Off-diagonal Yukawa Couplings in the $s$-channel
Charged Higgs Production at LHC

Majid Hashemi, Hossein Bakhshalizadeh

Physics Department and Biruni Observatory,
College of Sciences, Shiraz University, Shiraz 71454, Iran

E-mail: hashemi_mj@shirazu.ac.ir

ABSTRACT: The search for the heavy charged Higgs ($m_{H^\pm} > m_{t\bar{t}}$) has been mainly based on the off-shell top pair production process. However, resonance production in $s$-channel single top events is an important channel to search for this particle. In a previous work, it was shown that this process, i.e., $qq' \rightarrow H^+ \rightarrow t\bar{b} + \text{h.c.}$, can lead to comparable results to what is already obtained from LHC searches through $g\bar{b} \rightarrow tH^-$ process. What was obtained was, however, based on diagonal Yukawa couplings between incoming quarks assuming $c\bar{s}$ as the main incoming pair due to the CKM matrix element being close to unity. The aim of this paper is to show that off-diagonal couplings, like $c\bar{b}$, may lead to substantial contributions to the cross section, even if the corresponding CKM matrix element is two orders of magnitude smaller. For this reason, the cross section is calculated for each initial state including all diagonal and off-diagonal terms, and all is finally added together to get the total cross section which is observed to be $\sim 2.7$ times larger than what is obtained from $c\bar{s}$ initial state. Results are eventually reflected into 95% C.L. exclusion and 5$\sigma$ discovery contours at different integrated luminosities of LHC. A reasonable coverage of the parameter space is obtained by the 95% C.L. exclusion contour.
1 Introduction

The search for the charged Higgs boson within Supersymmetric Standard Model (MSSM) at the Large Hadron Collider (LHC) is currently extending the excluded area in the parameter space \( (m_{H^\pm}, \tan \beta) \) with no evidence of the particle in the low mass area \( (m_{H^\pm} < m_{t_{\text{top}}}) \). Here, \( \tan \beta \) is the ratio of vacuum expectation values of the two Higgs doublets.

The current main limits on the mass of the charged Higgs come from LEP II direct and indirect searches which, all together, set a lower limit on the charged Higgs mass as \( m_{H^\pm} > 125 \) GeV [1, 2]. The Tevatron searches by the D0 [3–6] and CDF Collaborations [7–10] exclude high \( \tan \beta \) values, however, they are confirmed and extended by current LHC results [11–16]. In this paper, we rely on the direct search results from LHC which exclude \( \tan \beta > 50 \) in the heavy charged Higgs area, i.e., \( m_{H^\pm} > 200 \text{ GeV} \).

The ongoing analyses at LHC focus on \( g \bar{b} \to tH^- \) process to search for the heavy charged Higgs. However, single top events have also been proved to be a significant source of the charged Higgs in both low and high mass regions. The light charged Higgs may be produced in a \( t\)-channel single top production through the top quark decay [17]. The heavy charged Higgs is, however, produced directly through the \( s\)-channel single top production with the signature of such events being the kinematic differences from pure Standard Model (SM) events [18]. The analysis performed in [18] has led to promising results comparable to what has been obtained from the analysis of \( g \bar{b} \to tH^- \) process at LHC.

The aim of this paper is show that there is still room to improve the signal sensitivity in \( s\)-channel single top analysis [18]. An analysis of the parton distribution functions (PDF) inside the incoming protons shows that heavy quark PDF (\( c \) and \( b \) quarks) is not negligible and can lead to sizable contribution to the rate of incoming partons in the interaction. On the other hand the vertex coupling in a process like \( c \bar{b} \to H^+ \) is proportional to the \( b \)-quark mass at high \( \tan \beta \) while the corresponding diagonal coupling which appears at \( c \bar{s} \to H^+ \) interaction is proportional to the \( s \)-quark mass. One should of course take into account the
Figure 1. The signal production process. The hermitian conjugate of the above process is included throughout the paper in all calculations even if not explicitly stated.

CKM matrix element suppression in the former, however, as will be shown, the suppression is not strong enough to decrease the rate dramatically. In fact it turns out that $c\bar{b}$ initiated process has a larger cross section than that initiated from $c\bar{s}$.

In what follows, details of the $s$-channel single top cross section calculation is presented, with a list of quark masses and CKM matrix element values used in the analysis. All possible initial states are included in the calculation and a total cross section is obtained as the sum of diagonal and off-diagonal couplings between incoming quarks and compared with what is obtained from the main diagonal coupling $c\bar{s}$. In order to visualize the results, event selectin efficiencies from [18] are used and updated contours are presented for a 5σ discovery or 95% C.L. exclusion.

2 Cross Section of Heavy Charged Higgs Production in Single Top Events

In this section a description of cross section calculation based on Yukawa couplings is presented. In order to be more specific, the Feynman diagram under study is illustrated in Fig. 1. The final evaluation and parameter dependence of the cross section is obtained using CompHEP [19, 20]. To this end, vertex couplings (to be described in the next subsection) are implemented in CompHEP and the cross section is calculated using Monte Carlo approach requiring a statistical error less than a percent.

2.1 Yukawa Coupling Lagrangian

The charged Higgs interaction with leptons and quarks can be formulated with the following Lagrangian:

$$\mathcal{L} = \sqrt{2} \sqrt{2} G_F \ H^+ \ [V_{ud}(m_u \cot \beta \ \bar{u} P_L d \ + \ m_d \tan \beta \ \bar{u} P_R d) \ + \ m_l \tan \beta \ \bar{\nu} P_R l] \quad (2.1)$$
Momentum fraction (x)

| x | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
|---|-----|-----|-----|-----|-----|-----|-----|-----|
| $xf(x,Q)$ | 0   | 0.2 | 0.4 | 0.6 | 0.8 | 1   | 1.2 | 0   |

$Q = 250$ GeV

gluon

where $P_L$ ($P_R$) are left (right) hand projection operators, and an implicit sum over $u$ (up type quarks) and $d$ (down type quarks) is assumed. The last term is not under consideration here, but the first two terms describe charged Higgs interaction with quarks. The interaction, as is seen from Eq. 2.1, is sensitive to the quark masses as well as the CKM matrix elements. This Lagrangian can be used to calculated a parton level cross section, however, in real proton-proton interactions, another issue is how likely a parton of a given type comes out of the proton and takes part in the interaction. This effect is described by the parton distribution function used in the analysis. Figure 2 shows typical distributions of the partons in a proton at a negative four momentum transfer set to $Q = 250$ GeV (a charged Higgs with $m_{H^\pm} = 250$ GeV). As is seen from Fig. 2 heavy quarks (even the $b$-quark) can still be visible although with a much smaller probability than valence quarks and gluons. A $b$-quark may appear directly or through a gluon splitting and its contribution to the Yukawa coupling is proportional to its mass at high $\tan \beta$. Therefore it may not be surprising that a $c\bar{b}$ initial state makes a larger contribution than diagonal $c\bar{s}$ term in spite of the strong CKM suppression.

### 2.2 Quark Masses and CKM Quark-Mixing Matrix Elements

For our calculations, we use Particle Data Group (pdg) data for quark masses as well as CKM matrix elements [21]. They are listed in Tabs. 1 and 2. The CKM elements listed in Tab. 2 are those related to the initial state quarks (incoming partons). The final state is set to a pair of top and bottom quark. Therefore the only CKM matrix element for the final state is $V_{tb}$ which is assumed to be unity (The recent CMS measurement at 7 TeV implies $V_{tb} = 1.14 \pm 0.22$).

In addition to parameters whose values were given in Tabs. 1 and 2, the charged Higgs width is also needed as it is involved as a propagator in the diagram shown in Fig. 1. The charged Higgs width depends on the charged Higgs mass and $\tan \beta$. A scan over selected
points in the parameter space \((m_{H^\pm}, \tan \beta)\) was performed and total widths were obtained using FeynHiggs 2.8.3 [22]. Results are shown in Fig. 3. Finally the integration over parton level cross sections is performed using CTEQ 6.6 PDF to obtain the cross section at real proton-proton interactions at LHC nominal center of mass energy \(\sqrt{s} = 14\) TeV.

| Quark flavor | Mass [GeV] |
|--------------|------------|
| \(u\)        | 0.0023     |
| \(d\)        | 0.0048     |
| \(s\)        | 0.095      |
| \(c\)        | 1.275      |
| \(b\)        | 4.18       |
| \(t\)        | 173        |

Table 1. Quark masses according to PDG 2012 [21].

2.3 Results

In this section, results of \(pp \rightarrow H^\pm \rightarrow tb\) cross section calculation are presented for different \(\tan \beta\) values. In Figs. 4, 5 and 6 results are presented including all initial states which are shown in separated curves. The total cross section is the sum of all initial states. As is seen the \(cb\) initial state has the largest contribution to the total cross section for any charged Higgs mass and \(\tan \beta\). The ratio of total cross section to that of \(cs\) initial state is shown in Fig. 7. Results are in reasonable agreement with [23] where a brief discussion on the contribution of \(cb\) and \(cs\) initial states has been presented. Finally Fig. 8 compares cross
| CKM matrix element | Value |
|-------------------|-------|
| $V_{ud}$          | 0.97  |
| $V_{us}$          | 0.22  |
| $V_{ub}$          | 0.004 |
| $V_{cd}$          | 0.23  |
| $V_{cs}$          | 1.00  |
| $V_{cb}$          | 0.04  |

Table 2. CKM quark-mixing matrix elements according to PDG 2012 [21].

**Figure 4.** Cross section of $pp \rightarrow H^\pm \rightarrow tb$ at $\tan \beta = 20$. Contribution of different initial states as well as the total value are shown separately.

sections at different $\tan \beta$ values including all initial states and reveals the fact that at high $\tan \beta$ the cross section grows rapidly.

### 3 The 95% C.L. Exclusion and 5σ Discovery Contours

Results of [18] are based on a cross section calculation including only $cs$ initial state. As Fig. 7 shows, the cross section is $\sim 2.7$ times larger if all initial states are included. This effect is almost independent of the charged Higgs mass and $\tan \beta$. Therefore using the same event selection efficiencies as in [18] and updated cross sections obtained in this paper, contours of 95% C.L. exclusion and 5σ discovery are produced using TLimit code implemented in ROOT [24]. Figures 9 and 10 show the 95% C.L. exclusion and 5σ discovery contours respectively.
Figure 5. Cross section of $pp \rightarrow H^\pm \rightarrow tb$ at $\tan \beta = 30$. Contribution of different initial states as well as the total value are shown separately.

Figure 6. Cross section of $pp \rightarrow H^\pm \rightarrow tb$ at $\tan \beta = 50$. Contribution of different initial states as well as the total value are shown separately.

4 Conclusions

The $s$-channel charged Higgs production was revisited with special care on the contribution of different incoming partons in the interaction. The total cross section was obtained including all initial states and it was concluded that off-diagonal terms in the Yukawa interaction of the charged Higgs and quarks play an important role even though partially
suppressed by the CKM matrix elements. The total cross section was obtained to be $\sim 2.7$ times the dominant digonal term, i.e., $cs$ initial state. Using selection efficiencies from an earlier analysis, contours of exclusion and discovery were updated. Results show that with this channel, almost all parameter space in the mass range $200 < m_{H^\pm} < 300$ GeV can be excluded even at $\tan \beta$ values as low as 10. This is a result which has not yet been obtained using current LHC experiments and is worth considering in their analyses.

Figure 7. Ratio of total cross section of $pp \to H^\pm \to tb$ to that of only $cs$ initial state.

Figure 8. Cross section comparison at different $\tan \beta$. 
Figure 9. The 95% C.L. exclusion contour at different integrated luminosities of 30, 60 and 100 $fb^{-1}$.

Figure 10. The $5\sigma$ discovery contour at different integrated luminosities of 30, 60 and 100 $fb^{-1}$.

References

[1] LEP Higgs Working Group, hep-ex/0107031
[2] LEP Higgs Working Group, hep-ex/0107030
[3] D0 Collaboration, Phys. Rev. Lett. 82 (1999) 4975
[4] D0 Collaboration, D0 Note 5715-CONF
[5] D0 Collaboration, arXiv:0906.5326 [hep-ex]
[6] D0 Collaboration, Phys. Rev. D 80 (2009) 071102(R)
[7] CDF Collaboration, Phys. Rev. Lett. 96 (2006) 042003
[8] G. Yu on behalf of the CDF Collaboration, AIP Conf. Proc. 1078 (2008) 198
[9] CDF Collaboration, arXiv:0907.1269 [hep-ex]
[10] CDF Collaboration, Phys. Rev. Lett. 103 (2009) 101803
[11] CMS Collaboration, CMS PAS HIG-12-050
[12] ATLAS Collaboration, ATLAS-CONF-2011-132
[13] ATLAS Collaboration, JHEP 1206 (2012) 039, arXiv:1204.2760 [hep-ex]
[14] ATLAS Collaboration, ATLAS-CONF-2013-090
[15] CMS Collaboration, JHEP 1207 (2012) 143, arXiv:1205.5736 [hep-ex]
[16] CMS Collaboration, CMS PAS HIG-12-052
[17] M. Hashemi, JHEP 1305 (2013) 112, arXiv:1305.2096 [hep-ph]
[18] M. Hashemi, JHEP 1311 (2013) 005, arXiv:1310.5209 [hep-ph]
[19] E. Boos, et al., Nucl. Instrum. Meth. A 534 (2004) 250, [arXiv:hep-ph/0403113]
[20] A. Pukhov, et al., Preprint INP MSU 98-41/542, [hep-ph/9908288]
[21] J. Beringer, et al. (Particle Data Group), Phys. Rev. D 86 (2012) 010001
[22] S. Heinemeyer, et al., CERN-TH/98-389
[23] S. Dittmaier, et al., Phys. Rev. D 77 (2008) 115001, arXiv:0708.0940 [hep-ph]
[24] R. Brun, F. Rademakers, NIM A 389 (1997) 81-86