Charged Higgs production at the LHC and CP asymmetries

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Abstract. We study CP violation in associated production of a charged Higgs boson and a top quark at the LHC, \( pp \to tH^\pm + X \). The asymmetry between the total cross sections for \( H^+ \) and \( H^- \) production at next-to-leading order in the MSSM is calculated analytically and a detailed numerical analysis is performed. Furthermore, subsequent decays of \( H^\pm \) to \( tb \) and \( \tau^\pm \nu_\tau \) are considered. In the case with \( H^\pm \to tb \) decay the asymmetry can go up to \( \sim 12\% \).

Keywords: SUSY phenomenology, CP violation, Charged Higgs physics

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INTRODUCTION

Complex MSSM parameters can induce CP violation (CPV) in charged Higgs production associated with a top quark at the LHC, \( pp \to tH^\pm + X \), [1, 2]. At parton level this process, based on bottom-gluon fusion\(^1\), contains similar CPV contributions as the decay \( H^\pm \to tb \), which was already studied in [3]. Therefore, one would expect CPV effects of the same order, but in the production we have additional box graph contributions. First we study CPV in the \( H^\pm \) production process only. Then we combine it with subsequent decays into \( tb \) and \( \tau^\pm \nu_\tau \). We present numerical results for the CP asymmetry induced by vertex, selfenergy and box corrections in the MSSM.

THE PROCESS

We consider associate production of a charged Higgs boson and a top quark at the LHC,

\[
p (P_A) + p (P_B) \to t, \bar{t} (p_t) + H^\pm (p_{H^\pm}) + X ,
\]

based on bottom-gluon fusion at parton level

\[
br (\bar{b}_r) + g_\mu^\alpha \longrightarrow t_s (\bar{t}_s) + H^\pm ,
\]

with the colour indices \( r, s = 1, 2, 3 \) and \( \alpha = 1, ..., 8 \). At tree-level the process (2) contains two graphs: with bottom quark exchange (s-channel), and top quark exchange (t-channel).\(^1\)

\(^1\) For \( m_{H^\pm} \geq 400 \text{ GeV} \) this is the leading parton level process.
CP VIOLATING ASYMMETRIES

We define the CPV asymmetry in the \( H^\pm \) production as the difference between the total number of produced \( H^+ \) and \( H^- \) in proton-proton collisions:

\[
A_{CP}^P = \frac{\sigma(pp \to \bar{t}H^+) - \sigma(pp \to tH^-)}{\sigma(pp \to \bar{t}H^+) + \sigma(pp \to tH^-)},
\]

where \( \sigma(pp \to \bar{t}H^+) \) and \( \sigma(pp \to tH^-) \) are the total cross sections for \( H^+ \) and \( H^- \) production at the LHC. The asymmetry (3) is caused by corrections to the \( H^\pm tb \)-vertex, selfenergy loops on the \( H^\pm \) line and box diagrams to both \( s \)- and \( t \)-channels in the MSSM with complex parameters [4].

Furthermore we define the CPV asymmetry in charged Higgs boson production in \( pp \to tH^\pm \) with a subsequent decay \( H^\pm \to f \), assuming CPV in both production and decay,

\[
A_{CP}^f = \frac{\sigma(pp \to \bar{t}H^+ \to \bar{t}f) - \sigma(pp \to tH^- \to tf)}{\sigma(pp \to \bar{t}H^+ \to \bar{t}f) + \sigma(pp \to tH^- \to tf)},
\]

where \( f \) stands for the chosen decay mode: \( f = t\bar{b} \); \( \tau^+ \nu_\tau \) and \( W^+ h^0 \). In narrow width approximation the asymmetry (4) is an algebraic sum of the CPV asymmetry \( A_{CP}^P \) in the production, and the CPV asymmetry \( A_{CP,D}^f \) in the decay \( f \) of the charged Higgs boson,

\[
A_{CP}^f = A_{CP}^P + A_{CP,D}^f.
\]

NUMERICAL RESULTS

The numerical code based on our analytical results is checked using FeynArts and FormCalc [5]. The Yukawa couplings of the third generation quarks \( (h_t, h_b) \) are taken to be running [3], at the scale \( Q = m_{H^\pm} + m_t \). For the evaluation of the parton distribution functions (PDF’s) we use CTEQ6L [6], with next-to-leading order \( \alpha_s \), at the same scale \( Q \). We assume GUT relation between \( M_1 \) and \( M_2 \) and take them both real. The contributions from diagrams with \( \tilde{\chi}^0, \tilde{\tau}, \tilde{\nu} \) are negligible and therefore only contributions from diagrams with \( \tilde{t}, \tilde{b} \) and \( \tilde{g} \) are shown. If not specified otherwise, we fix the following MSSM parameters: \( M_2 = 300 \) GeV, \( M_3 = 727 \) GeV, \( M_{\tilde{U}} = M_{\tilde{Q}} = M_{\tilde{D}} = 350 \) GeV, \( \mu = -700 \) GeV, \(|A_t| = |A_b| = 700 \) GeV, \( \tan \beta = 5 \), \( \phi_{A_t} = \pi/2 \), \( \phi_{A_b} = \phi_{\mu} = 0 \). The relevant masses of the sparticles for this choice of parameters, \( \tan \beta = 5 \) or 30 are shown in Table 1 of [4]. Our numerical results are in agreements with those shown in [1], but we disagree analytically and numerically with the results given in [2].

Production asymmetry

The CPV asymmetry \( A_{CP}^P \) in the production process can go up to \( \sim 20\% \) for relatively small \( m_{H^+} \) [3]. The contributions of the vertex, selfenergy and box graphs with \( \tilde{t}, \tilde{b} \) and \( \tilde{g} \) to \( A_{CP}^P \) as functions of \( m_{H^+} \) are shown on Fig. 1a. The large effect seen on the figure
is mainly due to the phase of $A_t$ and the asymmetry reaches its maximum for a maximal phase $\phi_{A_t} = \pi/2$. The asymmetry is significant for $\tan \beta = 5$ and falls down quickly with increasing $\tan \beta$. This dependence for $m_{H^+} = 550$ GeV is shown on Fig. 1b.

FIGURE 1. The various contributions to the asymmetry $A_{CP}^{P}$ at hadron level for the chosen set of parameters: a) as a function of $m_{H^+}$; b) as a function of $\tan \beta$, $m_{\tilde{g}} = 450$ GeV, $m_{H^+} = 550$ GeV. The red dotted line corresponds to box graphs with gluino, the solid blue one to the vertex graph with gluino, and the green dashed one to the $W^\pm - H^\pm$ selfenergy graph with $\tilde{t}\tilde{b}$ loop.

Production and decay asymmetry

The total production and subsequent decay rate asymmetry depends not only on the asymmetry $A_{CP}^{P}$, but also on the branching ratio (BR) of the relevant decay. For small $m_{H^+}$, below the $\tilde{t}\tilde{b}$ threshold, the dominant decay mode is $H^\pm \to t\bar{b}$, with BR $\gtrsim 0.9$, while the BR of $H^\pm \to \tau^\pm \nu_\tau$ is in the order of a few percent, decreasing with increasing $m_{H^+}$. When the $H^\pm \to \tilde{t}\tilde{b}$ channels are kinematically allowed, they start to dominate, and the BR of $H^\pm \to \tau^\pm \nu_\tau$ becomes zero to a good approximation. However, the BR of $H^\pm \to t\bar{b}$ remains stable of the order of 15-20%, see Fig. 9 in [4]. In Fig. 2a we show the total production and decay asymmetry $A_{CP}^{f}$ at hadron level, for $f = t\bar{b}$ and $f = \tau^\pm \nu_\tau$. The asymmetry $A_{CP}^{\tau^\pm \nu_\tau}$ can go up to $\sim 20\%$ for $m_{H^+} \approx 650$ GeV, but in the shown range its BR is too small and observation at LHC is impossible.

FIGURE 2. The total asymmetry $A_{CP}^{P}$ at hadron level for the chosen set of parameters: a) as a function of $m_{H^+}$. The blue line corresponds to the case when $H^\pm$ decays to $t\bar{b}$, and the green one to $H^\pm$ decay to $\tau^\pm \nu_\tau$; b) as a function of $|A_t|$, for three values of $m_{H^+}$ (in GeV).
On the other hand, as the asymmetries in the production only and the in decay in the case of $H^\pm \rightarrow tb$ are large and additive (5), one would suppose that the total asymmetry is also large. However, in [4] we show analytically that the $H^\pm - W^\pm$ selfenergy contribution to the asymmetry $A^\text{CP}_{tb}^P$ of the decay part cancels exactly the $W^\pm - H^\pm$ selfenergy contribution of the production part. Also the contributions of the vertex graphs from the production and from the decay can partially cancel numerically. However, as the box graphs do not have a real analogue in the decay, their contribution remains leading in our studied case. On Fig. 2b the dependence of $A^\text{CP}_{tb}$ on the absolute value of $A_t$ is shown for three different $H^\pm$ masses.

**SUMMARY**

We have calculated the CPV asymmetries $A^\text{CP}_P$, and $A^\text{CP}_f$, with $f = tb; \tau^\pm \nu_\tau$, between the total cross sections for $H^+$ and $H^-$ production in proton-proton collisions, proceeding at parton level through $bg$ fusion. We have performed a detailed numerical analysis, varying different relevant parameters and phases of the MSSM. The asymmetry $A^\text{CP}_P$ can go up to $\sim 20\%$ at $m_{H^\pm} \approx 600$ GeV, $\tan \beta = 5$ and a maximal phase of $A_t$. This effect is due to CPV vertex, selfenergy and box contributions with $\tilde{t}, \tilde{b}$ and $\tilde{g}$. The total asymmetry in the combined process of production and a subsequent decay is approximately the sum of $A^\text{CP}_P$ and $A^\text{CP}_{D,f}$, where $f$ is the relevant decay mode. Despite the fact that the dominant CPV contribution from the decay cancels with the relevant part of the production, most promising remains the $tb$ channel. The effect in this case is mainly due to box diagrams with gluino and the asymmetry $A^\text{CP}_{tb}$ can go up to $\sim 12\%$.

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