the progressively stronger mass bound on \( m_A \) for \( \tan \beta > 1 \). However, spontaneous CP violation might be possible in the unexcluded region of low \( \tan \beta \) and light \( m_A \) (despite a possible new physics threshold much below the GUT scale), thus motivating experimental consideration of this region.

A very light \( A^0 \) is not ruled out for \( \tan \beta < 1 \) because the standard search strategies which rely on \( b \) tagging the decays \( h^0 \rightarrow b\bar{b} \) or \( h^0 \rightarrow A^0A^0 \rightarrow b\bar{b}b\bar{b} \) become ineffective. In the \( \tan \beta < 1 \) region the decay \( h^0 \rightarrow A^0A^0 \) becomes increasingly important [12], thus suppressing \( \text{BR}(h^0 \rightarrow b\bar{b}) \). The subsequent
decay $A^0 \rightarrow \pi\pi$ has a sizeable branching ratio (BR) for $\tan \beta < 1$ and/or $m_A > 2m_b$ and so suppresses BR($A^0 \rightarrow b\bar{b}$), giving rise to topologies of $\pi\pi\pi\pi$ (from $e^+e^- \rightarrow h^0 A^0$) or $Z\pi\pi\pi$ (from $e^+e^- \rightarrow h^0 Z$). These final states elude the standard LEP searches, resulting in unexcluded regions in the $(m_h, m_A)$ plane.

The existence of a very light $A^0$ in the MSSM requires a light $H^\pm$ with $m_{H^\pm} < 80$ GeV, which may violate constraints on $m_{H^\pm}$ from other experiments e.g. i) direct searches at LEP II and the Tevatron Run I, and ii) the indirect effect of $H^\pm$ on flavour changing neutral current processes (FCNC) and electroweak precision measurements. Thus in the framework of the MSSM the unexcluded region of very light $A^0$ may be probed by searching for a light $H^\pm$. We will show that the direct searches for $H^\pm$ would be affected by the presence of a large BR for $H^\pm \rightarrow A^0 W^*$, and therefore such a $H^\pm$ may not be ruled out from current searches. However, the indirect effect of $H^\pm$ on electroweak observables which are sensitive to corrections to the $Zb_Lb_L$ vertex is very pronounced, and a light $H^\pm$ with $\tan \beta < 1$ is strongly disfavoured by LEP electroweak precision data.

Our work is organized as follows. In Section 2 we evaluate the BR($H^\pm \rightarrow A^0 W^*$) in the region of $(m_A, \tan \beta)$ unexcluded by direct searches for $h^0$ and $A^0$, which predicts $m_{H^\pm} < 76(78)$ GeV for $\tan \beta = 0$.6. It should be noted that there are sizeable corrections to the tree level sum rule, $m_{H^\pm} = \sqrt{m_W^2 + m_A^2}$ [13], and $m_{H^\pm}$ can be as light as 69 (73) GeV for $\tan \beta = 0.6(0.8)$. In this region there exists the following

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"This was first pointed out for LEP II searches in [4]."
mass hierarchy, $m_{H^0} \gg m_{A^0} \approx m_{H^\pm} \gg m_{A^\pm}$ which differs from the usual Higgs mass hierarchy $m_{H^0} \approx m_{A^0} > m_{h^0}$ for $\tan \beta > 1$ and $m_{A^0} > 130$ GeV. We will show results for the no mixing case, using the LEP values $\mu = -200$ GeV, $M_{SUSY} = 1$ TeV.

A. The decay $H^\pm \to A^0 W^*$

In the parameter space of low $\tan \beta$ and small $m_A$ the three body decay $H^\pm \to A^0 W^* \to A^0 f f'$ is sizeable. In Fig. 1 we show BR($H^\pm \to A^0 W^*$) as a function of $m_{H^\pm}$. One observes that BR($H^\pm \to A^0 W^*$) can be as large as 60% (45%) for $\tan \beta = 0.8(0.6)$. Note that these BRs are larger than those presented in [14] since this paper used $\tan \beta = 1.6$ and the (then) bound $m_{A^0} > 50$ GeV.

B. $H^\pm$ searches at LEP II

LEP II searches for $e^+ e^- \to H^+ H^-$ and has derived limits on $m_{H^\pm}$ as a function of BR($H^\pm \to \tau \nu \tau$), with the most conservative limit being $M_{H^\pm} > 78.6$ GeV [13]. The searches assume BR($H^\pm \to \tau \nu \tau$)+BR($H^\pm \to c \bar{s}$) = 1. The large BR($H^\pm \to A^0 W^*$) in the parameter space of interest would weaken the existing limits on $m_{H^\pm}$, allowing $m_{H^\pm} < 76(78)$ GeV for $\tan \beta = 0.8(0.6)$ i.e. the prediction for $m_{H^\pm}$ in the unexcluded region. Investigation of the impact of $H^\pm \to A^0 W^* \to A^0 f f'$ decays on the MSSM $H^\pm$ searches at LEP is in progress, and a preliminary search [16] for such decays has been performed in the context of the 2HDM (Model I), where BR($H^\pm \to A^0 W^*$) can reach 100% [17]. However, this search also required $b$-tagging and is only valid for $m_A > 2m_b$ and large BR($A^0 \to b\bar{b}$).

C. $H^\pm$ searches at the Tevatron

The Tevatron Run I searched for $t \to H^\pm b$ decays and rules out regions of the $(m_{H^\pm}, \tan \beta)$ plane which would correspond to values of BR($t \to H^\pm b$) incompatible with the observed events in $t\bar{t}$ production. The exact boundary of the excluded region depends sensitively on the theoretical cross section, $\sigma(p\bar{p} \to t\bar{t})$, with the most conservative excluded region occurring for larger theoretical cross–section. The region $m_{H^\pm} < 80$ GeV and $\tan \beta < 0.8$ has been ruled out at 95\% CL [2].

In the low $\tan \beta$ region, where $H^+ \to c\bar{s}$ is normally assumed to be the dominant channel, the contribution of $t \to b H^+ \to b c \bar{s}$ decays would cause a deficit in the expected number of leptonic ($e, \mu$) decays of the top ($t \to b W^+ \to b l^+ \nu_l$), thus giving a worse fit to the data. The suppression of BR($H^\pm \to c s, \tau \nu \tau$) by $H^\pm \to A^0 W^*$ (shown in Fig. 1) would be sufficient to shift the boundary of the excluded region to lower values of $\tan \beta$, thus narrowly permitting $m_{H^\pm} < m_W$ and $0.6 < \tan \beta < 0.8$. The new decay channel can give rise to the observed final states via $H^\pm \to A^0 W^* \to A^0 l^\pm \nu_l$. This was pointed out in [18] and [19] which concentrated on the region $\tan \beta > 1$ and $m_A > 90$ GeV. With 2 fb$^{-1}$ of data at the
Tevatron Run II, the region $m_{H^\pm} < 80$ GeV and $\tan \beta < 2.5$ will be ruled out at 95% CL [20]. Therefore this scenario of very light $A^0, h^0$ and light $H^\pm$ will be excluded or confirmed directly in $t \rightarrow H^\pm b$ decays very soon.

III. INDIRECT SEARCHES FOR $H^\pm$

The previous section showed that the unexcluded region from the searches for $e^+e^- \rightarrow h^0A^0$ and $e^+e^- \rightarrow Zh^0$ corresponds to a light $H^\pm$ which itself would have narrowly escaped detection in direct searches due to the large $\text{BR}(H^\pm \rightarrow A^0W^\ast)$. It is known that a light $H^\pm$ and low $\tan \beta$ would have large effects on various rare $K$ or $B$ meson decays as well as the electroweak precision measurements. In the following subsections we address the compatibility of $m_{H^\pm} < m_W$ and $\tan \beta < 1$ with these indirect constraints.

A. Constraints from FCNC processes

Owing to the large top quark Yukawa coupling, a light $H^\pm$ with $\tan \beta < 1$ would contribute strongly to processes like $b \rightarrow s\gamma$, $B^0\bar{B}^0$ and $K^0\bar{K}^0$ mixing, through top quark exchange diagrams [21,22]. However, contributions to these processes from supersymmetric particles depend strongly on the flavour structure of the MSSM which is completely arbitrary. It is known that the $H^\pm$ contribution to $b \rightarrow s\gamma$ can interfere destructively with the chargino contribution depending on the sign of $A_t$, $\mu$ and the mass insertion parameter $\delta_u^{23}$ in the up squark sector, [21,23,24]. More importantly, the unconstrained MSSM allows for gluino mediated $b - s$ transitions with arbitrary coupling strength $\delta_d^{23}$ [25], which can be chosen to cancel any large contribution from $H^\pm$. Given the possibility of FCNCs mediated by supersymmetric particles we conclude that no definite constraints on $H^\pm$ can be derived from these processes.

B. Constraints from electroweak precision measurements

Stringent constraints on a light $H^\pm$ are obtained from electroweak precision measurements, i.e. the $Z$-pole observables from LEP1 and SLC, and the $W$ mass from Tevatron and LEP2. The $Z$-pole observables consist of 8 line-shape parameters $\Gamma_Z, \sigma_h^0, R_t, A_{FB}^0(l = e, \mu, \tau)$, two asymmetries from the $\tau$-polarization data ($A_\tau, A_e$), the decay rates and the asymmetries of $b$- and $c$-quarks ($R_b, R_c, A_{FB}^{0,b}, A_{FB}^{0,c}$) and the asymmetries measured at SLC ($A_{LR}^0, A_b, A_c$). We use the experimental data of these observables reported at the 2001 summer conference [26]. Taking account of the $m_t$ data from Tevatron [27], the QCD coupling $\alpha_s(m_Z)$ [28] and the QED coupling $\alpha(m_Z^2)$ [29] at the $Z^0$-mass scale, we find that the SM best fit gives $\chi^2/(\text{d.o.f.}) = 25.3/(21 - 4)$ (9% CL) [29].
The Higgs bosons in the MSSM affect these electroweak observables through the radiative corrections to the gauge boson two-point functions (oblique corrections), and the vertex and box corrections. Among them, the $Zb_Lb_L$ vertex is most sensitive to small $m_A$ (i.e., small $m_{H^\pm}$) and small tan\(\beta\) through the charged Higgs boson and the top quark exchange, since the coupling $b_L-t_R-H^\pm$ is proportional to $m_t/\tan\beta$. In Fig. 2 we show the total $\chi^2$ as a function of $m_A$ for various values of tan\(\beta\). Four thick lines correspond to tan\(\beta\) = 0.5, 0.6, 0.7 and 1. The thick-dashed horizontal line denotes the minimum $\chi^2$ in the SM ($\chi^2 = 25.3$). The experimentally unexcluded $A^0$ mass is $m_A < 40$ GeV for tan\(\beta < 0.7\) (for the no mixing scenario that we consider).

It is easy to see that small tan\(\beta\) (<1) leads to a significantly large $\chi^2$ ($\approx 100$ for $m_A < 100$ GeV) due to the enhancement of the $b_L-t_R-H^\pm$ coupling which sizeably affects the partial decay width of $Z \to \bar{b}b(\Gamma_b)$. The observables which are sensitive to $\Gamma_b$ are $\Gamma_Z$, $R_l$ and $R_b$. For example, for tan\(\beta = 0.7\) and $m_A = 20$ GeV which corresponds to $m_{H^\pm} \approx 74$ GeV, the deviations of these three observables from the experimental data are $3.4\sigma(\Gamma_Z)$, $4.7\sigma(R_l)$ and $6.3\sigma(R_b)$, while the SM best fit gives $-0.6\sigma$, $0.9\sigma$ and $0.8\sigma$, respectively. The total $\chi^2$ for tan\(\beta < 1\) is almost flat for $m_A < 30$ GeV. This is because only $H^\pm$ sizeably contributes to the electroweak observables for tan\(\beta < 1\), and $m_{H^\pm}$ varies little with $m_A$ in this range. Since the fit shows $\Delta \chi^2 \equiv \chi^2_{\text{tot}}(\text{MSSM}) - \chi^2_{\text{tot}}(\text{SM}) \approx 75$ for small $m_A$ and small tan\(\beta\), the possibility of a very light $A^0$ is strongly disfavoured from electroweak precision measurements.

In the context of a non-supersymmetric two Higgs doublet model (2HDM) we note that a very light $A^0$ (even $m_A = 0.2$ GeV) is still consistent with electroweak precision data $[30]$. This is because the masses of the Higgs bosons in the 2HDM are free parameters (in contrast to the MSSM) and thus a very light $A^0$ does not require the other Higgs bosons to be light.

IV. CONCLUSIONS

The direct searches at LEP II for the neutral Higgs bosons $A^0$ and $h^0$ of the MSSM fail to exclude a light $A^0$ in the region of tan\(\beta < 1\). The mass of $H^\pm$ is predicted to be $\leq 76(78)$ GeV for tan\(\beta = 0.8(0.6)\), with a large branching ratio for $H^\pm \to A^0W^*$. The latter decay ensures that $H^\pm$ would have escaped the LEP searches, which rely on $H^\pm \to cs(\tau\nu)$ decays. Such a $H^\pm$ would have also have (narrowly) escaped detection at Run I of the Tevatron in the channel $t \to H^\pm b$, which is very sensitive to the region $m_{H^\pm} < 80$ GeV and tan\(\beta < 1\). The large BR($H^\pm \to A^0W^*$) shifts the excluded region to lower values of tan\(\beta\), thus allowing $H^\pm$ in the parameter space of interest. Run II will comfortably detect or rule out the region of $0.6 < \tan\beta < 0.8$ and $m_{H^\pm} < 78$ GeV, which in turn would directly confirm or rule out the possibility of a light $A^0$ ($m_A < 20$ GeV).

Such a $H^\pm$ would sizeably affect several low energy processes ($B^0$, $K^0$ decays) and electroweak precision measurements at LEP1 and SLC. Since the former are very sensitive to the (unknown) flavour structure
of the MSSM, no definite constraints on $H^\pm$ can be derived. However, we showed that $m_{H^\pm} < m_W$ and $\tan \beta < 1$ is strongly disfavoured by electroweak precision data, giving rise to exceedingly large $\chi^2$ values. Thus we conclude that the region of very light $A^0$ and $\tan \beta < 1$, although unexcluded by direct searches, is severely disfavoured by indirect constraints and will be probed directly in $t \rightarrow H^\pm b$ decays at the Tevatron Run II.

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FIG. 1. Branching ratios of $H^\pm$ as a function of $m_{H^\pm}$ for $\tan \beta = 0.6$ (dashed lines) and 0.8 (solid lines).
FIG. 2. The total $\chi^2$ as a function of $m_A$ for various values of $\tan \beta$. The four thick lines correspond to $\tan \beta = 0.5, 0.6, 0.7$ and 1. The thick horizontal dashed line denotes the minimum $\chi^2$ in the SM ($\chi^2 = 25.3$).