Energy correlation and asymmetry of secondary leptons originating in

\[ H \rightarrow t\bar{t} \] and \[ H \rightarrow W^+W^- \]

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Abstract

We study the energy correlation of charged leptons produced in the decay of a heavy Higgs particle \( H \rightarrow t\bar{t} \rightarrow b^+\nu_l\bar{b}l^-\bar{\nu}_l \) and \( H \rightarrow W^+W^- \rightarrow l^+\nu_l l^-\bar{\nu}_l \). The possible influence of \( CP \)-violation in the \( Ht\bar{t} \) and \( HW^+W^- \) vertices on the energy spectrum of the secondary leptons is analyzed. The energy distribution of the charged leptons in the decay \( H \rightarrow W^+W^- \rightarrow l^+\nu_l l^-\bar{\nu}_l \) is sensitive to the \( CP \)-parity of the Higgs particle and yields a simple criterion for distinguishing scalar Higgs from pseudoscalar Higgs.
1 Introduction

We wish to report results on the energy spectrum and energy correlation of charged lepton produced in the reactions

\begin{align*}
H \rightarrow t\bar{t} \rightarrow bl^+\nu_l\bar{b}l^-\bar{\nu}_l, \quad (1) \\
H \rightarrow W^+W^- \rightarrow l^+\nu_l\bar{l}^-\bar{\nu}_l. \quad (2)
\end{align*}

The above decays represent interesting leptonic signals of a heavy Higgs particle, that can be used to test the structure of Higgs couplings to fermions and gauge bosons [1]. (Note that the reaction (2), in the standard model, is about 27 times more frequent than the “gold-plated” reaction \( H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^- \)). We carry out the analysis in a general framework in which the couplings of the \( H \) to \( t\bar{t} \) and to \( W^+W^- \) are given by:

\begin{align*}
Ht\bar{t} &: \quad i(a + ib\gamma_5), \quad (3) \\
HW^+W^- &: \quad i2m_W^2\sqrt{G_F}\sqrt{2}(Bg_{\mu\nu} + \frac{D}{m_W^2}\epsilon_{\mu\nu\rho\sigma}p_{W^+}^\rho p_{W^-}^\sigma). \quad (4)
\end{align*}

Here \( p_{W^+} \) and \( p_{W^-} \) are the 4–momenta of the \( W \)–bosons. The terms proportional to \( b \) and \( D \) may arise as primary or induced effects in a generalized Higgs framework. Simultaneous presence of \( a \) and \( b \) or \( B \) and \( D \) is \( CP \)–violating [2]. Results will be obtained for the energy correlation of the two charged leptons in the \( H \) rest frame. A special result is a simple criterion for distinguishing a scalar Higgs from a pseudoscalar Higgs particle on the basis of the energy spectrum of any single charged lepton in \( H \rightarrow W^+W^- \rightarrow l^+\nu_l\bar{l}^-\bar{\nu}_l. \)
The vertex $Ht\bar{t}$ (Eq. (3)) gives rise to the following differential decay rate for $H(P) \rightarrow t(p_t, s_+)\bar{t}(p_{\bar{t}}, s_-)$:

\[
\frac{d\Gamma}{d\Omega_x}(s_+, s_-) = \frac{\beta_t}{64\pi^2 m_H} \left\{ (|a|^2 + |b|^2)(\frac{m_H^2}{2} - m_t^2 + m_t^2 s_+ s_-) + (|a|^2 - |b|^2)(P_{s_+} P_{s_-} - \frac{m_H^2}{2} s_+ s_- + m_t^2 s_+ s_- - m_t^2) - \text{Re}(ab^*) \varepsilon(Q, s_+, s_-) - 2\text{Im}(ab^*) m_t P(s_+ + s_-) \right\},
\]

(5)

where $P \equiv p_t + p_{\bar{t}}$, $Q = p_t - p_{\bar{t}}$, and $s_+$ and $s_-$ denote the polarization vectors of $t$ and $\bar{t}$, respectively. $\beta_t = \sqrt{1 - 4m_t^2/m_H^2}$ is the velocity of the top quarks in the Higgs rest frame. The symbol $\varepsilon(a, b, c, d)$ means $\varepsilon_{\mu\nu\rho\sigma} a^\mu b^\nu c^\rho d^\sigma$ with $\varepsilon_{0123} = +1$. The terms proportional to $\text{Re}(ab^*)$ and $\text{Im}(ab^*)$ represent the $CP$–violating part of the differential decay rate.

Using the method of Kawasaki, Shirafuji and Tsai [3], the differential decay rate $\frac{d\Gamma}{d\Omega_x}(s_+, s_-)$ yields the following normalized energy correlation of the charged leptons produced in the decay $H \rightarrow t\bar{t} \rightarrow l^+l^- + \cdots$ [F 1]:

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dx dx'}(H \rightarrow t\bar{t} \rightarrow l^+l^- + \cdots) = f(x) f(x') - \frac{1}{\beta_t^2} g(x) g(x') + \frac{2\text{Im}(ab^*)}{|a|^2 \beta_t^2 + |b|^2} \left[ f(x') g(x) - f(x) g(x') \right],
\]

(6)

where $x$ and $x'$ are the reduced energies

\[
x = \frac{2E(l^+)}{m_t} \sqrt{\frac{1 - \beta_t}{1 + \beta_t}}, \quad x' = \frac{2E(l^-)}{m_t} \sqrt{\frac{1 - \beta_t}{1 + \beta_t}},
\]

(7)

$E(l^+)$ and $E(l^-)$ being the energies of the final leptons $l^+$ and $l^-$ in the Higgs rest frame. $x$ and $x'$ are bounded by

\[
\frac{m_W^2}{m_t^2} \frac{1 - \beta_t}{1 + \beta_t} \leq x, x' \leq 1,
\]

(8)
assuming the narrow width approximation for the $W$–bosons in the top decay. The functions $f$ and $g$ are defined as follows (see [4]):

1. \[ \frac{m_W^2}{m_t^2} \geq \frac{1 - \beta_t}{1 + \beta_t} \]

\[
f(x) = \frac{3}{2W} \frac{\beta_t}{1 + \beta_t} \begin{cases} 
-2 \frac{m_W^2}{m_t^2} + \frac{m_W^4}{m_t^4} + 2x \frac{1 + \beta_t}{1 - \beta_t} - x^2 \left( \frac{1 + \beta_t}{1 - \beta_t} \right)^2 & : I_1 \\
1 - 2 \frac{m_W^2}{m_t^2} + \frac{m_W^4}{m_t^4} & : I_2 \\
1 - 2x + x^2 & : I_3 
\end{cases}
\]

\[
g(x) = \frac{3}{W} \frac{(1 + \beta_t)^2}{\beta_t} \begin{cases} 
-x \frac{m_W^2}{m_t^2} + x^2 \frac{1 + \beta_t}{1 - \beta_t} + x \ln \frac{m_W^2}{m_t^2} - x \ln \left( \frac{1 + \beta_t}{1 - \beta_t} \right) + \frac{1}{2} \left[ -2 \frac{m_W^2}{m_t^2} + \frac{m_W^4}{m_t^4} + 2x \frac{1 + \beta_t}{1 - \beta_t} - x^2 \left( \frac{1 + \beta_t}{1 - \beta_t} \right)^2 \right] & : I_1 \\
x - x \frac{m_W^2}{m_t^2} + x \ln \frac{m_W^2}{m_t^2} + \frac{1}{2} \left[ -2 \frac{m_W^2}{m_t^2} + \frac{m_W^4}{m_t^4} \right] & : I_2 \\
x - x^2 + x \ln x + \frac{1}{2} \left[ 1 - 2x + x^2 \right] & : I_3 
\end{cases}
\]

where the intervals $I_i$ are given by:

\[
I_1 : \frac{m_W^2}{m_t^2} \frac{1 - \beta_t}{1 + \beta_t} \leq x \leq \frac{1 - \beta_t}{1 + \beta_t}, \\
I_2 : \frac{1 - \beta_t}{1 + \beta_t} \leq x \leq \frac{m_W^2}{m_t^2}, \\
I_3 : \frac{m_W^2}{m_t^2} \leq x \leq 1.
\]

2. \[ \frac{m_W^2}{m_t^2} \leq \frac{1 - \beta_t}{1 + \beta_t} \]

\[
f(x) = \frac{3}{2W} \frac{1 + \beta_t}{\beta_t} \begin{cases} 
-2 \frac{m_W^2}{m_t^2} + \frac{m_W^4}{m_t^4} + 2x \frac{1 + \beta_t}{1 - \beta_t} - x^2 \left( \frac{1 + \beta_t}{1 - \beta_t} \right)^2 & : I_4 \\
-2x + x^2 + 2x \frac{1 + \beta_t}{1 - \beta_t} - x^2 \left( \frac{1 + \beta_t}{1 - \beta_t} \right)^2 & : I_5 \\
1 - 2x + x^2 & : I_6 
\end{cases}
\]
\[ g(x) = \frac{3}{W} \frac{(1 + \beta_t)^2}{\beta_t} \begin{cases} 
-x^2 + x^2 \frac{1 + \beta_t}{1 - \beta_t} + x \ln \frac{m_W^2}{m_t^2} - x \ln \left( \frac{1 + \beta_t}{1 - \beta_t} \right) 
+ \frac{1}{2} \left[ -2 \frac{m_W^2}{m_t^2} + \frac{m_W^4}{m_t^4} + 2x \frac{1 + \beta_t}{1 - \beta_t} - x^2 \left( \frac{1 + \beta_t}{1 - \beta_t} \right)^2 \right] & : I_4 \\
-x^2 + x^2 \frac{1 + \beta_t}{1 - \beta_t} + x \ln \frac{1 - \beta_t}{1 + \beta_t} + \frac{1}{2} \left[ -2x + x^2 \right] 
+ 2x \frac{1 + \beta_t}{1 - \beta_t} - x^2 \left( \frac{1 + \beta_t}{1 - \beta_t} \right)^2 & : I_5 \\
x - x^2 + x \ln x + \frac{1}{2} \left[ 1 - 2x + x^2 \right] & : I_6 
\end{cases} \]

with the intervals \( I_i \):

\[ \begin{align*}
I_4 & : \quad \frac{m_W^2}{m_t^2} \frac{1 - \beta_t}{1 + \beta_t} \leq x \leq \frac{m_W^2}{m_t^2}, \\
I_5 & : \quad \frac{m_W^2}{m_t^2} \leq x \leq \frac{1 - \beta_t}{1 + \beta_t}, \\
I_6 & : \quad \frac{1 - \beta_t}{1 + \beta_t} \leq x \leq 1,
\end{align*} \]

and

\[ W = \left( 1 - \frac{m_W^2}{m_t^2} \right)^2 \left( 1 + 2 \frac{m_W^2}{m_t^2} \right). \tag{9} \]

The normalizations of \( f \) and \( g \) are

\[ \int f(x) dx = 1, \]
\[ \int g(x) dx = 0. \tag{10} \]

The functions \( f \) and \( g \) represent the spin–independent and spin–dependent parts of the lepton spectrum in \( t \)--decay. Eq. (6) can also be written as

\[ \frac{1}{\Gamma} \frac{d\Gamma}{dx dx'} (H \rightarrow t\bar{t} \rightarrow l^+ l^- + \cdots) = S_t(x, x') + \Delta A_t(x, x'), \tag{11} \]
where
\[ S_t(x, x') = f(x)f(x') - \frac{1}{\beta_t^2} g(x)g(x'), \]
\[ A_t(x, x') = f(x')g(x) - f(x)g(x'), \]
\[ \Delta = \frac{2\text{Im}(ab^*)}{|a|^2\beta_t^2 + |b|^2}. \] (12)

\( S_t(x, x') \) and \( A_t(x, x') \) represent the symmetric and antisymmetric part of the energy correlation. These are plotted in Figs. (1a) and (1b).

The symmetric (\( CP \)-conserving) part of the two–dimensional distribution \( \frac{1}{\Gamma} \frac{d\Gamma}{dx dx'} \) does not depend on the coupling constants \( a \) and \( b \). This means that in the \( CP \)-conserving limit the energy correlation of secondary leptons arising from \( H \to t\bar{t} \) is independent of the \( CP \)-parity of the decaying Higgs particle.

Integration over \( x \) or \( x' \) yields the single lepton energy spectra
\[ \frac{1}{\Gamma} \frac{d\Gamma}{dx} (H \to t\bar{t} \to l^\pm + \cdots) = f(x) \pm \Delta g(x). \] (13)

Eq. (13) agrees with the energy spectrum obtained by Chang and Keung using a different method. The single energy spectra are plotted in Fig. 2. The parameter \( \Delta \) is calculated within a 2–Higgs Doublet Model in Refs. [5, 6].

3 \( H \to W^+W^- \)

The differential decay rate for the reaction \( H(P) \to W^+W^- \to l^+(q_1)\nu_l(q_2)l^-(q_3)\bar{\nu}_l(q_4) \), arising from the \( HW^+W^- \) vertex given in Eq. (4), is
\[ d^8\Gamma = 8\sqrt{2} \frac{G_F}{m_H} D_W \left[ |B|^2 S + \frac{|D|^2}{m_W^4} P + \frac{\text{Re}(BD^*)}{m_W^2} Q - \frac{\text{Im}(BD^*)}{m_W^2} R \right] \cdot dLips. \] (14)

The Lorentz invariant phase space is given by
\[ dLips = (2\pi)^4 \delta^{(4)}(P - q_1 - q_2 - q_3 - q_4) \prod_{i=1}^{4} \frac{d^3q_i}{(2\pi)^3 2q_i^0}. \] (15)
In the massless fermion approximation,

\[ S = (q_2 \cdot q_3)(q_1 \cdot q_4), \]
\[ P = -\left\{ (q_2 \cdot q_3)(q_1 \cdot q_4) - (q_2 \cdot q_4)(q_1 \cdot q_3) \right\}^2 + \frac{m_W^4}{4} \left\{ (q_2 \cdot q_3)^2 + (q_1 \cdot q_4)^2 + 2(q_2 \cdot q_4)(q_1 \cdot q_3) - \frac{m_W^4}{4} \right\}, \]
\[ Q = \varepsilon(q_1, q_2, q_3, q_4) \left\{ (q_2 \cdot q_3) + (q_1 \cdot q_4) \right\}, \]
\[ R = \left\{ (q_2 \cdot q_3) - (q_1 \cdot q_4) \right\} \left( \frac{m_W^4}{4} + (q_2 \cdot q_3)(q_1 \cdot q_4) - (q_2 \cdot q_4)(q_1 \cdot q_3) \right), \] (16)

while \( D_W \) is the propagator factor

\[ D_W = m_W^4 \prod_{j=1}^2 \frac{g^2}{(s_j - m_W^2)^2 + m_W^2 \Gamma_W^2}, \] (17)

with \( s_1 = (q_1 + q_2)^2, s_2 = (q_3 + q_4)^2 \). In the narrow width approximation, the total decay rate is given by

\[ \Gamma(H \to W^+W^- \to l^+\nu l^-\bar{\nu}) = \frac{g^6 m_H^3 \beta_W}{9 \cdot 2^{16} \pi^3 \Gamma_W^2} \left\{ 1 \right\} |B|^2 (3 - 2\beta_W^2 + 3\beta_W^4) + 8 |D|^2 \beta_W^2, \] (18)

in agreement with the result of Osland and Skjold \[1\].

We now introduce scaled energy variables in the \( H \) rest frame:

\[ y = \frac{4E(l^+)}{m_H}, \quad y' = \frac{4E(l^-)}{m_H}, \] (19)

which are bounded by

\[ 1 - \beta_W \leq y, y' \leq 1 + \beta_W, \] (20)

where \( \beta_W = \sqrt{1 - 4m_W^2/m_H^2} \). The two-dimensional spectrum in the variables \( y \) and \( y' \) is then given by

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dydy'}(H \to W^+W^- \to l^+\nu l^- + \cdots) = \frac{1}{|B|^2 (3 - 2\beta_W^2 + 3\beta_W^4) + 8 |D|^2 \beta_W^2} \cdot \frac{9}{32 \beta_W^6}.
\]
\[
\left\{ |B|^2 \left[ (3 + 2\beta_W^2 + 3\beta_W^4)((y - 1)^2 - \beta_W^2)((y' - 1)^2 - \beta_W^2) + 2\beta_W^2(1 - \beta_W^2)^2(y - y')^2 \right] + 4\beta_W^2|D|^2 \left[ ((y - 1)^2 + \beta_W^2)((y' - 1)^2 + \beta_W^2) - 4\beta_W^2(y - 1)(y' - 1) \right] + 8\beta_W^2\text{Im}(BD^*)(1 - \beta_W^2) \left[ \beta_W^2 - (y - 1)(y' - 1) \right] \right\}. \tag{21}
\]

Neglecting terms proportional to $|D|^2$, the correlation can be written as

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dydy'}(H \to W^+W^- \to l^+l^- + \cdots) = S_W(y, y') + \frac{\text{Im}(BD^*)}{|B|^2} A_W(y, y') + O(|D|^2/|B|^2). \tag{22}
\]

Here $S_W(y, y')$ and $A_W(y, y')$ represent the symmetric and antisymmetric parts of the energy correlation of the charged leptons, the latter being multiplied by the $CP$–violating coefficient $\text{Im}(BD^*)/|B|^2$. These functions are plotted in Figs. (3a) and (3b).

There is an interesting difference in the energy characteristics of the leptons emanating from $H \to W^+W^- \to l^+\nu_l l^-\bar{\nu}_l$, dependent on whether $H$ is a scalar $(0^+)$ or pseudoscalar $(0^-)$ particle. The correlated energy spectrum of the $l^+l^-$ pair can be derived from Eq. (21) by taking $D = 0$ (scalar case) or $B = 0$ (pseudoscalar case), with the result

\[
\frac{1}{\Gamma} \frac{d\Gamma(0^+)}{dydy'} = S_W(y, y') = \frac{9}{32\beta_W^6} \frac{1}{3 - 2\beta_W^2 + 3\beta_W^4} \left[ 2\beta_W^2(1 - \beta_W^2)^2(y - y')^2 + (3 + 2\beta_W^2 + 3\beta_W^4)((y - 1)^2 - \beta_W^2)((y' - 1)^2 - \beta_W^2) \right], \tag{23}
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma(0^-)}{dydy'} = P_W(y, y') = \frac{9}{64\beta_W^6} \left[ ((y - 1)^2 + \beta_W^2)((y' - 1)^2 + \beta_W^2) - 4\beta_W^2(y - 1)(y' - 1) \right]. \tag{24}
\]

These two functions are strikingly different, as shown in Figs. (3a) and (3c). This difference persists even if we consider the energy spectrum of a single lepton. Inte-
grating Eqs. (23, 24) over \( y' \), we have

\[
\frac{1}{\Gamma} \frac{d\Gamma(0^+)}{dy} = \frac{3}{2\beta_W} \frac{1 + \beta_W^4 - 2(y - 1)^2}{3 - 2\beta_W^2 + 3\beta_W^4}, \tag{25}
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma(0^-)}{dy} = \frac{3}{8\beta_W^3} (\beta_W^2 + (y - 1)^2). \tag{26}
\]

These distributions are clearly quite distinct (Fig. 4) and provide a simple criterion for distinguishing \( 0^+ \) and \( 0^- \) objects decaying into \( W^+W^- \) pairs. Indeed, the single lepton spectra (Eqs. (25), (26)) are also valid for the inclusive process \( H \to W^+W^- \to l^\pm X \), where only one of the \( W \)–bosons decays leptonically. The difference in the lepton energy spectrum for the \( 0^+ \) and \( 0^- \) cases is intimately related to the different helicity structure of the \( W \)–bosons produced in the two cases [8]. It should be stressed that the correlations and spectra given above (Eqs. (21)–(26)) refer directly to energies measured in the \( H \) rest frame, and do not require reconstruction of the decay planes of \( W^+ \) and \( W^- \). In this respect, the present criterion provides a useful alternative to other criteria that have recently been proposed in the literature [8, 9]. Finally, we note that the energy spectrum in the \( 0^+ \) case agrees with that obtained by Chang and Keung [3], after correction of a minor typographical error [F 2].

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Footnotes

[F 1 ] Some of the essential steps in the procedure of Ref. [3] can be found in Ref. [4].

[F 2 ] Eq. (15) of Ref. [4] should read

\[
\frac{1}{N} \frac{dN}{dx(l^\pm)} = \left( \frac{(1 + \beta_W^2)^2}{3 - 2\beta_W^2 + 3\beta_W^4} \right) \frac{3[\beta_W^2 - (1 - x)^2]}{4\beta_W^4} + \sum_{s=-1,+1} \ldots
\]
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Figure Captions

Fig. 1. CP–conserving (a) and CP–violating (b) part of the normalized energy correlation in the decay $H \rightarrow t\bar{t} \rightarrow l^+l^- + \cdots$ for $m_H = 400$ GeV and $m_t = 150$ GeV.

Fig. 2. Single particle energy spectra of $l^+$ (dotted curve) and $l^-$ (full curve) in the decay $H \rightarrow t\bar{t}$ for $\Delta = 0.1$, $m_H = 400$ GeV and $m_t = 150$ GeV.

Fig. 3. CP–conserving (a) and CP–violating (b) part of the normalized energy correlation in the decay $H \rightarrow W^+W^- \rightarrow l^+l^- + \cdots$ for $m_H = 300$ GeV. Fig. 3(c) shows the normalized energy correlation for the decay of a pseudoscalar Higgs $H \rightarrow W^+W^- \rightarrow l^+l^- + \cdots$ for $m_H = 300$ GeV.

Fig. 4. Energy distribution of a single lepton in the decay $H \rightarrow W^+W^- \rightarrow l^\pm + \cdots$ for $m_H = 300$ GeV. The full curve represents the scalar case and the dotted curve shows the pseudoscalar case.
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\[ \Gamma^{-1} \frac{d\Gamma}{dx} (H \rightarrow t\bar{t} \rightarrow l^\pm + \ldots) \]

\[ m_H = 400 \text{ GeV} \]
\[ m_t = 150 \text{ GeV} \]
\[ \Delta = 0.1 \]

**Fig. 2.**
$\Gamma^{-1} \frac{d\Gamma}{dy} (H \rightarrow W^+ W^- \rightarrow l^\pm + ...)$

Fig. 4.
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http://arxiv.org/ps/hep-ph/9408316v1
$S_W(y, y')$

$m_h = 300$ GeV

Fig. 3(a).
$A_W(y, y^l)$

$m_H = 300 \text{ GeV}$

Fig. 3(b).
$P_w(y, y')$

$m_H = 300 \text{ GeV}$

Fig. 3(c).
$S_t(x, x^1)$

$m_H = 400 \text{ GeV}$

$m_t = 150 \text{ GeV}$

Fig. 1(a).
\[ A_r(x, x^l) \]

\( m_H = 400 \text{ GeV} \)
\( m_\tau = 150 \text{ GeV} \)

Fig. 1(b).