CP violation in the associated production of a charged Higgs boson with a top quark at the CERN Large Hadron Collider

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Abstract

We explore the CP violation in the charged Higgs production associated with a top quark at the LHC in the MSSM. The supersymmetric phases of gaugino masses and trilinear $A$ terms lead to a CP violation of the cross section in the $pp \rightarrow gb \rightarrow tH^{\pm}$ process through loop corrections to the $tbH^{\pm}$ vertex. We find that more than 10% of CP violating asymmetry is possible when the charged Higgs boson is heavy enough.
The Higgs mechanism provoked by the non-zero vacuum expectation value (VEV) of a scalar doublet is the key structure of the Standard Model (SM), which gives rise to the electroweak symmetry breaking and the generation of fermion masses. There is one SU(2) doublet of scalar field in the SM lagrangian and only one neutral Higgs boson exists as a physical state after the breakdown of the electroweak symmetry. The Higgs boson is the only unobserved ingredient of the SM. LEP experiment favors a light Higgs boson from the global fit of data and has suggested a candidate of the Higgs boson of 115 GeV [1]. The discovery of the Higgs boson is the principal goal of the CERN Large Hadron Collider (LHC). For the SM Higgs boson, LHC promises to cover the wide range of Higgs boson mass [2].

Most extensions of the SM require the introduction of extended Higgs sector to the theory. Generically, charged Higgs boson arises in the extended Higgs sector, which does not exist in the SM. It implies that the observation of a charged Higgs boson is a clear evidence for existence of the new physics beyond the SM. The minimal supersymmetric standard model (MSSM) is one of the most promising candidate for physics beyond the SM. In the MSSM, we need two Higgs doublets to preserve the supersymmetry and then there are a pair of charged Higgs boson $H^\pm$ with two neutral CP-even Higgs bosons $h^0, H^0$, and a neutral CP-odd Higgs boson $A^0$ in the particle spectrum of the MSSM. Direct experimental search for $H^\pm$ at LEP II has set the lower bound of mass to be 79.9 GeV [3] through $e^-e^+ \rightarrow H^-H^+$ production. The direct and indirect studies of $H^\pm$ at the Tevatron constrain the parameter space of $(m_{H^\pm}, \tan \beta)$. CDF and D0 groups have excluded the low and high tan $\beta$ regions up to $\sim 160$ GeV [4]. The discovery potential of the charged Higgs boson at the LHC has been studied by ATLAS [5] and CMS [6] groups. We expect to discover a charged Higgs boson as heavy as 1 TeV at the 5-$\sigma$ confidence level, or may exclude it up to the mass of 1.5 TeV at 95 % C.L. at the LHC with the MSSM radiative corrections [7]. We concentrate on the process $gb \rightarrow tH^\pm$ which is the most promising channels for the charged Higgs boson production at the LHC when $H^\pm$ is heavier than the top quark. The discovery potential of this channel has been studied in the Ref. [8, 9]. The Drell-Yan mechanism $gg, q\bar{q} \rightarrow H^-H^+$ and the associated production with a $W$ boson, $q\bar{q} \rightarrow H^\pm W^\mp$ are suppressed due to the weak couplings, low quark luminosity, and loop suppressions. If the mass of $H^\pm$ is below the top quark mass, $H^\pm$ is produced by the sequential decay of top quark $t \rightarrow bH^\pm$ following the $t\bar{t}$ pair production.

Exotic CP violating phenomena are generically predicted in the MSSM due to new com-
plex phases. Assuming the R-symmetry and the gauge coupling unification at the GUT scale, the physical phases come from the $\mu$ parameter, the soft trilinear coupling $A$ terms, and two gaugino masses after rotating away other phases. Then the supersymmetric loop corrections to the $tbH^\pm$ vertex involving squarks, charginos, gluinos and neutralinos generically lead to the manifest CP violation in charged Higgs production and decay due to the SUSY CP phases. The CP violation in the decays of $H^\pm$ into $t, b$ quarks and $\tau, \nu$ has been studied in Ref. [10, 11]. In this work, we investigate the direct CP violating asymmetry in the MSSM charged Higgs boson production in association with a single top quark at the LHC.

In the MSSM, the relevant interaction lagrangian of the charged Higgs boson production is given by

$$\mathcal{L}_{\text{int}} = V_{tb}\bar{t}(Y^+_tP_L + Y^+_bP_R)bH^+ + H.c.,$$

(1)

ignoring the light quark masses and mixing. We incorporate the SUSY correction in this Yukawa coupling to make the effective vertex. The SUSY loop corrections arise through the vertex corrections with $\bar{t} - \bar{b} - \tilde{g}(\chi^0)$ loop, $\chi^\pm - \chi^0 - \bar{t}(\bar{b})$ loop, $H^0 - W^\pm - t(b)$ loop, and the $H^\pm - W^\pm$ self-energy diagram with $\chi^\pm - \chi^0$ loop, $\bar{t} - \bar{b}$ loop, $H^0 - W^\pm$ loop. We parametrize the Yukawa couplings as $Y^i_{t,b} = y^0_{t,b} + \delta y^i_{t,b} + \frac{1}{2}\delta y^i_{t,b}^{\text{CP}}$, where the SUSY loop corrections consist of the CP invariant part $\delta y^i_{t,b}$ and the CP violating part $\delta y^i_{t,b}^{\text{CP}}$. The relevant quantity for the CP violation is $\text{Re} \, \delta y^i_{t,b}^{\text{CP}} \equiv \text{Re} (Y^i_t - Y^i_b)$ where $i = t, b$ of which analytic form is derived in Ref. [10] for the decay of the charged Higgs boson. Since we consider the one loop correction to the vertex, the effective vertex is expressed by one loop integral and, in consequence by the Passarino-Veltman function. We note that the $t$ ($\bar{t}$) quark of the $tbH^\pm$ vertices is not on shell for the $t$-channel process and the argument of the Passarino-Veltman function should be the partonic Mandelstam variable $\hat{t}$ instead of $m_t^2$. The principal contribution to $\text{Re} \, \delta y^i_{t,b}^{\text{CP}}$ comes from $\bar{t} - \bar{b} - \tilde{g}(\chi^0)$ loop and $\bar{t} - \bar{b}$ loop diagrams depicted in Fig. 1. With the minimal supergravity (mSUGRA) type particle spectrum, contributions of $\chi^\pm - \chi^0 - \bar{t}(\bar{b})$, $H^0 - W^\pm - t(b)$, $\chi^\pm - \chi^0$ and $H^0 - W^\pm$ loops to $\text{Re} \, \delta y^i_{t,b}^{\text{CP}}$ are less than 1% for any value of the charged Higgs mass and irrelevant for observation in the experiment.

In terms of the couplings given in Eq. (1), we write the scattering amplitude as

$$iM(g\bar{b} \rightarrow \bar{t}H^+) = ig_{s}\bar{b} \left[T_{ab}^c \right. \frac{\epsilon(p_g)}{\hat{p}_b - \hat{p}_H - m_t} + \left. \frac{\epsilon(p_g)}{\hat{p}_t - \hat{p}_b - m_b} T_{ab} \right] t, \quad (2)$$

In terms of the couplings given in Eq. (1), we write the scattering amplitude as
and obtain the partonic cross section as
\[
\hat{\sigma}(g\bar{b} \rightarrow \bar{t}H^+) = \frac{1}{32\pi\hat{s}} \sqrt{(\hat{s} - m_t^2 - m_H^2)^2 - 4m_H^2 m_t^2} |\mathcal{M}|^2,
\]
where the colliding energy is kinematically allowed if \(\hat{s} > (m_t + m_H)^2\). We define the direct CP asymmetry at the parton level
\[
\hat{A}_{CP} = \frac{\hat{\sigma}(g\bar{b} \rightarrow \bar{t}H^+) - \hat{\sigma}(gb \rightarrow tH^-)}{\hat{\sigma}(gb \rightarrow tH^+) + \hat{\sigma}(gb \rightarrow tH^-)} \approx \frac{y_t^0 \text{Re} \delta y_t^\text{CP} + y_b^0 \text{Re} \delta y_b^\text{CP}}{|y_t^0|^2 + |y_b^0|^2},
\]
when assuming \(\delta y_i^\text{CP} \ll y_i^0\). The relevant quantity for the CP asymmetry \(\text{Re} \delta y_i^\text{CP} \equiv \text{Re}(Y_i^+ - Y_i^-)\) consists of the supersymmetric CP violating phase part and imaginary part of the loop integrals such that \(\text{Re} \delta y_i^\text{CP} \propto \text{Im}(\text{squark couplings})\). \(\text{Im}(C_I, B_0), I = 0, 1, 2\) where \(C_I, B_0\) are 3-point and 2-point Passarino-Veltman functions [12]. The SUSY phases in trilinear \(A\) terms, \(\mu\) parameter and gaugino masses lead to nonzero imaginary part of squark couplings. On the other hand, for the non-zero imaginary part of the Passarino-Veltman function, a pair of internal lines of the loop should be on-shell, and thus the mass of the charged Higgs should exceed the sum of the stop and sbottom masses, \(m_{H^\pm} > m_t + m_b\). Then the gluino loop and \(\bar{t} - \bar{b}\) self-energy contribution to \(\text{Re} \delta y_i^\text{CP}\) are switched on and we obtain a sizable CP violating asymmetry. It is also possible to obtain non-zero \(\text{Im}(C_I, B_0)\) when \(\sqrt{t}\) exceeds the sum of the gluino and stop masses, \(\sqrt{t} > m_{\tilde{g}} + m_t\), but this effect is convoluted by the parton distributions and brings on fluctuations as shown in the figures.

The hadronic cross section is given by
\[
\sigma(pp \rightarrow g\bar{b} \rightarrow \bar{t}H^+) = \int dx \ dy \ f_g(x) \ f_b(y) \ \hat{\sigma}(g\bar{b} \rightarrow \bar{t}H^+),
\]
where \(f_g\) and \(f_b\) are the parton distribution functions (PDF) for gluon and \(b\)-quark respectively. We use the leading order MRST functions for a gluon and a \(b\)-quark PDF in a proton [13]. The QCD factorization and renormalization scales \(Q\) are set to be the \(gb\) invariant mass, \(i.e., \sqrt{\hat{s}}\). The \(Q^2\)-dependence will be small by the cancellation in the CP asymmetry which is of our main interest. The center-of-momentum (c.m.) energy of \(pp\) collisions at the LHC is \(\sqrt{s} = 14\) TeV and the kinematic cuts of \(p_T \geq 25\) GeV and \(|\eta| \leq 2.5\) have been employed in this paper. The CP violating asymmetry is defined at the hadronic level by
\[
A_{CP} = \frac{\sigma(pp \rightarrow g\bar{b} \rightarrow \bar{t}H^+) - \sigma(pp \rightarrow gb \rightarrow tH^-)}{\sigma(pp \rightarrow g\bar{b} \rightarrow \bar{t}H^+) + \sigma(pp \rightarrow gb \rightarrow tH^-)}.
\]
We do not assume the specific SUSY model in our analysis but just fix a few parameters in order to avoid the confusion caused by too many parameters. The values of parameters are taken to be

\[ M_2 = 200 \text{ GeV}, \quad m_{\tilde{Q}} = 350 \text{ GeV}, \]

\[ |A_t| = |A_b| = 500 \text{ GeV}, \quad \mu = 500 \text{ GeV}, \]

and the GUT relation is assumed for the gaugino masses. The phase of \( \mu \) is strictly constrained by the electric dipole moments (EDM) of the electron and neutron in the mSUGRA. Although the constraint on the phase of \( \mu \) would not be serious in other SUSY models, we ignore the \( \mu \) phase for simplicity in this work. Consequently varied parameters are the charged Higgs mass, \( \tan \beta \), and phases of \( A_t, A_b, \) and \( M_3 \). For instance, our choice of parameters yields the sparticle spectrum as follows:

\[ m_{\tilde{t}} = 208.84, \ 473.62 \text{ GeV}, \]

\[ m_{\tilde{b}} = 351.66, \ 371.13 \text{ GeV}, \]

\[ m_{\tilde{\chi}^0} = 97.70, \ 189.04, \ -503.81, \ 517.27 \text{ GeV}, \]

\[ m_{\tilde{\chi}^\pm} = 204.51, \ 715.25 \text{ GeV}, \]

\[ m_{\tilde{g}} = 703.65 \text{ GeV}, \]

for \( m_{H^\pm} = 800 \text{ GeV}, \tan \beta = 5 \). Our choice is similar to the sparticle spectra of the typical or the light stop scenario in the mSUGRA model [14].

In the Fig. 2 and 3, we show the behaviors of the CP violating asymmetry with respect to \( m_{H^\pm} \) when the phases of \( A_t \) and \( M_3 \) are nonzero. We take \( \theta_t = \pi/2 \) and other phases are set to be zero in Fig 2 and take \( \theta_t = \pi \) and \( \phi_3 = \pi/2 \) in Fig. 3 to maximize \( A_{CP} \). Since the CP violating correction \( \text{Re} \delta y_{t}^{CP} \) is generically larger than \( \text{Re} \delta y_{b}^{CP} \), the CP violating asymmetry becomes larger as \( \tan \beta \) decreases in the plots. We can see that the sizable \( A_{CP} \) arises around 600 GeV when \( m_{H^\pm} \) exceeds \( m_{\tilde{t}_1} + m_{\tilde{b}_1} \) and the Passarino-Veltman function develops the non-zero imaginary part. The next rising-up of the plot arises caused by the loops with the internal lines of heavier stop around \( m_{H^\pm} = 850 \text{ GeV} \), that is, when \( m_{H^\pm} > m_{\tilde{t}_2} + m_{\tilde{b}_1} \).

At a collider, what we observe is not the charged Higgs boson itself but its decay products. The charged Higgs boson dominantly decays into \( tb \) and \( \tau \nu_\tau \) pair if \( m_{H^\pm} > m_t \). The CP violating SUSY corrections to the Yukawa coupling \( tbH^\pm \) also give rise to a difference between
decay rates of $H^+ \rightarrow t\bar{b}$ and $H^- \rightarrow t\bar{b}$ indicating a CP violation as considered in Ref. [10]. Therefore the measured asymmetry is actually the combined asymmetry

$$A_{\text{tot}}^{CP} = \frac{\sigma(pp \rightarrow g\bar{b} \rightarrow tH^+)\Gamma(H^+ \rightarrow t\bar{b}) - \sigma(pp \rightarrow gb \rightarrow tH^-)\Gamma(H^- \rightarrow t\bar{b})}{\sigma(pp \rightarrow g\bar{b} \rightarrow tH^+)\Gamma(H^+ \rightarrow t\bar{b}) + \sigma(pp \rightarrow gb \rightarrow tH^-)\Gamma(H^- \rightarrow t\bar{b})}. \quad (9)$$

Under the assumption of $\text{Re}\, \delta y_i^{CP} \ll y_i^0$, the asymmetry is approximately the sum of the production asymmetry and the decay asymmetry,

$$A_{\text{tot}}^{CP} \approx \frac{\Delta \sigma}{\sigma} + \frac{\Delta \Gamma}{\Gamma} = A_{\text{prod}}^{CP} + A_{\text{decay}}^{CP}. \quad (10)$$

Thus it is expected that the total asymmetry is amplified due to the asymmetry in decay. We show the total asymmetry with respect to $m_{H^\pm}$ in Fig. 4. If we consider the events with $H^\pm$ decays into $\tau\nu$, it is enough to consider the asymmetry of Eq. (6) since the rate asymmetry of $H^\pm \rightarrow \tau\nu$ is nothing but of order $10^{-3}$ [11].

It is known that the SUSY corrections play an important role in the charged Higgs production processes. They can enhance the signal-background ratio to shift the reach of the LHC search by a few hundred GeV and may yield CP violation in the charged Higgs production [7]. The QCD corrections and SUSY corrections to the gluonic vertex and propagators are canceled out in the CP asymmetry and we do not consider them here. We find that the CP violating asymmetry can reach more than 10 % when the mass of the charged Higgs boson is larger than 850 GeV. If we consider the CP asymmetry of decay products, $pp \rightarrow t\bar{b}/\bar{t}b$, it is amplified by the CP violation of decay process and we could obtain the asymmetry more than 25 % as shown in Fig. 4. In conclusion, the CP violation in the charged Higgs boson production associated with a top quark can be large dependent on SUSY phases and $m_{H^\pm}$. Thus we expect that the CP violating asymmetry could be detected in the charged Higgs boson production at the LHC.

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FIG. 1: Diagrams of dominant SUSY correction to the $tbH^\pm$ vertex.
FIG. 2: CP violating asymmetry due to the SUSY correction with varying $m_{H^\pm}$ and $\theta_t = \pi/2$. Other phases are set to be 0. The solid line denotes $\tan \beta = 5$, the dashed line $\tan \beta = 10$, and the dash-dotted line $\tan \beta = 30$. 
FIG. 3: CP violating asymmetry due to the SUSY correction with varying $m_{H^\pm}$ and $\theta_t = \pi$, $\phi_3 = \pi/2$. Other phases are set to be 0. The solid line denotes $\tan \beta = 5$, the dashed line $\tan \beta = 10$, and the dash-dotted line $\tan \beta = 30$. 
FIG. 4: Total CP violating asymmetry and production CP asymmetry due to the SUSY correction with varying $m_{H^\pm}$ and $\theta_t = \pi/2$. The solid line denotes the total asymmetry for the $H^\pm$ production and the decay into $tb$ pair. The dashed line denotes the asymmetry for the $H^\pm$ production only.