Top quark spin and $Htb$ interaction in charged Higgs and top quark associated production at LHC

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We study the charged Higgs production at LHC via its associated production with top quark. The kinematic cuts are optimized to suppress the background processes so that the reconstruction of the charged Higgs and top quark is possible. The angular distributions with respect to top quark spin are explored to study the $Htb$ interaction at LHC.

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I. INTRODUCTION

The Standard Model (SM) of particle physics, with great success, is based on two cornerstones: gauge symmetry and electroweak spontaneous symmetry breaking mechanism (EWSB). The gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ of the SM has been confirmed by the discovery of $W/Z$ bosons and lots of precision measurements. As the other cornerstone, the mechanism of EWSB is implemented by introducing only one complex Higgs doublet $\Phi$ in the SM and then triggering EWSB after the neutral component of $\Phi$ developing a vacuum expectation value (vev). In the meanwhile, the masses of weak gauge bosons and fermions are generated. In the SM, there is only one physical neutral Higgs boson $H$ after EWSB. The discovery of the Higgs boson will help to unveil the mysteries of EWSB and mass generation of SM particles. Recently, one Higgs-like particle around 126 GeV has been discovered at LHC by ATLAS and CMS collaborations[1, 2]. It is important to further confirm the identity of this particle. In the SM, only one complex scalar doublet is introduced based on the “minimal principle”. It is natural to consider more complex scalars, for example, the two Higgs doublet structure.

Especially, there are many motivations to study the two Higgs doublet model (2HDM). Such as, in the supersymmetric models, a single Higgs doublet is unable to give mass simultaneously to the charge 2/3 and charge -1/3 quarks and the anomaly cancellation also require an additional Higgs doublet. Another motivation for 2HDM is that it could generate a baryon asymmetry of the universe of sufficient size. Interestingly, ATLAS and CMS announced that there is an enhancement in the di-photon channel of Higgs decay $h \rightarrow \gamma \gamma [1, 2]$. This enhancement can also be explained by charged Higgs from 2HDM[3].

There are many scenarios in 2HDM structure [1, 3]. Without imposing any discrete symmetry, the 2HDM suffers serious flavour changing neutral currents (FCNC) at tree-level. For the suppression of leading order FCNC as well as CP violation in the Higgs sector, we consider CP-conserving 2HDMs with extra discrete symmetry. Popular Type I and II 2HDMs belong to this kind. As one of the minimal extensions of the SM, 2HDMs [1, 3], has five physical Higgs scalars after the spontaneous symmetry breaking, i.e., two neutral CP-even bosons $h_0$ and $H_0$, one neutral CP-odd boson $A$, and two charged bosons $H^\pm$. In diverse models, different scalar multiplets and singlets could generate neutral scalars and there exists mixing between neutral scalars which makes it difficult to untangle the Higgs properties and confirm the existence of extended Higgs sector. However, the discovery of the charged Higgs boson could provide an unambiguous signature of the extended Higgs sector and help to further distinguish from different models.

Motivated by above reasons, the charged Higgs $H^\pm$ has been searched for at colliders in recent years. One model-independent direct limit is from the LEP experiments gives $M > 78.6$ GeV at 95% C.L., where $M$ represents the mass of charged Higgs by exclusive decay channels of $H^+ \rightarrow cs$ and $H^+ \rightarrow \tau^+ \nu$. At hadron colliders, the search approaches for the charged Higgs are different in low mass range $M < m_t$ and in large mass range $M > m_t$. In the low mass range $M < m_t - m_b$, the search for the signal mainly focus on the top quark decay $t \rightarrow H^+ b$ followed by decay mode $H^+ \rightarrow \tau^{\pm} \nu$. On the other hand, for large mass range $M > m_t + m_b$, the signal is from the dominant production process, the $gb$ fusion process $gb \rightarrow tH^-$, followed by dominant decay modes $H^- \rightarrow tb$ and $H^- \rightarrow \tau \nu$. The Tevatron has put a constraint on 2HDM in the small $\tan \beta$ and large $\tan \beta$ regions for a charged Higgs boson with mass up to $\sim 160$ GeV [3]. In addition, the indirect constraints can be extracted from B-meson decays since the charged Higgs contributes to the FCNC at one loop level. In Type II 2HDM, a limit on the charged Higgs mass $M > 316$ GeV at 95% C.L. is obtained dominantly from $b \rightarrow s \gamma$ branching ratio measurement irrespective of the value of $\tan \beta$.
However, in Type III or general 2HDM the phases of the Yukawa couplings are free parameters so that \( M \) can be as low as 100 GeV \cite{9}. For more detailed discussions on phenomenological constraints on charged Higgs, we refer to Ref. \cite{10}.

Along with the experimental search for the charged Higgs boson, extensive phenomenological studies on charged Higgs boson production have been carried out \cite{11} \cite{18}. Especially, the \( gb \) fusion process \( gb \rightarrow tH^- \) for \( M > m_t + m_b \) \cite{13} \cite{19} has drawn more attentions due to the large couplings of \( Htb \) interaction. The next-to-leading QCD corrections to this process has also been performed in order to make the theoretical predictions more reliable \cite{20}.

In this work, we revisit this process at the LHC and take a method similar to Ref. \cite{21} to distinguish the signal from backgrounds. As demonstrated in Ref. \cite{21}, the angular distribution related to top quark spin is efficient to disentangle the chiral coupling of the \( W^\prime \) boson to SM fermions. The left-right asymmetry induced by top quark spin for \( pp \rightarrow tH^- \) process has been analyzed in Ref. \cite{22}. Here we further investigate this kind of effects after including the decay information of charged Higgs and top quark, and we employ the angular distributions of the top quark and the lepton resulting from top and charged Higgs decay to disentangle \( Htb \) couplings at LHC.

This paper is organized as follows. In Section \( \| \), the corresponding theoretical framework is briefly introduced. Section \( \| \| \) is devoted to the numerical analysis of top quark and charged Higgs associated production. Specifically, the correlated angular distributions are investigated to identify the interaction of top-bottom quark and charged Higgs. Finally, a short summary is given.

II. THEORETICAL FRAMEWORK

A. Lagrangian related to the interaction of Higgs and quarks

We start with a brief introduction to the two-Higgs-Doublet Model (2HDM) which is one of the minimal extensions of SM. Different from SM, 2HDM involves two complex \( SU(2)_L \) doublet scalar fields,

\[
\Phi_i = \begin{pmatrix} H^+_i \\ (H^0_i + i A^0_i)/\sqrt{2} \end{pmatrix},
\]

where \( i = 1, 2 \). Imposing CP invariance and U(1)\(_{\text{EM}}\) gauge symmetry, the minimization of potential gives

\[
\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix},
\]

with \( v_i \ (i = 1, 2) \) is non-zero vev. One important parameter in 2HDM \( \tan \beta \equiv v_2/v_1 \) is defined accordingly, which determines the interactions of the various Higgs fields with the vector bosons and fermions, it has substantial meaning in discussing phenomenology. The most severe constraints on \( \tan \beta \) and \( M \) come from flavour physics including \( B \) and \( D \) mesons, \( \Delta M_{B_s} \), \( b \rightarrow s\gamma \) and \( Z \rightarrow b\bar{b} \) \cite{24}. Large \( \tan \beta \) is favored by \( B \) meson rare decays \cite{24} \cite{25}. Specifically, for the Type II model, the upper bound on \( \tan \beta \) from \( D_s \rightarrow \tau\nu_\tau \) is \( \tan \beta \leq 50 \) with charged Higgs mass \( M = 600 \text{ GeV} \).

In this work we aim to study the charged Higgs phenomenology with large \( \tan \beta \) and choose the Type II Yukawa couplings as the working model

\[
-\mathcal{L} = -\cot \beta \frac{m_u}{v} \bar{u}_L(H + iA)u_R + \tan \beta \frac{m_d}{v} \bar{d}_L(H - iA)d_R - \sqrt{2} \cot \beta \frac{m_u}{v} V^\dagger u d_L H^- u_R - \sqrt{2} \tan \beta \frac{m_d}{v} V d_L \bar{d} L H^+ d_R + \text{h.c..} \quad (3)
\]

The vev of SM Higgs is related as \( v = \sqrt{v_1^2 + v_2^2} \). \( tbH^- \) vertex given in Ref. \cite{2} can be written as

\[
g_{H^-tb} = g_a + g_b \gamma_5. \quad (4)
\]

Within the type II 2HDM,

\[
g_{a,b} = g(cot\beta m_t \pm tan\beta m_b)/(2\sqrt{2}m_W).
\]

In the specific discussions below in Sec. III, we will investigate various combinations of \( (g_a, g_b) \) accordingly not limited in type II 2HDM.

B. Charged Higgs production associated with single top quark at hadron colliders

We begin to consider the following process(Fig. \( \| \))

\[
g(p_1) + b(p_2) \rightarrow t(p_3, s_t) + H^- (p_4) \rightarrow t(p_3, s_t) + b(p_5) + \bar{t}(p_6, s_t), \quad (5)
\]

where \( p_i \) denotes the 4-momentum of the corresponding particle. \( s_t(s_i) \) is the top(antitop) quark spin in 4-dimension and \( s_t = s_i = -1 \), \( p_3 \cdot s_t = p_6 \cdot s_i = 0 \).

Under the narrow width approximation of the charged Higgs, i.e., the charged Higgs is produced on-shell,

\[
\lim_{\Gamma \rightarrow 0} \frac{1}{(p_4^2 - M^2)^2 + \Gamma^2 M^2} \rightarrow \frac{\pi}{\Gamma M} \delta(p_4^2 - M^2), \quad (6)
\]

where \( \Gamma \) and \( M \) respectively denote the decay width and mass of the charged Higgs boson. The matrix element

**FIG. 1:** Feynman diagrams for \( gb \rightarrow tH^- \rightarrow t\bar{b}H \) process.
squared including top quark spin information for the process (5) can be written as follows

$$|\mathcal{M}(s_t, s_i)|^2 = |\mathcal{M}_{gb\to tH^-}(s_t)|^2 |\mathcal{M}_{H^-\to t\bar{b}}(s_i)|^2 \times \frac{\pi}{M^2} \delta(p_t^2 - M^2),$$

where

$$|\mathcal{M}_{gb\to tH^-}(s_t)|^2 = \frac{g_2^2}{2N_c} \left\{ A + B_1(p_1 \cdot s_t) + B_2(p_2 \cdot s_t) \right\},$$

and

$$|\mathcal{M}_{H^-\to t\bar{b}}(s_i)|^2 = (g_a^2 + g_b^2)(M^2 - m_b^2 - m_t^2) - 2(g_a^2 - g_b^2)m_b m_t - 4g_a g_b m_t(p_5 \cdot s_i).$$

The formula for $A$, $B_1$ and $B_2$ are listed in the following

$$A = (g_a^2 + g_b^2) A_1 + m_b m_t (g_b^2 - g_a^2) A_2,$$

with

$$A_1 = \frac{\hat{s}(p_1 \cdot p_3) - m_b^2 (4p_1 \cdot p_3 + 3p_2 \cdot p_3)}{(s - m_b^2)^2} + \frac{\hat{s}(p_1 \cdot p_3) + m_b^2 (s - 2p_2 \cdot p_3)}{4(p_1 \cdot p_3)^2} - \frac{1}{2(p_1 \cdot p_3)(s - m_b^2)} \left\{ m_b^2 (s - 2m_b^2) - 2(p_1 \cdot p_3)m_b^2 + 2(s - 2p_2 \cdot p_3)(p_1 \cdot p_3 + p_2 \cdot p_3) \right\},$$

$$A_2 = \frac{(\hat{s} + 2m_b^2)}{(s - m_b^2)^2} + \frac{m_b^2 - p_1 \cdot p_3}{2(p_1 \cdot p_3)^2} - \frac{2p_1 \cdot p_3 + 4p_2 \cdot p_3 - \hat{s}}{2(p_1 \cdot p_3)(s - m_b^2)},$$

and

$$B_1 = 2g_a g_b m_t \left\{ \frac{4m_b^2 - \hat{s}}{(s - m_b^2)^2} + \frac{2p_2 \cdot p_3 - \hat{s}}{4(p_1 \cdot p_3)^2} + \frac{1}{p_1 \cdot p_3} - \frac{p_2 \cdot p_3}{(p_1 \cdot p_3)(s - m_b^2)} \right\},$$

$$B_2 = 2g_a g_b m_t \left\{ \frac{3m_b^2}{(s - m_b^2)^2} + \frac{m_b^2 - p_1 \cdot p_3}{2(p_1 \cdot p_3)^2} + \frac{\hat{s} - p_1 \cdot p_3 - 2p_2 \cdot p_3}{(p_1 \cdot p_3)(s - m_b^2)} \right\}.$$

The matrix element squared for the process $gb \to \bar{t}H^+ \to t\bar{b}$ can be obtained from the above equations by using CP-invariance. Obviously, the top quark spin effects are related to the product $g_a g_b$ and disappear for a pure scalar or pseudo-scalar charged Higgs boson. In particular, for $pp \to tH^- \to t\bar{b}$ process, this feature can be reflected by the following spin observable

$$<\mathcal{O}_t> = 2 <\mathbf{S}_t \cdot \hat{a}> \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)}.$$
Another top that is leptonically decay, the 4-momentum of the neutrino should be known. But the neutrino is an unobservable particle, so we have to utilize kinematical constraints to reconstruct its 4-momentum. Its transverse momentum can be obtained by momentum conservation from the observed particles
\[ \mathbf{p}_{\nu T} = - (\mathbf{p}_{T} + \sum_{j=1}^{5} \mathbf{p}_{jT}), \] (22)
while its longitudinal momentum can not be determined in this way due to the unknown boost of the partonic c.m. system. Alternatively, it can be solved with twofold ambiguity through the on shell condition for the W-boson
\[ m_{W}^2 = (p_{\nu} + p_{l})^2. \] (23)
Furthermore one can remove the ambiguity through the reconstruction of another top quark. For each possibility we evaluate the invariant mass
\[ M_{jj\nu}^2 = (p_{j} + p_{\nu} + p_{j'})^2, \] (24)
where \( j \) refers to the any one of the two left jets and pick up the solution which is closest to the top quark mass. With such a solution, one can reconstruct the 4-momentum of the neutrino and that of another top quark.

In our following numerical calculations, we apply the basic acceptance cuts (referred to as cut I)
\begin{align*}
p_{T} &> 20 \text{ GeV}, \quad p_{jT} > 20 \text{ GeV}, \quad \not{\mathbf{E}}_{T} > 20 \text{ GeV},
|\eta_{l}| &< 2.5, \quad |\eta_{j}| < 2.5, \quad \Delta R_{jj(j\bar{j})} > 0.4,
|M_{j\bar{l}l\nu} - m_{t}| &\leq 30 \text{ GeV}, \quad |M_{j_{a,b},\bar{c}} - m_{t}| \leq 30 \text{ GeV},
|M_{j_{a,b},\bar{c}} - m_{W}| &< 10 \text{ GeV}. \quad (25)
\end{align*}

Once the events were fully reconstructed after smearing and including the cut I, we can further reconstruct the invariant mass between the reconstructed top (antitop) and the remaining jet. We display the distributions \( 1/\sigma(d\sigma/dM_{top} + d\sigma/dM_{\bar{b}}) \) in Fig. 3, where the resonance peak can easily be seen for different charged Higgs masses. Due to the existence of the resonance peak, we further employ another cut (referred to as cut II)
- Cut II: \( |M_{jj_h,j_{a,b}} - M| \leq 10\% \ M \) or \( |M_{j_{h,b},l\nu} - M| \leq 10\% \ M \).

Comparing our signal process with the dominant background process \( pp \rightarrow t\bar{t}j \), it is easy to notice that, after reconstructing the top and antitop quarks, the remaining jet is a b-jet for our signal while it is a light jet for the background with large probability. Therefore to further purify the signal, we adopt the following cut (referred to as cut III)
- Cut III: We demand the remaining jet that cannot be used to reconstruct top quarks to be a b-jet.
The $b$-tagging efficiency is assumed to be 60% while the miss-tagging efficiency of a light jet as a $b$ jet is taken as transverse momentum dependent \( \varepsilon_t \):\(^{(29)} \)

\[
\varepsilon_t = \begin{cases} 
\frac{1}{150} + \frac{P_T}{25\text{GeV}} - 1, & P_T < 100\text{ GeV}, \\
\frac{1}{50}, & 100\text{ GeV} \leq P_T < 250\text{ GeV}, \\
1, & P_T \geq 250\text{ GeV}.
\end{cases}
\]

(26)

The cross sections for the signal processes \((19)\) and \((20)\) with different charged Higgs mass after each cuts at LHC 8 and 14 TeV are respectively listed in Table \(1\). The dominant SM background related to the signal is \(pp \to tH \to l^\pm + 5\text{jets} + E_T\) process. We employ MadEvent \((30)\) to simulate the background processes. The other SM background processes, e.g., \(Wjjjj, WWjjj\), etc. are dramatically reduced by the acceptance cuts we adopt and therefore we neglected them here. Supposing the integral luminosity to be 20 $fb^{-1}$ at $\sqrt{s} = 8$ TeV, one can notice that it is difficult for the charged Higgs associated with a top quark to be detected when its mass is above 500 GeV. While with 300 $fb^{-1}$ integral luminosity at 14 TeV, the $tH^-$ production is easier to be observed. Detailed analysis shows that for \(pp \to tH^- \to tfb \to t^\pm (or \ l^-) + b\bar{b}jjj + E_T\) process at 14 TeV, the significance of signal to background can also be above three sigma for the charged Higgs mass $M \leq 1$ TeV. Therefore, in the following, we will focus on the \(tH^-\) production at $\sqrt{s} = 14$ TeV.

From Eqs. \((5)\) and \((9)\), one can notice that top quark spin effect is related to the product \((g_a g_b)\). Using the same method as in Ref. \((31)\), we find that this kind of top quark spin effects can be translated into the angular distributions of the charged lepton. Corresponding to the process \((19)\) and \((20)\), we obtain two kinds of angular distributions

\[
\frac{1}{\sigma} \frac{d \sigma}{d \cos \theta^*} = \frac{1}{2} \left[ 1 + A_{FB} \cos \theta^* \right],
\]

\[
\frac{1}{\sigma} \frac{d \sigma}{d \cos \beta^m} = \frac{1}{2} \left[ 1 + \tilde{A}_{FB} \cos \beta^m \right],
\]

(27)

with

\[
\cos \theta^* = \hat{p}_l^+ \cdot \hat{p}_l^-,
\]

\[
\cos \beta^m = \hat{p}_l^+ \cdot \hat{p}_l^-,
\]

(28)

where \(\hat{p}_l^+\) is the unit 3-momentum of charged lepton in the top quark rest frame, and \(\hat{p}_l^-\) is the unit 3-momentum of charged lepton in the anti-top quark rest frame. Without smearing effect and any acceptance cuts, \(A_{FB} (\tilde{A}_{FB})\) can be related to the top quark spin observables \(O_i (\bar{O}_i)\), i.e.,

\[
A_{FB} = \kappa_c < O_i > = 2\kappa_c < S_t \cdot \hat{p}_l^- >,
\]

\[
\tilde{A}_{FB} = \kappa_c < \bar{O}_i > = 2\kappa_c < S_t \cdot \hat{p}_l^- >.
\]

(29)

(30)

Obviously for the charged lepton in semileptonic top quark decay, \(A_{FB} = < O_i >\) and \(\tilde{A}_{FB} = < \bar{O}_i >\) before smearing effect and cuts.

According to Eq. \((27)\), \(A_{FB}\) and \(\tilde{A}_{FB}\) can also be determined as follows

\[
A_{FB} = \frac{\sigma(\cos \theta^* > 0) - \sigma(\cos \theta^* < 0)}{\sigma(\cos \theta^* > 0) + \sigma(\cos \theta^* < 0)},
\]

\[
\tilde{A}_{FB} = \frac{\sigma(\cos \beta^m > 0) - \sigma(\cos \beta^m < 0)}{\sigma(\cos \beta^m > 0) + \sigma(\cos \beta^m < 0)}.
\]

(31)

As discussed above, these observables can be used to discriminate different $Htb$ interactions. Within the framework of type II 2HDM, the form of the Yukawa coupling is fixed with only one free parameter $\tan \beta$. As displayed in Fig. 4, we calculate the values of $A_{FB}$ before any acceptance cuts with respect to $\tan \beta$ for $M=300, 500$ and 800 GeV at LHC 14 TeV. The results for $A_{FB}$ before any acceptance cuts are also shown in Fig. 4. $A_{FB}$ is related to the charged Higgs boson decay and we find it does not depend on the charged Higgs mass. Combining the results of the $tH^-$ production cross section together with the forward-backward asymmetry $A_{FB}$ and $\tilde{A}_{FB}$, one can abstract the useful information of $\tan \beta$ related to the $Htb$ coupling. Next, we extend our discussions beyond 2HDM and investigate the $Htb$ coupling in a general model where the Yukawa coupling of the charged Higgs bosons to fermions is a free parameter and so one can regard the scalar and pseudo-scalar parts of the Yukawa coupling as completely independent and free parameters. In the following, as an example, we choose $\tan \beta = 30$ and investigate the charged lepton angular distributions for three different combinations of \((g_a g_b)\):

- \((g_a g_b) > 0\), e.g.,
  \[
  g_a = \pm g(\cot \beta m_t + \tan \beta m_b)/(2\sqrt{2} m_W),
  \]
  \[
  g_b = \pm g(\cot \beta m_t - \tan \beta m_b)/(2\sqrt{2} m_W),
  \]

- \((g_a g_b) = 0\), e.g.,
  \[
  g_a = 0, g_b = g(\cot \beta m_t - \tan \beta m_b)/(2\sqrt{2} m_W) \quad \text{or}
  \]
  \[
  g_a = g(\cot \beta m_t + \tan \beta m_b)/(2\sqrt{2} m_W), g_b = 0.
  \]

- \((g_a g_b) < 0\), e.g.,
  \[
  g_a = \mp g(\cot \beta m_t + \tan \beta m_b)/(2\sqrt{2} m_W),
  \]
  \[
  g_b = \mp g(\cot \beta m_t - \tan \beta m_b)/(2\sqrt{2} m_W).
  \]

The charged lepton angular distributions with respect to $\cos \theta^*$ and $\cos \beta^m$ before and after all cuts are respectively shown in Figs. \((5)\) and \((7)\). The related predictions for $A_{FB}$ and $\tilde{A}_{FB}$ are listed in Table \((11)\). Due to the fact that the contribution from the $s$-channel (Fig.\((1a)\)) decreases as the charged Higgs mass increases, before all the acceptance cuts, the $\cos \theta^*$ distribution and the related results for $A_{FB}$ which are related to $tH^-$ production also depend on $M$; while the $\cos \beta^m$ distribution and the related results for $A_{FB}$ which are related to the charged Higgs decay do not depend on $M$. The $\cos \theta^* = -1(\cos \theta^* = -1)$ region corresponds to lepton that is emitted into the hemisphere opposite to the top(antitop) direction of flight in the $tH^-$ c.m. frame. These leptons are therefore less energetic on average and thus more strongly affected by the acceptance cuts than...
FIG. 3: The distributions $1/\sigma (d\sigma/dM_{tb} + d\sigma/dM_{\bar{t}b})$ with respect to the invariant mass between the reconstructed top (anti-top) and the remaining jet for the process of $pp \rightarrow tH^- \rightarrow t^+ + bjets + E_T$ after cut I at LHC for (a) 8 TeV and (b) 14 TeV.

FIG. 4: The $A_{FB}$ before any acceptance cuts with respect to tan $\beta$ at LHC 14TeV.

FIG. 5: The $\bar{A}_{FB}$ before any acceptance cuts with respect to tan $\beta$.

IV. SUMMARY

The observation of charged Higgs would be an unambiguous signal for the existence of new physics beyond SM. Therefore it is important to study the related phenomena both at theory and experiments. In this paper, we study the $tH^-$ associated production via $pp \rightarrow tH^- \rightarrow t\bar{t}b \rightarrow t^\pm + bbjj + E_T$ process at LHC. It is found that with 300 $fb^{-1}$ integral luminosity at $\sqrt{s} = 14$ TeV, the signal can be distinguished from the backgrounds for the charged Higgs mass up to 1 TeV or even larger. If the $tH^-$ production is observed at LHC, one of the key questions is to identify the $Htb$ interaction. For this aim, we investigate the angular distributions of those in the remaining region. Therefore the presence of the acceptance cuts severely distort these distributions in the vicinity of $\cos \theta^* = -1 (\cos \bar{\theta}^* = -1)$ region as shown in Figs. 6 and 7. Therefore for $A_{FB}$ and $\bar{A}_{FB}$ after all acceptance cuts, we choose $\cos \theta$ ranging from $-0.5$ to $0.5$. It seems that after the acceptance cuts, the angular distribution with respect to $\cos \theta^*(\cos \bar{\theta}^*)$ and $A_{FB}(\bar{A}_{FB})$ is more helpful to investigate the $Htb$ interaction for light/heavy charged Higgs production associated with top quark at LHC.
FIG. 6: The angle distribution of the charged lepton for $M = 300, 800$ GeV with nocut and all cuts at $\sqrt{s} = 14$ TeV respectively for the process of $pp \rightarrow tH^- \rightarrow l^+ + 5$jets + $E_T$. The solid line represents $(g_1 g_2) > 0$. The dashed line represents $(g_1 g_2) = 0$. The dotted line represents $(g_1 g_2) < 0$.

FIG. 7: The angle distribution of charged lepton for $M = 300, 800$ GeV with nocut and all cuts at $\sqrt{s} = 14$ TeV respectively for the process of $pp \rightarrow tH^- \rightarrow l^- + 5$jets + $E_T$. The solid line represents $(g_1 g_2) > 0$. The dashed line represents $(g_1 g_2) = 0$. The dotted line represents $(g_1 g_2) < 0$. 
the charged leptons and the related forward-backward asymmetry induced by top quark spin. It is found that

\[
\sigma(pp \to tH^- \to t\bar{b} \to t^\pm + 5jets + E_T) \quad (fb)
\]

| Signal | \(\sigma(pp \to tH^- \to t\bar{b} \to t^\pm + 5jets + E_T)\) (fb) | M(TeV) | M(TeV) |
|--------|------------------------------------------------|-------|-------|
| No cuts | 0.3 | 0.5 | 0.5 | 0.5 | 1.0 | 1.0 | 1.0 |
| Cut I  | 45.18 | 86.62 | 1.62 | 0.30 |
| +Cut II | 11.72 | 2.60 | 0.25 | 0.07 |
| +Cut III | 9.59 | 1.73 | 0.20 | 0.05 |
| Background | 5.76 | 1.04 | 0.12 | 0.03 |

TABLE I: The cross section of the signal process \(pp \to tH^- \to t^\pm + 5jets + E_T\) at \(\sqrt{s} = 8\) TeV after each cut.

these distributions and observables are sensitive to the product \((g_3g_8)\), so that they can be used to identify the \(Htb\) interaction. Though further studies are still necessary both at theory and experiments, the \(Htb\) interaction can be studied by the help of the charged lepton angular

\[
A_{FB}
\]

| \(A_{FB}\) | \(A_{FB}\) | \(A_{FB}\) |
|----------|----------|----------|
| M(TeV) | 0.3 | 0.5 | 0.8 | 1.0 | 0.3 | 0.5 | 0.8 | 1.0 |
| \((g_3g_8) > 0\) | 0.124 | 0.075 | 0.023 | -0.003 | -0.013 | -0.017 | -0.017 | -0.017 |
| \((g_3g_8) = 0\) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| \((g_3g_8) < 0\) | -0.125 | -0.076 | -0.024 | 0.001 | 0.017 | 0.017 | 0.017 | 0.017 |

TABLE III: The forward-backward asymmetry \(A_{FB}(\bar{A}_{FB})\) for \(pp \to tH^- \to t^+(l^-)+5jets + E_T\) at \(\sqrt{s} = 14\) TeV before and after all cuts.

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