CP violation in Charged Higgs Bosons decays $H^\pm \rightarrow W^\pm (\gamma, Z)$ in the Minimal Supersymmetric Standard Model (MSSM)

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One loop mediated charged Higgs bosons decays $H^\pm \rightarrow W^\pm V$, $V = Z, \gamma$ are studied in the Minimal Supersymmetric Standard Model (MSSM) with and without CP violating phases. We evaluate the MSSM contributions to these processes taking into account $B \rightarrow X_s \gamma$ constraint as well as experimental constraints on the MSSM parameters. In the MSSM, we found that in the intermediate range of $\tan \beta < 10$ and for large $A_t$ and large $\mu$, where the lightest top squark becomes very light and hence non-decoupled, the branching ratio of $H^\pm \rightarrow W^\pm Z$ can be of the order $10^{-3}$ while the branching ratio of $H^\pm \rightarrow W^\pm \gamma$ is of the order $10^{-5}$. We found also that the CP violating phases of soft SUSY parameters can modify the branching ratio by about one order of magnitude. We also show that MSSM with CP violating phases lead to CP-violating asymmetry in the decays $H^+ \rightarrow W^+ V$ and $H^- \rightarrow W^- V$. Such CP asymmetry can be rather large and can reach 80% in some region of parameter space.

1. Introduction

Supersymmetric (SUSY) theories, in particular the Minimal Supersymmetric Standard Model (MSSM), are currently considered as the most theoretically well motivated extensions of the Standard Model. Recently, phenomenology of the MSSM with complex SUSY parameters has received growing attention\textsuperscript{1}. Such complex phases provide new sources of CP violation which may explain electroweak baryogenesis scenarios\textsuperscript{2}, and CP violating phenomena in $K$ and $B$ decays\textsuperscript{3}. It has
been shown in [4] that by assuming universality of the gaugino masses at a high energy scale, the effects of complex soft SUSY parameters in the MSSM can be parameterized by two independent CP violating phases: the phase of the Higgsino mass term $\mu$ ($\text{Arg}(\mu)$) and the phase of the trilinear scalar coupling parameters $A = A_f$ ($\text{Arg}(A_f)$) of the sfermions $\tilde{f}$. The presence of large SUSY phases can give contributions to electric dipole moments of the electron and neutron (EDM) which exceed the experimental upper bounds. In a variety of SUSY models such phases turn out to be severely restricted by such constraints, i.e. $\text{Arg}(\mu) < (10^{-2})$ for a SUSY mass scale of the order of few hundred GeV [5]. However, the possibility of having large CP violating phases can still be consistent with experimental data in any of the following three scenarios: i) Effective SUSY models [6], ii) Cancellation mechanism [7] and iii) Non-universality of trilinear couplings $A_f$ [7]. In the MSSM, after electroweak symmetry breaking we are left with 5 physical Higgs particles (2 charged Higgs $H^\pm$, 2 CP-even $H^0, h^0$ and one CP-odd $A^0$). In this study, our concerns is the charged Higgs decays $H^\pm \to W^\pm V$, $V = Z, \gamma$ with and without CP violating phases. Those channels have a very clear signature and might emerge easily at future colliders. For instance, if $H^\pm \to W^\pm Z$ is enhanced enough, this decay may lead to three leptons final state if both $W$ and $Z$ decay leptonically and that would be the corresponding golden mode for charged Higgs boson. Charged Higgs phenomenology has been extensively studied in the literature. It has been shown that SUSY one-loop contributions can lead to decay rates asymmetry of $H^\pm \to t\bar{b}, b\bar{t}$, $H^\pm \to \tilde{u}_i\tilde{d}_j, \tilde{u}_i^*\tilde{d}_j^*$ and $H^\pm \to \chi_i^+\chi_j^0, \chi_i^-\chi_j^0$ [8]. Similar study has been done for the single charged Higgs production at hadron collider [9] and shown that SUSY CP phases can lead to CP asymmetry.

In this paper, we will discuss both the branching ratios of $H^\pm \to W^\pm V$ with $V = Z, \gamma$ [10] as well as the CP-violating asymmetry in the decay rates $H^+ \to W^+ V$ and $H^- \to W^- V$ that emerge from the presence of CP violating phases in MSSM.

The paper is organized as follows. In section II, we describe our calculations and the one-loop renormalization scheme we will use for $H^\pm \to W^\pm V$ and present the source of CP violation in $H^\pm \to W^\pm V$. In Section III, we present our numerical results and discussions, and section IV contains our conclusions.

2. CP violation in Charged Higgs decay: $H^\pm \to W^\pm V$

2.1. One loop amplitude $H^\pm \to W^\pm V$

In MSSM, at tree level, the coupling $H^\pm W^\pm \gamma$ is absent because of electromagnetic gauge invariance $U(1)_{\text{em}}$, while the absence of $H^\pm W^\pm Z$ is due to the isospin symmetry of the kinetic Lagrangian of the Higgs doublet fields. We emphasize here that it is possible to construct models with an even larger scalar sector than 2 Higgs doublets. One of the most popular being the Higgs Triplet Model (HTM) [11]. A noteworthy difference between MSSM and HTM is that the HTM contains a tree level $ZW^\pm H^\mp$ coupling. Therefore, in MSSM, decays modes like $H^\pm \to W^\pm \gamma$, $H^\pm \to W^\pm Z$, $H^\pm \to W^\pm \gamma_1 Z_2$, $H^\pm \to W^\pm \gamma_1 \phi_2$ and $H^\pm \to W^\pm \gamma_1 \phi_2 Z_3$ are suppressed compared to the MSSM case. We consider the following decay modes of charged Higgs bosons: $H^+ \to W^+ V$, $H^- \to W^- V$, $H^\pm \to \tilde{u}_i \tilde{d}_j$, $H^\pm \to \chi_i^+ \chi_j^0$, $H^\pm \to \chi_i^- \chi_j^0$. The one-loop amplitude for these decay modes can be written as:

$$
\mathcal{M}_{H^\pm \to W^\pm V} = \frac{g}{\sqrt{2}} v \left[ \bar{u}_i \gamma^\mu (1 - \gamma^5) d_j \right] W^\mu V - \text{c.c.}
$$

where $v$ is the vacuum expectation value and $\bar{u}_i$ and $d_j$ are the sfermion fields. The CP-violating phase enters through the Higgsino mass term and the trilinear scalar coupling parameters $A_f$.

The one-loop amplitude for the decay $H^\pm \to \tilde{u}_i \tilde{d}_j$ can be written as:

$$
\mathcal{M}_{H^\pm \to \tilde{u}_i \tilde{d}_j} = (16\pi) \frac{g}{\sqrt{2}} v \left[ \bar{u}_i \gamma^\mu Z^\mu \right] \tilde{d}_j - \text{c.c.}
$$

where $Z^\mu$ is the gauge boson field. The CP-violating phase enters through the trilinear scalar coupling parameters $A_f$. The one-loop amplitude for the decay $H^\pm \to \chi_i^+ \chi_j^0$ can be written as:

$$
\mathcal{M}_{H^\pm \to \chi_i^+ \chi_j^0} = (16\pi) \frac{g}{\sqrt{2}} v \left[ \bar{u}_i \gamma^\mu Z^\mu \right] \tilde{d}_j - \text{c.c.}
$$

where $\chi_i^+$ and $\chi_j^0$ are the neutralinos.

The one-loop amplitude for the decay $H^\pm \to \chi_i^- \chi_j^0$ can be written as:

$$
\mathcal{M}_{H^\pm \to \chi_i^- \chi_j^0} = (16\pi) \frac{g}{\sqrt{2}} v \left[ \bar{u}_i \gamma^\mu Z^\mu \right] \tilde{d}_j - \text{c.c.}
$$

where $\chi_i^-$ and $\chi_j^0$ are the charginos.

The decay rates for these channels can be calculated using the one-loop amplitude and the on-shell renormalization scheme. The CP-violating asymmetry in the decay rates can be calculated using the CP-violating phases of the Higgsino mass term and the trilinear scalar coupling parameters $A_f$. The details of the calculations are given in the following sections.
The one-loop amplitude for a scalar decaying to two gauges bosons $V_1$ and $V_2$ can be written as

\[ M = \frac{g^3 \epsilon_{V_1}^{\mu\nu} \epsilon_{V_2}^{\rho\sigma}}{16\pi^2m_W} M_{\mu\nu} \]

where $\epsilon_{V_i}$ are the polarization vectors of the $V_i$. According to Lorentz invariance, the general structure of the one loop amplitude $M_{\mu\nu}$ of $S \rightarrow V_1^\mu V_2^\nu$ decay is

\[ M_{\mu\nu}(S \rightarrow W^\nu V^\mu) = F_1 g_{\mu\nu} + F_2 p_{1\mu} p_{2\nu} + F_3 i\epsilon_{\mu\nu\rho\sigma} p_1^{\rho} p_2^{\sigma} \]

where $p_{1,2}$ are the momentum of $V_1$, $V_2$ vector bosons, $F_{1,2,3}$ are form factors, and $\epsilon_{\mu\nu\rho\sigma}$ is the totally antisymmetric tensor. The form factor $F_1$ has dimension 2 while the other are dimensionless. Therefore, it is expected that in case of $H^\pm \rightarrow W^\pm Z$ decay, $F_1$ will grow quadratically with internal top quark mass while $F_{2,3}$ will have only logarithmic dependence.\[13\]

Quite contrary, for $H^\pm \rightarrow W^\pm \gamma$ decay, the electromagnetic gauge invariance implies that $F_1$ and $F_2$ are related by $F_1 = 1/2(m_W^2 - m_{H^\pm}^2)F_2$. This means that only $F_2$ and $F_3$ will contribute to the decay $H^\pm \rightarrow W^\pm \gamma$ and then the amplitude of $H^\pm \rightarrow W^\pm \gamma$ will not grow quadratically with internal fermionic masses. In case of $H^\pm \rightarrow W^\pm Z$, there is no such constraint on the form factors. In fact the CP asymmetry in this process $H^\pm \rightarrow W^\pm Z$ is very large compared to the CP asymmetry in $H^+ \rightarrow t\bar{b}$. The reason is that $H^\pm \rightarrow W^\pm Z$ is loop dominated, while $H^+ \rightarrow t\bar{b}$ is dominated by the tree level contribution which is CP conserving.

The one-loop amplitude for $H^\pm \rightarrow W^\pm V$ is evaluated in the ’t Hooft-Feynman gauge using dimensional regularization. The typical Feynman diagrams that contribute to $H^\pm \rightarrow W^\pm V$ are depicted in Fig. 1. Those diagrams contain vertex diagrams (Fig. 1.1 \rightarrow 1.11), $W^\pm - H^\pm$ mixing (Fig. 1.12 \rightarrow 1.14), $H^\pm - G^\pm$ mixing (Fig. 1.15 \rightarrow 1.17) and $H^\pm - W^\pm$ mixing (Fig. 1.18 \rightarrow 1.20).

Note that the mixing $H^\pm - W^\pm$ (Fig. 1.12, 1.13, 1.14) vanishes for an on-shell transverse $W$ gauge boson. There is no contribution from the $W^\pm - G^\mp$ mixing because $\gamma G^\pm H^\mp$ and $Z G^\pm H^\mp$ vertices are absent at the tree level. All the Feynman diagrams have been generated and computed using FeynArts and FormCalc packages. We also used the fortran FF–package in the numerical analysis.

Although the amplitude for our process is absent at the tree level, complications like tadpole contributions and vector boson–scalar boson mixing require a

\[ ^{\dagger}\text{As it has been shown in Ref.} \ [13], \text{the top quark contribution does not decouple while squarks contributions does.} \]
careful treatment of renormalization. We adopt, hereafter, the on-shell renormalization scheme of Ref. [19], for the Higgs sector. In this scheme, field renormalization is performed in the manifest-symmetric version of the Lagrangian. A field renormalization constant is assigned to each Higgs doublet $\Phi_1, \Phi_2$. We follow closely the same approach adopted in Refs. [10, 20] for $W^\pm - H^\mp$ and $H^\pm - G^\mp$ mixing as well as renormalization of $\gamma W^\pm H^\mp$ and $Z W^\pm H^\mp$. We will use the following on shell renormalization conditions [10,20]:

- The renormalized tadpoles, i.e. the sum of tadpole diagrams $T_{h,H}$ and tadpole counter-terms $\delta_{h,H}$ vanish:

$$T_H + \delta t_H = 0, \quad T_H + \delta t_H = 0.$$
2.1a \ H \ W +, W - \\
2.1b \ H \ W +, W - \\
2.1c \ H \ W +, W - \\
2.1d \ H \ W +, W - \\
2.1e \ H \ W +, W - \\
2.1f \ H \ W +, W - \\
2.2a \ H \ W +, W - \\
2.2b \ H \ W +, W - \\
2.2c \ H \ W +, W - \\
2.2d \ H \ W +, W - \\

Fig. 2. Generic contributions to $H^\pm \rightarrow W^\pm (\gamma, Z)$ in MSSM.

CP violation in Charged Higgs Bosons decays $H^\pm \rightarrow W^\pm (\gamma, Z)$ in MSSM

Lagrangian $\mathcal{L}_R$ are located at the minimum of the one-loop potential.

- The real part of the renormalized non-diagonal self-energy $\hat{\Sigma}_{H^\pm W^\pm}(k^2)$ vanishes for an on-shell charged Higgs boson. This renormalization condition determines the counter term for $\delta[A_\nu W^\mu H^\mp]$ and $\delta[Z_\nu W^\mu H^\mp]$.

Using the Slavnov–Taylor identity, which relates $H^\pm W^\pm$ and $H^\mp G^\mp$ self energies, the last renormalization condition about $H^\pm W^\pm$ mixing is sufficient to discard the real part of the $H^\pm-G^\pm$ mixing contribution as well.

2.2. CP violation in $H^\pm \rightarrow W^\pm V$

The CP violating phases of MSSM can lead to CP-violating asymmetry in the decay rates $H^+ \rightarrow W^+ V$ and $H^- \rightarrow W^- V$. In what follow, we will study the following CP-violating asymmetry

$$\delta^{CP} = \frac{\Gamma(H^+ \rightarrow W^+ V) - \Gamma(H^- \rightarrow W^- V)}{\Gamma(H^+ \rightarrow W^+ V) + \Gamma(H^- \rightarrow W^- V)} , \quad V = \gamma, Z$$

and show that the MSSM with complex phases together with the absorptive part emerging from some loop integrals can lead to non-vanishing $\delta^{CP}$. Generically, in
the case of $H^\pm \to W^\pm \gamma$, the form factors $\mathcal{F}_{1,3}$ take the following form

$$
\mathcal{F}_1(H^- \to W^\gamma) = \sum_{i,j,k} a_{1,ijk} PV_{1,ijk} + a_{2,ijk} PV_{2,ijk}
$$

$$
\mathcal{F}_3(H^- \to W^\gamma) = \sum_{i,j,k} b_{1,ijk} PV_{1,ijk} + b_{2,ijk} PV_{2,ijk}
$$

$$
\mathcal{F}_1(H^+ \to W^\gamma) = \sum_{i,j,k} a'_{1,ijk} PV_{1,ijk} + a'_{2,ijk} PV_{2,ijk}
$$

$$
\mathcal{F}_3(H^+ \to W^\gamma) = \sum_{i,j,k} b'_{1,ijk} PV_{1,ijk} + b'_{2,ijk} PV_{2,ijk}
$$

where $(a,b)_{a,ijk}$ $(\alpha = 1, 2$ and $i, j$ and $k$ label the particles inside the loop) are combination of MSSM couplings, namely charged Higgs couplings to charginos-neutralinos and charged Higgs couplings to squarks. $PV_{a,ijk}$ and $PV_{a,ijk}$ are Passarino-Veltman functions. The CP asymmetry \(^{(3)}\) takes the following form

$$
\delta^{CP} \propto \frac{\left|\mathcal{F}_1(H^-)\right|^2 - \left|\mathcal{F}_3(H^-)\right|^2 - \left|\mathcal{F}_1(H^+)\right|^2 + \left|\mathcal{F}_3(H^+)\right|^2}{all}
$$

$$
\propto \sum_{a,ijk} \sum_{\alpha,\beta} \sum_{\alpha,ijk} 3m(a_{a,ijk} a'_{\beta,ijk}) 3m(PV_{a,ijk} PV_{\beta,ijk}) + (\alpha \leftrightarrow \beta, PV \leftrightarrow \overline{PV})
$$

It is clear from the above that in order to have a non-vanishing $\delta^{CP}$ we need both complex couplings $a_{a,ijk}$ as well as an absorptive part from the Passarino-Veltman functions. For example, diagrams Fig.1.1c and Fig.1.18 \((\alpha, \beta)\) will develop some absorptive parts if the decay channels $H^\pm \to \tilde{\chi}_i^\pm \tilde{\chi}^0_j$ \((H^\pm \to \tilde{q}_i^\pm \tilde{q}_j^\pm)\) is open, i.e. $m_{H^\pm} > m_{\chi_i} - m_{\chi_j}$ \((m_{H^\pm} > m_{q_i} - m_{q_j})\).

3. Numerics and discussions

In our numerical evaluations, we use the following experimental input quantities.\(^{(21)}\)

$$
\alpha^{-1} = 129, m_Z, m_W, m_t, m_b = 91.1875, 80.45, 174.3, 4.7 \text{ GeV.}
$$

In the MSSM, we specify the free parameters that will be used as follows: $i)$ The MSSM Higgs sector is parameterized by the CP-odd mass $m_{h^0}$ and $\tan \beta$, taking into account one-loop radiative corrections from \(^{(22)}\), and we assume $\tan \beta \gtrsim 3$. $ii)$ The chargino-neutralino sector can be parameterized by the gaugino-mass terms $M_1$, $M_2$, and the Higgsino-mass term $\mu$. For simplification, GUT relation $M_1 \approx M_2/2$ is assumed. $iii)$ Sfermions are characterized by a common soft-breaking sfermion mass $M_{SUSY} \equiv M_L = M_R$, $\mu$ the parameter and the soft trilinear couplings for third generation scalar fermions $A_{t,b,\tau}$. For simplicity, we will take $A_t = A_b = A_\tau$.

When varying the MSSM parameters, we take into account also the following constraints: $i)$ The extra contributions to the $\delta \rho$ parameter from the Higgs scalars should not exceed the current limits from precision measurements.\(^{(21)}\)$ [\(\delta \rho \leq 0.003\).

$ii)$ $b \to s \gamma$ constraint. The present world average for inclusive $b \to s \gamma$ rate is \(^{(21)}\)

$$
\mathcal{B}(B \to X_s \gamma) = (3.3 \pm 0.4) \times 10^{-4}\text{.}
$$

We keep the $B \to X_s \gamma$ branching ratio in the 3$\sigma$ range of $(2.1 - 4.5) \times 10^{-4}$. The SM part of $B \to X_s \gamma$ is calculated up to NLO
CP violation in Charged Higgs Bosons decays \( H^\pm \to W^\pm Z \) in MSSM

Figure 3. Branching ratios of \( H^\pm \to W^\pm Z \) (left) and \( H^\pm \to W^\pm \gamma \) (right) as a function of \( m_{H^\pm} \) in the MSSM and 2HDM for \( M_{\text{SUSY}} = 500 \text{ GeV}, M_2 = 175 \text{ GeV}, \mu = -1.4 \text{ TeV} \) and \( A_t = A_b = A_\tau = -\mu \) for various values of \( \tan \beta \).

Using the expression given in [23]. While for the MSSM part, the Wilson coefficients \( C_7 \) and \( C_8 \) are included at LO in the framework of MSSM with CKM as the only source of flavor violation and are taken from [24].

(iii) We will assume that all SUSY particles sfermions and charginos are heavier than about 100 GeV; for the light CP even Higgs we assume \( m_{h^0} > \sim 98 \text{ GeV} \) and \( \tan \beta > \sim 325 \). For charged Higgs boson we assume that \( m_{H^\pm} \geq 78 \text{ GeV} \) from LEP experiments [26]. As the experimental bound on \( m_{h^0} \) is concerned, care has to be taken. Since we are using only one-loop approximation for the Higgs spectrum, and as is well known, higher order corrections [27] may reduce the light CP-even Higgs mass in some cases. It may be possible that some parameter space region, shown in this analysis, which survives the experimental limit \( m_{h^0} > \sim 98 \text{ GeV} \) with one loop calculation may disappear, once the higher order correction to the Higgs spectrum are included.

The total width of the charged Higgs is computed at tree level from [28] without any QCD improvement for its fermionic decays \( H^\pm \to \bar{f}f' \). The SUSY channels like \( H^+ \to f_i \bar{f}_j \) and \( H^+ \to \bar{\chi}_i^0 \chi_j^+ \) are included when kinematically allowed. In Fig. 3 we show branching ratios of \( H^\pm \to W^\pm Z \) (left) and \( H^\pm \to W^\pm \gamma \) (right) as a function of charged Higgs mass for \( \tan \beta = 16 \) and 25. In those plots, we have shown both the pure 2HDM and the full MSSM contributions. As it can be seen from those plots, both for \( H^\pm \to W^\pm Z \) and \( H^\pm \to W^\pm \gamma \) the 2HDM contribution is rather small. Once we include the SUSY particles, we can see that the branching fractions get enhanced and can reach \( 10^{-3} \) in the case of \( H^\pm \to W^\pm Z \) and \( 10^{-5} \) in the case of \( H^\pm \to W^\pm \gamma \). The source of this enhancement is mainly due to the presence of the Higgs sector.

Pure 2HDM means that we include just the 2HDM part of the MSSM that contributes here in the loop, i.e. only SM fermions, gauge bosons and Higgs bosons with MSSM sum rules for the Higgs sector.
scalar fermions contributions in the loop which are amplified by threshold effects from the opening of the decay $H^\pm \to \tilde{t}_i \tilde{b}_j^*$. It turns out that the contribution of chargino-neutralino loops do not enhance the branching fractions significantly as compared to scalar fermions loops. The plots also show that the branching fractions are more important for intermediate $\tan \beta = 16$ and are slightly reduced for larger $\tan \beta = 25$.

We now illustrate in Fig. 4 the branching fraction of $H^\pm \to W^\pm Z$ (left) and $H^\pm \to W^\pm \gamma$ (right) as a function of $A_t$ in the MSSM with $M_{SUSY} = 500$ GeV, $M_2 = 200$ GeV, $m_{h^\pm} = 500$ GeV, $A_t = A_b = A_\tau = -\mu$ and $-2$ TeV $< \mu < -0.1$ TeV for various values of $\tan \beta$.

Fig. 4. Branching ratios for $H^\pm \to W^\pm Z$ (left) and $H^\pm \to W^\pm \gamma$ (right) as a function of $A_t$ in the MSSM with $M_{SUSY} = 500$ GeV, $M_2 = 200$ GeV, $m_{h^\pm} = 500$ GeV, $A_t = A_b = A_\tau = -\mu$ and $-2$ TeV $< \mu < -0.1$ TeV for various values of $\tan \beta$. 

As we can see from these figures, the plots stops at $A_t = 1.1$ TeV and $\tan \beta = 3$, because for larger $A_t$ the $\delta \rho$ constraint will be violated. For $\tan \beta = 10$ and 20, the plots stop for the same reason. In case of $H^\pm \to W^\pm Z$, for $A_t \lesssim 1$ TeV it is the pure 2HDM contributions which dominate and that is why it is almost independent of $A_t$, while for larger $A_t$ the branching ratios increase with $A_t$. It is clear that the larger $A_t$ is the larger the branching ratios, which can be of the order of $10^{-3}$ for $H^\pm \to W^\pm Z$ with $\tan \beta = 10$, for example. As we know from $h^0 \to \gamma \gamma$ and $h^0 \to \gamma Z$ in MSSM [30], the squarks contributions decouple except in the light stop mass and large $A_t$ limit. In $H^\pm \to W^\pm V$ case, the same situation happens. As we can see from Fig. 4 (left), for intermediate $A_t$, 300 $< A_t < 1000$ GeV, the squarks are rather heavy and hence their contributions are small compared to 2HDM one. While for large $A_t$ the stop becomes very light $\lesssim 200$ GeV and hence it can enhance the $H^\pm \to W^\pm V$ width. Of course this enhancement is also amplified by $\tilde{t}_{L,R} \tilde{b}_{R,L}^*$ couplings which are directly proportional to $A_{t,b}$. In the case of...
CP violation in Charged Higgs Bosons decays $H^\pm \rightarrow W^\pm (\gamma, Z)$ in MSSM

$H^\pm \rightarrow W^\pm \gamma$ decay, the pure 2HDM and sfermions contribution are of comparable size, the branching ratio increases with $A_t$. We have also studied the effect of the MSSM CP violating phases on charged Higgs decays. For $H^\pm \rightarrow W^\pm Z$ and $H^\pm \rightarrow W^\pm \gamma$ decays which are sensitive to MSSM CP violating phases through squarks and chargino-neutralino contributions, it turns out that the effect of MSSM CP violating phases is important and can enhance the rate by about one order of magnitude. For illustration we show in Fig. 5 the effect of $A_t, b, \tau$ CP violating phases for $M_{SUSY} = 500$ GeV, $A_t, b, \tau = -\mu = 1$ TeV and for various values of $\tan \beta$. The observed cuts in the plot are due to $b \rightarrow s\gamma$ constraint. In Fig.(6) we show the CP asymmetry $\delta_{CP}$ for $H^\pm \rightarrow W^\pm Z$ (left) and $H^\pm \rightarrow W^\pm \gamma$ (right) as a function of charged Higgs mass. As one can see in both plots, for $m_{H^\pm} \lesssim 512$ GeV, $\delta_{CP}$ is very small, of the order $10^{-3}$. In this case, the main contributions to $\delta_{CP}$ arise both from diagrams Fig.1.1 and Fig.1.18 with absorptive parts and real couplings and diagrams Fig.1.2 and Fig.1.19 with complex couplings and no absorptive part (the channel $H^\pm \rightarrow \tilde{t}_1 \tilde{b}_j^*$ is not yet open!). However, once $m_{H^\pm} \gtrsim 512$ GeV, the channel $H^\pm \rightarrow \tilde{t}_1 \tilde{b}_j^*$ is open, the diagrams Fig.1.2 and Fig.1.19 have an absorptive part and consequently they contribute to $\delta_{CP}$, which can go up to several percent. The thresholds of $H^\pm \rightarrow \tilde{t}_1 \tilde{b}_1^*$ at $m_{H^\pm} \approx 512$ GeV and of $H^\pm \rightarrow \tilde{t}_1 \tilde{b}_2^*$ at $m_{H^\pm} \approx 740$ GeV are clearly visible in Fig.(6).

4. Conclusion

In the framework of MSSM, we have studied charged Higgs decays into a pair of gauge bosons, namely, $H^\pm \rightarrow W^\pm Z$ and $H^\pm \rightarrow W^\pm \gamma$. We have also studied
Fig. 6. Total $\delta \epsilon_R$ in the $H^\pm \rightarrow W^\pm Z$ (left) and $H^\pm \rightarrow W^\pm \gamma$ (right) as a function of $m_{H^\pm}$ in the MSSM, with $M_{SUSY} = 500$ GeV, $M_2 = 175$ GeV, $\tan \beta = 16$, $\mu = -1.4$ TeV, $A_t = A_b = A_{\tau \tau} = -\mu$, for different values of $\text{Arg}(A_t)$.

the effects of MSSM CP violating phases in these processes. In contrast to previous studies, we have performed the calculation in the ’t Hooft-Feynman gauge and used a renormalization prescription to deal with tadpoles, $W^\pm-H^\pm$ and $G^\pm-H^\pm$ mixings. The study has been carried out taking into account the experimental constraints on the $\rho$ parameter as well as the inclusive $b$-decay $b \rightarrow s\gamma$. Numerical results for the branching ratios have been presented. In the MSSM, we have shown that the branching ratio of $H^\pm \rightarrow W^\pm Z$ can reach $10^{-3}$ in some cases while $H^\pm \rightarrow W^\pm \gamma$ never exceed $10^{-5}$. Branching ratio of the order $10^{-3}$ might provide an opportunity to search for a charged Higgs boson at the LHC through $H^\pm \rightarrow W^\pm Z$. The effect of MSSM CP violating phases is also found to be important and can change the size of the branching ratios of $H^\pm \rightarrow W^\pm V$ by about an order of magnitude compared to the CP conserving case. The CP-violating asymmetry in the decays $H^+ \rightarrow W^+ V$ and $H^- \rightarrow W^- V$ can be rather important and can reach 80% in some region of parameter space [31].

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