# DECAYS OF SUPERSYMMETRIC HIGGS BOSONS INTO FERMIONS

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In the framework of the Minimal Supersymmetric Standard Model we investigated the decay channels of Higgs bosons $H(h,A), H^{\pm}$ into arbitrarily polarized fermions: $H(h,A)\to f\bar{f}$, $H^{+}\to f\bar{f}'$, $H(A)\to f\bar{f}'W^{-}$, $H^{+}\to f\bar{f}W^{+}$. Analytical expressions for the widths of these decays are obtained, the transverse spin asymmetries and the degree of longitudinal polarization of fermion are determined. The dependence of the asymmetries and the widths of the decays on the mass of the Higgs bosons are studied.

**Keywords:** Minimal Supersymmetric Standard Model, Higgs boson, fermion pair, decay width, helicity.
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## 1. INTRODUCTION

Standard model (SM) interactions of elementary particles is a combination theory of electroweak interactions based on the symmetry group $SU_L(2)\times U_Y(1)$ and Quantum Chromodynamics (QCD), based on a gauge group $SU_C(3)$. The Group $SU_L(2)\times U_Y(1)$ has satisfactorily describes electroweak interactions leptons, quarks and gauge bosons [1-3] and QCD-strong interactions of quarks and gluons [4, 5].

The amazing feature of CM is the phenomenon of spontaneous electroweak symmetry group violations as a result of which gauge bosons, the charged leptons and quarks are acquire mass [1-3]. A doublet of scalar fields $\varphi=\begin{pmatrix}\varphi^{+}\\ \varphi^{0}\end{pmatrix}$ is introduced into the theory, the neutral component of which has a vacuum value different from zero. As a result of the electroweak group $SU_L(2)\times U_Y(1)$ spontaneously broken to electromagnetic symmetry group $U_Q(1)$. Three of the four components of a scalar field $\varphi$ absorbed $W^{\pm}$- и $Z^{0}$-vector bosons. The fourth component neutral condition of the scalar field is the Higgs boson $H_{SM}$.

In various laboratories in the world carried out searches for Higgs bosons. Discover the Higgs boson $H_{SM}$ and study its physical properties was one of the main tasks of the large Hadron Collider (LHC). Finally, in 2012 year a scalar Higgs boson has been discovered at the LHC collider by the ATLAS and CMS collaborations [6.7] (see also reviews [8-10]), and this began a new phase of research to determine the nature of this particle.

It should be noted that along with SM, widely discussed in the literature the Minimal Supersymmetric Standard Model (MSSM) [11-13]. Here, in contrast to SM injected two doublet complex scalar field with hyper-charges-1 and 1

$$\varphi_1=\begin{pmatrix}H_1^{0}\\ H_1^{-}\end{pmatrix},\quad \varphi_2=\begin{pmatrix}H_2^{+}\\ H_2^{0}\end{pmatrix}.$$

To obtain the physical fields of the Higgs bosons, the fields $\varphi_1$ and $\varphi_2$ are represented in the form

$$\varphi_1=\frac{1}{\sqrt{2}}\begin{pmatrix}\upsilon_1+H_1^{0}+iP_1^{0}\\ H_1^{-}\end{pmatrix},$$
$$\varphi_2=\frac{1}{\sqrt{2}}\begin{pmatrix}H_2^{+}\\ \upsilon_2+H_2^{0}+iP_2^{0}\end{pmatrix}.$$

Here $H_1^0, P_1^0, H_2^0, P_2^0$ are fields that describe the excitation system on vacuum states $\langle\varphi_1\rangle=\frac{1}{\sqrt{2}}\upsilon_1$ and $\langle\varphi_2\rangle=\frac{1}{\sqrt{2}}\upsilon_2$.

Mixing fields $H_1^0$ and $H_2^0$, get CP-even Higgs bosons $H$ and $h$ (mixing angle $\alpha$):

$$\begin{pmatrix}H\\ h\end{pmatrix}=\begin{pmatrix}\cos\alpha & \sin\alpha\\ -\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}H_1^{0}\\ H_2^{0}\end{pmatrix}.$$

Similarly, mixing the fields $P_1^0$ and $P_2^0$, and also $H_1^{\pm}$ and $H_2^{\pm}$, we obtain a CP-odd Higgs boson $A$ and charged Higgs bosons $H^{+}$ and $H^{-}$ (mixing angle $\beta$):

$$\begin{pmatrix}G^{0}\\ A\end{pmatrix}=\begin{pmatrix}\cos\beta & \sin\beta\\ -\sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}P_1^{0}\\ P_2^{0}\end{pmatrix},$$

$$\begin{pmatrix}G^{\pm}\\ H^{\pm}\end{pmatrix}=\begin{pmatrix}\cos\beta & \sin\beta\\ -\sin\beta & \cos\beta\end{pmatrix}\begin{pmatrix}H_1^{\pm}\\ H_2^{\pm}\end{pmatrix}.$$

$G^0$ And $G^{\pm}$ − neutral and charged Goldstone bosons.

Consequently, after the spontaneous symmetry breaking, five Higgs particles appear in the MSSM: CP-even $h$- and $H$-bosons, CP-odd $A$-bison and charged $H^{+}$- and $H^{-}$-bosons.

In the MSSM, the Higgs sector is characterized by six parameters $M_h, M_H, M_A, M_{H^{\pm}}, \alpha$ and $\beta$. Of these,

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only two parameters are free, such parameters usually take the mass $M_A$ and the parameter $tg\beta$. This parameter is equal to the ratio $\frac{\upsilon_2}{\upsilon_1}$ and varies within

$$1 \le \tan\beta \le \frac{m_t}{m_b} = 35.5,$$

where $m_t = 173.2$ GeV and $m_b = 4.88$ GeV are the masses of $t$ - and $b$ -quarks.

The masses of CP- odd $h$ - and $H$ -bosons (charged $H^{\pm}$ -bosons) are expressed by the masses $M_A$ and $M_Z$ ($M_A$ and $M_W$):

$$M^2_{h(H)} = \frac{1}{2}[M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}], \quad M^2_{H^{\pm}} = M_A^2 + M_W^2 .$$

Figure 1 shows the dependence of the masses $h$ - , $H$ - and $H^+$ -bosons as a function of the mass of the pseudoscalar $A$ -boson at a value of the parameter $tg\beta = 3$ and masses $M_Z = 91.1875$ GeV, $M_W = 80.385$ GeV. With an increase the mass of the $A$ -boson from 100 GeV to 400 GeV, the mass of the light $h$ -boson varies from 60 GeV to 72.255 GeV while the masses of the $H(H^+)$ -bosons vary from 121.216 (128.303) GeV up to 403.85 (407.987) GeV.

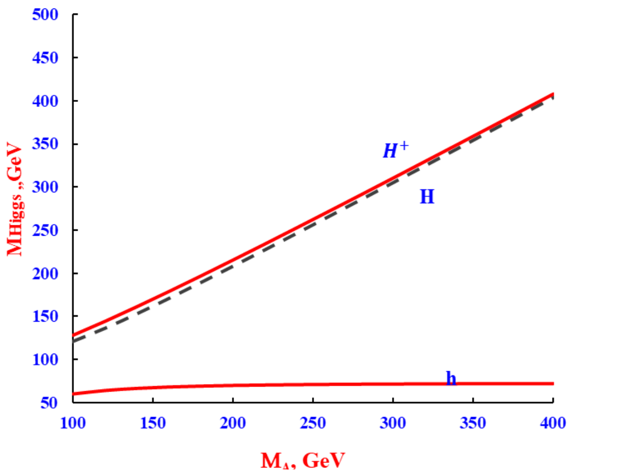


*Fig.1.* The dependence of the masses of the $h$ -, $H$ - and $H^+$ -bosons on the mass $M_A$

The mixing angles of the fields $\alpha$ and $\beta$ are related by:

$$\tan 2\alpha = \tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}, \quad \left(-\frac{\pi}{2} \le \alpha < 0\right).$$

We note that the decay channels of the standard Higgs boson have been studied in a number of works [2, 14-18]. In this paper we have studied the decays of the Higgs bosons of MSSM through channels:

$$h(H;A) \to f + \bar{f}, \tag{1}$$

$$H^+ \to f + \overline{f'}, \tag{2}$$

$$H(A) \to t + \bar{b} + W^-, \tag{3}$$

$$H^{\pm} \to b + \bar{b} + W^{\pm}, \tag{4}$$

Here $f\bar{f}$ ($f\overline{f'}$) is a fermion (lepton or quark) pair. These channels of Higgs bosons decay were previously considered in a number of papers (see [11] and there references to primary sources). However, in these papers the polarization states of fermions are not considered. Our analysis shows that the study of the polarization characteristics of fermions in these decays can provide valuable information on the nature of Higgs bosons. We obtained analytical expressions for the width of the reduced decays with allowance for arbitrary polarization of the fermions, the dependence of the decay width and spin asymmetries on the mass of the Higgs bosons was studied.

## 2. THE DECAYS OF $h(H;A) \to f + \bar{f}$

The Feynman diagram of the decay of a neutral Higgs boson into a fermion pair is shown in Fig. 2, where four impulses and the polarization vectors of the particles are written in parentheses.

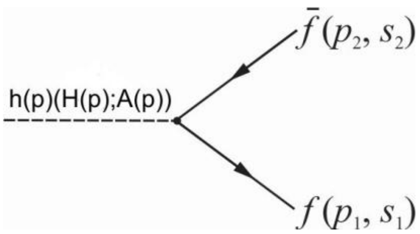


*Fig.2.* The Feynman diagram of the decay $h(H;A) \to f + \bar{f}$

MSSM claims that the $h$ - and $H$ -bosons are CP - even particles, and the $A$ -boson CP is odd. In this connection, we consider the decay of a boson $\Phi$ whose interaction with the fermion pair simultaneously contains the CP - even and odd components:

$$M(\Phi \to f\bar{f}) = g_{\Phi ff}[\bar{u}_f(p_1, s_1)(a + b\gamma_5)\upsilon_f(p_2, s_2)]\Phi(p), \tag{5}$$

where $g_{\Phi ff}$ is the interaction constant of the Φ-boson with the fermion pair, $a$ and $b$ are some constant parameters,, and for $a=1$ and $b=0$ we obtain the decay amplitudes of the CP-even $h$- and $H$-bosons, and for $a=0$ and $b=1$ it is the decay amplitude of the pseudoscalar $A$-boson, $\Phi(p)$ is the wave function of the Φ boson normalized to unity.

The width of the decay of the Φ boson into a fermion pair is proportional to the square of the matrix element (5):

$$\frac{d\Gamma(\vec{\xi}_1,\vec{\xi}_2)}{d\Omega}=\frac{\beta_f}{64\pi^2 M_\Phi}\left|M(\Phi\to f\bar{f})\right|^2=\frac{N_C\beta_f}{128\pi^2}g^2_{\Phi ff}M_\Phi\{|a|^2\beta_f^2[1+(\vec{\xi}_1\vec{\xi}_2)-2(\vec{n}\vec{\xi}_1)(\vec{n}\vec{\xi}_2)]+|b|^2[1-(\vec{\xi}_1\vec{\xi}_2)]+$$
$$+2\,\mathrm{Re}(ab^*)\beta_f[(\vec{n}\vec{\xi}_1)-(\vec{n}\vec{\xi}_2)]+2\,\mathrm{Im}(ab^*)\beta_f(\vec{n}[\vec{\xi}_1\vec{\xi}_2])\},\qquad(6)$$

where $N_C$ is the color factor ($N_C=1$ for the production of the lepton pair and $N_C=3$ for the production of the quark pair), $m_f$ and $M_\Phi$ are the fermion and Φ boson masses, $\beta_f=\sqrt{1-4\frac{m_f^2}{M_\Phi^2}}$ is the fermion velocity , $\vec{n}$ – is the unit vector along the fermion momentum, $\vec{\xi}_1$ and $\vec{\xi}_2$ – are unit vectors directed along the spins of the fermion and antifermion in their rest systems.

Suppose that the fermion pair is transversely polarized ($\vec{\xi}_1=\vec{\eta}_1$, $\vec{\xi}_2=\vec{\eta}_2$, $\vec{\eta}_1$ and $\vec{\eta}_2$ are the transverse components of the spin vectors of the fermion pair):

$$(\vec{n}\vec{\eta}_1)=(\vec{n}\vec{\eta}_2)=0\,.$$

In this case, the width of the decay $\Phi\to f+\bar{f}$ is:

$$\frac{d\Gamma(\vec{\eta}_1,\vec{\eta}_2)}{d\Omega}=\frac{N_C g^2_{\Phi ff}\beta_f}{128\pi^2}M_\Phi\{|a|^2\beta_f^2(1+\vec{\eta}_1\vec{\eta}_2)+|b|^2(1-\vec{\eta}_1\vec{\eta}_2)\}.\qquad(7)$$

From this formula it follows that if the transverse polarizations of the fermion pair are parallel $(\vec{\eta}_1\vec{\eta}_2=1)$, then the decay of the Φ-boson can occur only due to the CP-even interaction:

$$\frac{d\Gamma(\vec{\eta}_1\vec{\eta}_2=1)}{d\Omega}\sim|a|^2\beta_f^3\,.$$

The decay of the Φ boson due to CP-odd interaction can occur only for antiparallel transverse polarizations of the fermion pair $(\vec{\eta}_1\vec{\eta}_2=-1)$:

$$\frac{d\Gamma(\vec{\eta}_1\vec{\eta}_2=-1)}{d\Omega}\sim|b|^2\beta_f\,.$$

(8)

If the angle between the transverse polarization vectors of the fermion pair $\vec{\eta}_1$ and $\vec{\eta}_2$ is the $\varphi$, then the decay width of the a $\Phi\to f+\bar{f}$ takes the form:

$$\frac{d\Gamma(\vec{\eta}_1,\vec{\eta}_2)}{d\Omega}=\frac{N_C g^2_{\Phi ff}\beta_f}{128\pi^2}M_\Phi\{|a|^2\beta_f^2(1+\eta_1\eta_2\cos\varphi)+|b|^2(1-\eta_1\eta_2\cos\varphi)+2\,\mathrm{Im}(ab^*)\beta_f\eta_1\eta_2\sin\varphi\}.\qquad(10)$$

In this case, two types of transverse spin asymmetries can arise:

$$A_1=\frac{1}{\eta_1\eta_2}\frac{d\Gamma(\varphi=\frac{\pi}{2})/d\Omega-d\Gamma(\varphi=-\frac{\pi}{2})/d\Omega}{d\Gamma(\varphi=\frac{\pi}{2})/d\Omega+d\Gamma(\varphi=-\frac{\pi}{2})/d\Omega}=\frac{2\,\mathrm{Im}(ab^*)}{|a|^2+|b|^2},\qquad(11)$$

$$A_2=\frac{1}{\eta_1\eta_2}\frac{d\Gamma(\varphi=0)/d\Omega-d\Gamma(\varphi=\pi)/d\Omega}{d\Gamma(\varphi=0)/d\Omega+d\Gamma(\varphi=\pi)/d\Omega}=\frac{|a|^2-|b|^2}{|a|^2+|b|^2}.\qquad(12)$$

The transverse spin asymmetry $A_1$ differs from zero only in the case when the Φ-boson is a mixture of the CP-even and odd states, and this asymmetry can reach values of the order of 1 if the parameters $a$ and $b$ are approximately the same. For a pure CP state, one of the parameters $a$ and $b$ is zero, then the transverse spin asymmetry $A_2$ will be either +1 or -1, depending on whether the Higgs boson is a CP-even or an odd particle.

Now suppose that the fermion pair is longitudinally polarized:

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$$(\vec{n}\vec{\xi}_1) = \lambda_1, \ (\vec{n}\vec{\xi}_2) = -\lambda_2, \ (\vec{\xi}_1\vec{\xi}_2) = -\lambda_1\lambda_2,$$

where $\lambda_1$ and $\lambda_2$ are the helicities of the fermion and antifermion.

The total width of the decay of the $\Phi$ boson into a longitudinally polarized fermionic pair is:

$$\Gamma(\lambda_1,\lambda_2) = \frac{N_C\beta_f}{32\pi} g^2_{\Phi ff} M_\Phi \{[|a|^2\beta_f^2 + |b|^2](1+\lambda_1\lambda_2) + 2\,\mathrm{Re}(ab^*)\beta_f(\lambda_1+\lambda_2)\}. \quad (13)$$

It follows that in the decay of the $\Phi$-boson to the fermionic pair of the helicity of the fermion and antifermion must be the same ($\Phi \to f_R \overline{f_R}$ or $\Phi \to f_L \overline{f_L}$, where $f_R$ and $f_L$ are right-handed and left-handed polarized fermions). This is due to the conservation of the total angular momentum in the decay $\Phi \to f + \overline{f}$. We determine the degree of longitudinal polarization of the fermion in the decay of $\Phi \to f + \overline{f}$ by formula

$$P_f = \frac{\Gamma(\lambda_1 = 1) - \Gamma(\lambda_1 = -1)}{\Gamma(\lambda_1 = 1) + \Gamma(\lambda_1 = -1)} = \frac{2\,\mathrm{Re}(ab^*)\beta_f}{|a|^2\beta_f^2 + |b|^2}.$$

As can be seen, the degree of longitudinal polarization of the fermion, as well as the transverse spin asymmetries $A_1$ and $A_2$, is a source of information about the interference of the CP- even and CP-odd amplitudes in the decay $\Phi \to f + \overline{f}$.

The total width of the decay $\Phi \to f + \overline{f}$, summed over the spin states of the fermion pair, is given by:

$$\Gamma(\Phi \to f\overline{f}) = \frac{N_C\beta_f}{8\pi} M_\Phi g^2_{\Phi ff}[|a|^2\beta_f^2 + |b|^2].$$

According to the MSSM, the coupling constants of the $H_{SM}$, $h$, $H$ and $A$ bosons with a fermion pair are determined by the expressions given in Table 1.

Table1.
The Higgs coupling constants of bosons with a fermion pair in the MSSM

| $\Phi$ | $g_{\Phi tt}$ | $g_{\Phi bb}$ |
|---|---|---|
| $H_{SM}$ | $\frac{m_t}{\eta}$ | $\frac{m_b}{\eta}$ |
| $h$ | $\frac{m_t}{\eta}\frac{\cos\alpha}{\sin\beta}$ | $-\frac{m_b}{\eta}\frac{\sin\alpha}{\cos\beta}$ |
| $H$ | $\frac{m_t}{\eta}\frac{\sin\alpha}{\sin\beta}$ | $-\frac{m_b}{\eta}\frac{\cos\alpha}{\cos\beta}$ |
| $A$ | $\frac{m_t}{\eta} ctg\beta$ | $\frac{m_b}{\eta} tg\beta$ |

We note that in the table the $\eta$ is the vacuum value of the standard Higgs boson field

$$\eta = (\sqrt{2}G_F)^{-1/2} = 246\,\mathrm{GeV},$$

$G_F$ is the Fermi constant of weak interactions.

As follows from the decay width (15) and from Table 1, with increasing mass of the Higgs boson $M_\Phi$ and fermion $m_f$ the probability of $\Phi \to f + \overline{f}$ decay increases. Because of the smallness of the masses of the electron, muon, $u$-, $d$- and $s$-quarks, the decays $\Phi \to e^- + e^+, \Phi \to \mu^- + \mu^+, \Phi \to u + \overline{u}$, (14) $\Phi \to d + \overline{d}$ and $\Phi \to s + \overline{s}$ are suppressed. Higgs bosons $h$, $H$ and $A$ can decay into a pair of $\tau^-\tau^+$-leptons, and a pair of $c\overline{c}$-, $b\overline{b}$-quarks. The heavier $H$ and $A$-bosons can decay into a pair of $t$ -quarks.

Fig. 3 shows the dependence of the decay widths $\Gamma(H \to t\overline{t})$ and $\Gamma(A \to t\overline{t})$ on the mass of the Higgs boson at a parameter $tg\beta = 3$ and $m_t = 173.2$ GeV. As noted above, with increasing mass of the Higgs boson, the $H \to t\overline{t}$ decay widths increase. In addition, as seen from Fig.3, the width of the decay (15) $A \to t + \overline{t}$ predominates over the width of the decay $H \to t + \overline{t}$.

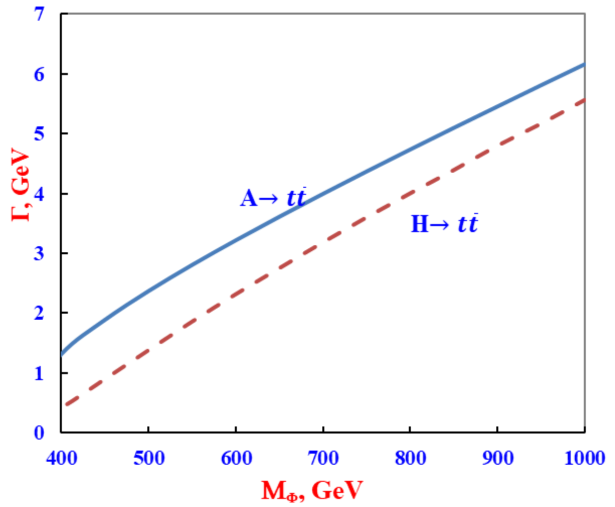


*Fig. 3.* The dependence of the decay widths $H \to t\overline{t}$ and $A \to t\overline{t}$ on the mass $M_\Phi$

### 3. THE DECAY OF $H^{\pm} \to f + \overline{f'}$

The charged Higgs boson can decay into a lepton pair $H^{+} \to l^{+} + \nu_l\,(H^{-} \to l^{-} + \bar{\nu}_l)$ or a quark pair $H^{+} \to t + \bar{b}$ $(H^{-} \to b + \bar{t}$ ). The Feynman diagram of the decay $H^{+} \to f + \overline{f'}$ is analogous to the diagram shown in Fig.2.

According to the MSSM, the matrix element of the decay $H^{+} \to f + \overline{f'}$ can be represented in the form:

$$M(H^{+} \to f + \overline{f'}) = -\frac{U_{ff'}}{\sqrt{2}\eta}\bar{u}_f(p_1, s_1)[m_f ctg\beta(1+\gamma_5) + m_{f'} tg\beta(1-\gamma_5)]\upsilon_{f'}(p_2, s_2)H^{+}(p)\,, \qquad (16)$$

here $U_{ff'}$ is an element of the Kobayashi-Maskawa matrix in the case of the creation of a quark pair $(f\overline{f'} = q\overline{q'})$ , and at the production of a lepton pair $U_{ff'} = 1$.

For the Higgs decay width of the boson on the polarized fermionic pair $H^{+} \to f + \overline{f'}$ the following expression is obtained:

$$\frac{d\Gamma(\vec{\xi}_1, \vec{\xi}_2)}{d\Omega} = \frac{|U_{ff'}|^2 N_C}{128\pi^2\eta^2} M_{H^+}\sqrt{(1 - r_f - r_{f'})^2 - 4r_f r_{f'}} \times \{[m_f^2 ctg^2\beta + m_{f'}^2 tg^2\beta]\cdot[1 - r_f - r_{f'} - 2\sqrt{r_f r_{f'}}(\vec{\xi}_1\vec{\xi}_2)] -$$
$$-(x_1 - 2r_f - 2\sqrt{r_f r_{f'}})(\vec{n}\vec{\xi}_1)(\vec{n}\vec{\xi}_2)] + [m_f^2 ctg^2\beta - m_{f'}^2 tg^2\beta]\times\sqrt{x_1^2 - 4r_f}\,[(\vec{n}\vec{\xi}_1) - (\vec{n}\vec{\xi}_2)] - 4m_f m_{f'}\sqrt{r_f r_f'} +$$
$$+(1 - r_f - r_f')[2m_f m_{f'}(\vec{\xi}_1\vec{\xi}_2) + (x_1 M_{H^+}^2 - 2m_f^2 - 2m_f m_{f'})(\vec{n}\vec{\xi}_1)(\vec{n}\vec{\xi}_2)] - M_{H^+}^2(x_1 - 4r_f)(\vec{n}\vec{\xi}_1)(\vec{n}\vec{\xi}_2)\}. \qquad (17)$$

The notations are introduced:

$$x_1 = \frac{2E_f}{M_{H^+}},\; r_f = \frac{m_f^2}{M_{H^+}^2},\; r_{f'} = \frac{m_{f'}^2}{M_{H^+}^2}\;.$$

In the case of the production of a transversely polarized fermion pair $(\vec{n}\vec{\xi}_1) = (\vec{n}\vec{\eta}_1) = 0$ , $(\vec{n}\vec{\xi}_2) = (\vec{n}\vec{\eta}_2) = 0$ and the decay width will take the form:

$$\frac{d\Gamma(\vec{\eta}_1, \vec{\eta}_2)}{d\Omega} = \frac{|U_{ff'}|^2 N_C}{128\pi^2\eta^2} M_{H^+}\sqrt{(1 - r_f - r_{f'})^2 - 4r_f r_{f'}} \times \{[m_f^2 ctg^2\beta + m_{f'}^2 tg^2\beta]\cdot[1 - r_f - r_{f'} - 2\sqrt{r_f r_{f'}}(\vec{\eta}_1\vec{\eta}_2)] -$$
$$-4m_f m_{f'}\sqrt{r_f r_f'} + 2m_f m_{f'}(1 - r_f - r_f')(\vec{\eta}_1\vec{\eta}_2)\} \qquad (18)$$

We determine the transverse spin asymmetry in the decay $H^{+} \to f + \overline{f'}$ by the relation:

$$A = \frac{d\Gamma(\vec{\eta}_1\vec{\eta}_2 = 1)/d\Omega - d\Gamma(\vec{\eta}_1\vec{\eta}_2 = -1)/d\Omega}{d\Gamma(\vec{\eta}_1\vec{\eta}_2 = 1)/d\Omega + d\Gamma(\vec{\eta}_1\vec{\eta}_2 = -1)/d\Omega} = = \frac{2\sqrt{r_f r_f'}(1 - r_f - r_{f'} - r_f ctg^2\beta - r_{f'} tg^2\beta)}{[1 - r_f - r_{f'}]\cdot[r_f ctg^2\beta + r_{f'} tg^2\beta] - 4r_f r_{f'}}. \qquad (19)$$

When a longitudinally polarized fermion pair is produced in the decay of $H^{+} \to f + \overline{f'}$ the total probability is expressed by the formula

$$\Gamma(\lambda_1, \lambda_2) = \frac{|U_{ff'}|^2 N_C}{32\pi\eta^2} M_{H^+}\sqrt{(1 - r_f - r_{f'})^2 - 4r_f r_{f'}}\{[m_f^2 ctg^2\beta + m_{f'}^2 tg^2\beta]\times$$
$$\times[1 - r_f - r_{f'} + (x_1 - 2r_f)\lambda_1\lambda_2] + [m_f^2 ctg^2\beta - m_{f'}^2 tg^2\beta]\times$$
$$\times\sqrt{x_1^2 - 4r_f}(\lambda_1 + \lambda_2) - 4m_f m_{f'}\sqrt{r_f r_f'} - (1 - r_f - r_f')(x_1 M_{H^+}^2 - 2m_f^2)\lambda_1\lambda_2\}. \qquad (20)$$

We determine the degrees of longitudinal polarization of the $t$-quark in the decay $H^{+} \to t+\bar{b}$ by the formula (with respect to the polarizations $b$-quark is summed)

$$P_t = \frac{\Gamma(\lambda_1=1)-\Gamma(\lambda_1=-1)}{\Gamma(\lambda_1=1)+\Gamma(\lambda_1=-1)} = \frac{[r_t ctg^2\beta - r_b tg^2\beta]\sqrt{(1-r_t-r_b)^2-4r_t}}{[r_t ctg^2\beta + r_b tg^2\beta](1-r_t-r_b)^2-4r_t r_b}. \quad (21)$$

Figure 4 shows the dependence of the transverse spin asymmetry (19) on the mass of the Higgs boson in the decay of $H^{+} \to t+\bar{b}$ at $m_t = 173.2$ GeV, $m_b = 4.88$ GeV and $tg\beta = 3$.

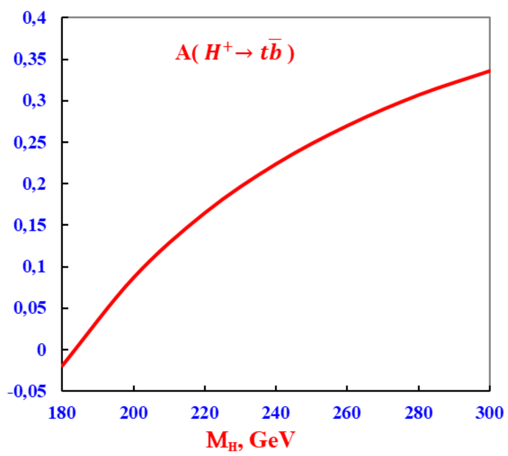


*Fig. 4.* The dependence of the transverse spin asymmetry on the mass $M_{H^+}$ in the decay $H^{+} \to t\bar{b}$.

Figure 5 illustrates the dependence of the degree of longitudinal polarization of the $t$-quark in the decay $H^{+} \to t+\bar{b}$ on the mass of the Higgs boson at $tg\beta = 3$ and $tg\beta = 30$.

Note that using the ATLAS detector in the process of producing a $t\bar{t}$-quark pair in proton-proton collisions at $\sqrt{s} = 7$ TeV the degree of longitudinal polarization of the $t$-quark was measured [19].

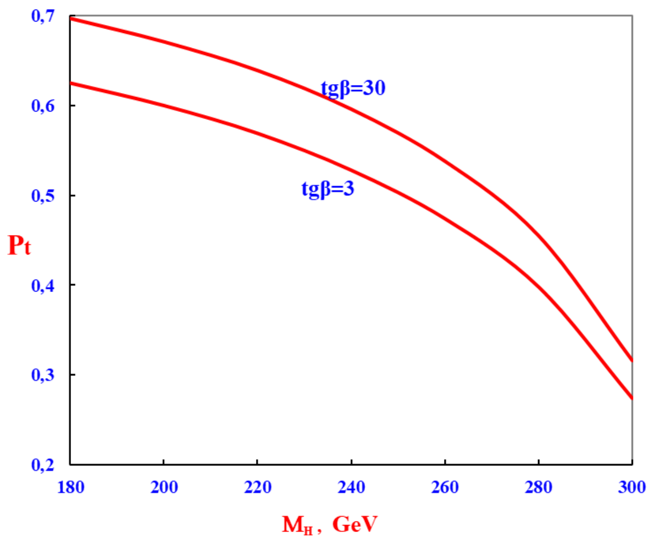


*Fig. 5.* The dependence of the degree of longitudinal polarization of the $t$-quark in the decay $H^{+} \to t\bar{b}$ on the mass $M_{H^+}$

The total decay width $H^{+} \to t\bar{b}$, summed over the polarization states of the quarks, is:

$$\Gamma(H^{+} \to t\bar{b}) = \frac{|U_{tb}|^2 N_C}{8\pi\eta^2} M_{H^+} \sqrt{(1-r_t-r_b)^2-4r_t r_b}\ [(m_t^2 ctg^2\beta + m_b^2 tg^2\beta)(1-r_t-r_b) - 4m_t m_b\sqrt{r_t r_b}]. \quad (22)$$

Fig. 6 illustrates the dependence of the total width of the decay $H^+ \to t\bar{b}$ on the Higgs mass of the boson $M_{H^+}$ at $tg\beta = 3$ and $tg\beta = 30$.

As can be seen, with increasing mass of the Higgs boson, the decay width increases, an increase in the parameter $tg\beta$ also leads to an increase in the width of the decay.

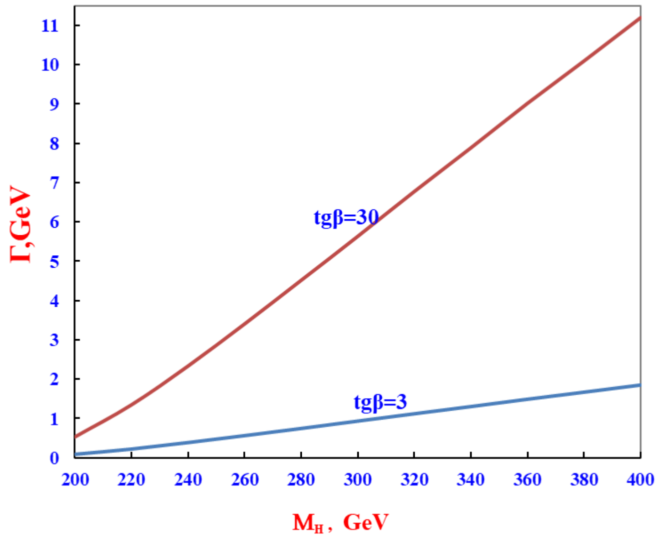


*Fig. 6.* Dependence of the decay width $\Gamma(H^+ \to t\bar{b})$ on the mass of $M_{H^+}$

## 4. THE DECAY OF $H(A) \to t + \bar{b} + W^-$

If the masses of the heavier $H$ and $A$ bosons are slightly less than the masses of the $t\bar{t}$-quark pair $M_H(M_A) < 2m_t$ ,then they can decay into the real and virtual top quarks:

$$H(A) \to t + \bar{t}^* \to t + \bar{b} + W^-,$$
$$H(A) \to \bar{t} + t^* \to \bar{t} + b + W^+.$$

The decay of $\Phi \to t + \bar{b} + W^-$ (where $\Phi \equiv H$ or $A$) is described by the Feynman diagram shown in Fig.7. In the MSSM, the matrix element corresponding to this diagram can be written as:

$$M(\Phi \to t\bar{b}W^-) = g_{\Phi tt}\frac{g_w}{2\sqrt{2}}U^*_\mu(k)\,[\bar{u}(p_1,s_1)\hat{O}\frac{\hat{p}-\hat{p}_1-m_t}{(p-p_1)^2-m_t^2+im_t\Gamma_t}\gamma_\mu(1+\gamma_5)\upsilon(p_2,s_2)], \qquad (23)$$

where $U^*_\mu(k)$ is the 4-vector polarization of the $W^-$ − boson, $g_w$ is the interaction constant of the $W$ boson with the quark pair $t\bar{b}$, related to the Fermi constant by the relation $\frac{g_w}{8M_w^2} = \frac{G_F}{\sqrt{2}}$, $\Gamma_t$ is the decay width of the $t$-quark, and the matrix $\hat{O}$ depends on the scalarity or pseudoscalarity of $\Phi$-boson:
for $\Phi \equiv H$ the $\hat{O}$ is the identity matrix ($\hat{O} = I$), and in the case $\Phi \equiv A$ the $\hat{O} = \gamma_5$.

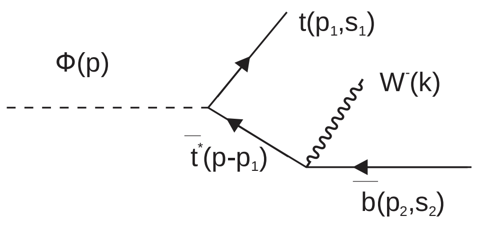


*Fig. 7.* The Feynman diagram of the decay $\Phi \to t\bar{b}W^-$

After squaring the amplitude of the process $\Phi \to t + \bar{b} + W^-$ we will have:

$$\left|M(\Phi \to t\bar{b}W^-)\right|^2 = \frac{g_{\Phi tt}^2 g_w^2}{8M_\Phi^4[(1-x_t)^2 + r_t\gamma_t]} G_{\mu\nu} I_{\mu\nu}(\Phi \to t\bar{b}W^-), \tag{24}$$

where the notations are introduced:

$$x_t = \frac{2E_t}{M_\Phi}, \; r_t = \left(\frac{m_t}{M_\Phi}\right)^2, \; \gamma_t = \left(\frac{\Gamma_t}{M_\Phi}\right)^2,$$

$G_{\mu\nu}-$ is the $W$ boson tensor arising when summing over the polarization states of the vector boson

$$G_{\mu\nu} = \sum_{pol} U_\mu^*(k) U_\nu(k) = -g_{\mu\nu} + \frac{k_\mu k_\nu}{M_w^2}, \tag{25}$$

and $I_{\mu\nu}(\Phi \to t\bar{b}W^-)$ is the quark tensor, which is given in Appendix $A$.

The product of the $W$-boson and quark tensors $G_{\mu\nu} I_{\mu\nu}(\Phi \to t\bar{b}W^-)$ is given in Appendix $B$.

The width of the Higgs boson decay of the $\Phi \to t + \bar{b} + W^-$ channel is expressed by the formula

$$d\Gamma(\Phi \to t + \bar{b} + W^-) = \frac{(2\pi)^4}{2M_\Phi}\left|M(\Phi \to t\bar{b}W^-)\right|^2 \frac{d\vec{k}}{(2\pi)^3 2E_w} \frac{d\vec{p}_1}{(2\pi)^3 2E_t} \frac{d\vec{p}_2}{(2\pi)^3 2E_b} \delta(p - p_1 - p_2 - k). \tag{26}$$

We define the quark spectrum in the case of the production of a longitudinally polarized $t$-quark . For this, we must take the integral over the phase volume of the vector $W$-boson. Then the expression for the decay width will have the form:

$$d\Gamma(\Phi \to t + \bar{b} + W^-) = \frac{1}{16(2\pi)^5 M_H} \int \frac{\overline{\left|M(\Phi \to t\bar{b}W^-)\right|^2}}{E_w E_t E_b} d\vec{p}_1 d\vec{p}_2 \delta(M_\Phi - E_t - E_b - E_w), \tag{27}$$

where the bar over the square of the matrix element means that is summed over the polarizations of the $\bar{b}$ - antiquark. Integrating now over the emission angles of $t$- and $b$-quarks, for the decay width $\Phi \to t + \bar{b} + W^-$ we obtain expression:

$$\frac{d\Gamma(\Phi \to t + \bar{b} + W^-)}{dx_t dx_b} = \frac{1}{2} \frac{d\Gamma_0(\Phi \to t + \bar{b} + W^-)}{dx_t dx_b}(1 + \lambda_1 P_t) \tag{28}$$

Here

$$\frac{d\Gamma_0(\Phi \to t + \bar{b} + W^-)}{dx_t dx_b} = \frac{g_{\Phi tt}^2 G_F}{32\sqrt{2}\pi^3} \frac{M_\Phi}{(1-x_t)^2 + r_t\gamma_t} f_1 \tag{29}$$

the width of the decay $\Phi \to t + \bar{b} + W^-$ at the creation of polarized quarks, $\lambda_1$ is helicity of the $t$-quark, and $P_t$ is its degree of longitudinal polarization

$$P_t = \frac{f_2}{f_1}, \tag{30}$$

the functions $f_1$ and $f_2$ are obtained from the product of the $G_{\mu\nu} I_{\mu\nu}(\Phi \to t\bar{b}W^-)$, tensors given in Appendix $B$ .In the decay of the scalar boson $H \to t + \bar{b} + W^-$ the functions are equal to:

$$f_1 = r_w[x_b(x_t - 4r_t) + (4r_t - 1)(1 - x_w + r_w - r_t - r_b)] +$$

$$+ (1 - x_t + r_t - r_w - r_b)[x_w(x_t - 4r_t) + (4r_t - 1)(1 - x_b + r_b - r_w - r_t)],$$

$$f_2 = r_w\{\sqrt{x_t^2-4r_t}\,[x_b(x_t+\frac{5}{2}-2r_t)-2(1+r_w+r_t-r_b)]+$$

$$+\frac{x_t}{\sqrt{x_t^2-4r_t}}(x_t-\frac{1}{2}-2r_t)[2(1-x_w+r_w-r_t-r_b)-x_t x_b]\}+$$

$$+(1-x_t+r_t-r_w-r_b)\{[x_b(x_t+\frac{1}{2}-2r_t)-x_t-2(r_b+r_t-r_w)]\sqrt{x_t^2-4r_t}+$$

$$+(x_t-\frac{1}{2}-2r_t)[2(1-x_b-r_t-r_w+r_b)-x_t x_w]\frac{x_t}{\sqrt{x_t^2-4r_t}}\}; \qquad (31)$$

In the decay of the pseudoscalar boson $A \to t+\bar{b}+W^-$ these functions are given by expressions:

$$f_1 = r_w[x_t x_b - 1 + x_w + r_t + r_b - r_w] + (1-x_t+r_t-r_w)(x_t x_w - 1 + x_b - r_b + r_t + r_w);$$

$$f_2 = r_w[(1+r_t)x_b\sqrt{x_t^2-4r_t} - \frac{x_t r_t}{2\sqrt{x_t^2-4r_t}}(2(1-x_t-x_b-r_w+r_b+r_t)+x_t x_b)]+$$

$$+(1-x_t+r_t+r_w-r_b)[(x_t+r_t x_w)\sqrt{x_t^2-4r_t}-(x_b-x_w-x_t+x_t x_w+2(r_w+r_t-r_b))\frac{r_t x_t}{\sqrt{x_t^2-4r_t}}] \qquad (32)$$

Here $x_b = \dfrac{2E_{\bar{b}}}{M_\Phi}$, $x_w = \dfrac{2E_w}{M_\Phi} = 2 - x_t - x_b$ are the scaling energies of the antiquark $\bar{b}$ - and $W$ -boson,

$$r_w = \left(\frac{M_w}{M_\Phi}\right)^2, \qquad r_b = \left(\frac{m_b}{M_\Phi}\right)^2.$$

Figure 8 shows the dependence of the longitudinal polarization degree of the $t$ -quark on the scaling energy $x_t$ at $M_\Phi = 300\,\text{GeV}$, $x_b = 0{,}3$ and $M_w = 80.385\,\text{GeV}$. As follows from the figure, with increasing $t$ -quark energy, the degree of its longitudinal polarization in $H \to t+\bar{b}+W^-$ decay decreases, and in the decay of $A \to t+\bar{b}+W^-$ increases.

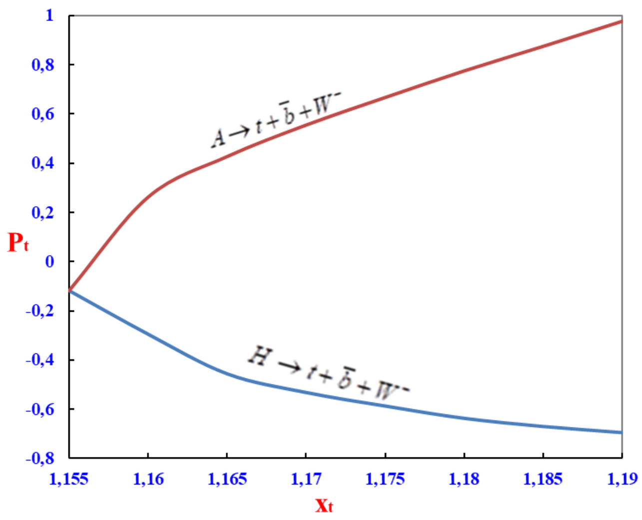


*Fig. 8.* Energy dependence of the degree of longitudinal polarization of the $t$ -quark

## 5. THE DECAY OF $H^{\pm} \to b + \bar{b} + W^{\pm}$

If the mass of the charged Higgs boson is $M_{H^{\pm}} < m_t + m_b$, then the decay of this boson into a virtual $t$-quark and the real $b$ - antiquark is possible, and $t$-quark can decay into a $W^+$ vector boson and $b$ is a quark. Thus, one of the possible decays of a charged Higgs boson is the $H^+ \to \bar{b} + t^* \to b + \bar{b} + W^+$ process. This decay is described by the Feynman diagram shown in Fig. 9.

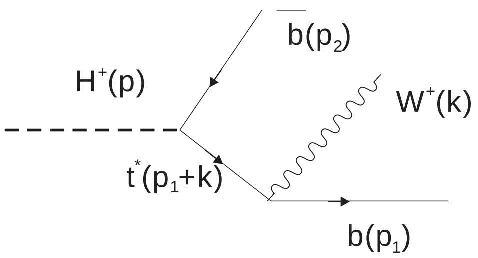


Fig. 9. The Feynman diagram of $H^+ \to b\bar{b}W^+$ decay.

The matrix element of the decay $H^+ \to b + \bar{b} + W^+$ can be represented in the form:

$$M(H^+ \to b\bar{b}W^-) = \frac{g_w}{2\sqrt{2}} \frac{U_{tb}}{\sqrt{2}\eta} U_\mu(k) \times$$

$$\times \bar{u}(p_1)\gamma_\mu(1+\gamma_5)\frac{\hat{p}_1 + \hat{k} + m_t}{(p_1+k)^2 - m_t^2 + im_t\Gamma_t}[m_b tg\beta(1-\gamma_5) + m_t ctg\beta(1+\gamma_5)]\upsilon(p_2). \tag{33}$$

On the basis of this matrix element for the width of the $H^+ \to b + \bar{b} + W^+$ decay, we have expression:

$$\frac{d\Gamma(H^+ \to b\bar{b}W^+)}{dx_1 dx_2} = \frac{3G_F^2 M_{H^+}^3 |U_{tb}|^2}{32\pi^3[(1-x_2+r_b-r_t)^2 + r_t\gamma_t]}\{m_b^2[tg^2\beta(x_2-2r_b) - 2r_t]\times$$

$$\times[r_w(3(1-x_2-r_w)+2r_b) + (1-x_2-r_w)^2] + [m_t^2 r_t ctg^2\beta - m_b^2 tg^2\beta(1-x_2+r_b)]\times$$

$$\times[r_w(1-x_w+r_w-2r_b) + (1-x_1-r_w)(1-x_2+r_w)]\}. \tag{34}$$

Here $x_1$ and $x_2$ are the scaling energies of the quark $b$ and antiquark $\bar{b}$, and $r_t$, $r_b$ and $r_w$ are given above.

If the mass of a charged Higgs boson is $M_{H^+} > 90$ GeV, then $b$-quark mass $m_b$ can be neglected in the decay width (34). In this case, the width of the $H^+ \to b + \bar{b} + W^+$ decay is greatly simplified:

$$\frac{d\Gamma(H^+ \to b\bar{b}W^+)}{dx_1 dx_2} = \frac{3G_F^2 M_{H^+}|U_{tb}|^2 m_t^4 ctg^2\beta}{32\pi^3[(1-x_2-r_t)^2 + r_t\gamma_t]}[r_w(x_1+x_2-1) + (1-x_1-r_w)(1-x_2+r_w)]. \tag{35}$$

Integrating this expression with respect to the variables $x_1$ and $x_2$, for the total decay width $H^+ \to b + \bar{b} + W^+$ we obtain the expression:

$$\Gamma(H^+ \to b + \bar{b} + W^+) = \frac{3G_F^2 m_t^4 ctg^2\beta}{64\pi^3} M_{H^+}\{\frac{r_w^2}{r_t^3}(4r_w r_t + 3r_t - 4r_w)\ln\frac{r_t - r_w}{r_w(r_t-1)} +$$

$$+(3r_t^2 - 4r_t - 3r_w^2 + 1)\ln\frac{r_t - r_w}{r_t - 1} - \frac{5}{2} + \frac{1-r_w}{r_t^2}(3r_t^3 - r_t r_w - 2r_t r_w^2 + 4r_w^2) + r_w(4 - \frac{3}{2}r_w)\}. \tag{36}$$

This expression of the decay width is valid for a mass of a charged Higgs boson $M_{H^+} < m_t + m_b - \Gamma_t$.

Fig.10 illustrates the dependence of the decay width $\Gamma(H^+ \to b\bar{b}W^+)$ on the mass of Higgs the boson $M_{H^+}$. It is evident that with an increase in the mass of the charged Higgs boson, the width of its decay along the channel $H^+ \to \bar{b} + t^* \to b + \bar{b} + W^+$ increases from 5.838 MeV to 6.415 MeV, and then monotonically decreases to 0.675 MeV.

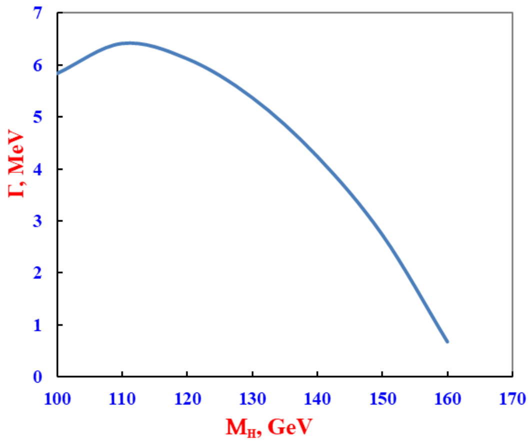


*Fig. 10.* The dependence of the decay width $H^+ \to b\bar{b}W^+$ on the mass $M_{H^+}$

**CONCLUSION**.

Within the framework of the MSSM, we discussed the decays of neutral and charged Higgs bosons into polarized fermions: $h(H;A) \to f + \bar{f}$, $H^+ \to f + \bar{f}'$, $H(A) \to t + \bar{b} + W^-$ and $H^{\pm} \to b + \bar{b} + W^{\pm}$. Analytical expressions for the widths of these decays are obtained, transverse spin asymmetries and the degree of longitudinal polarization of fermions are determined. The dependence of the asymmetries and the widths of the decays on the mass of the Higgs bosons are studied. Numerical calculations are presented in the form of graphs for the decay channels $H(A) \to t + \bar{t}$, $H^+ \to t + \bar{b}$, $H(A) \to t + \bar{b} + W^-$ and $H^+ \to b + \bar{b} + W^+$.

**APPENDIX** $A$

Here we give the quark tensor expression in $H \to t + \bar{b} + W^-$ and $A \to t + \bar{b} + W^-$ decays.

In the decay of $H \to t + \bar{b} + W^-$

$$I_{\mu\nu}(H \to t\bar{b}W^-) = 4[(p \cdot p_1) - 2m_t^2][(p, p_2)_{\mu\nu} + m_b(p, s_2)_{\mu\nu}] + +2(4m_t^2 - M_H^2)[(p_1, p_2)_{\mu\nu} +$$

$$+ m_b(p_1, s_2)_{\mu\nu}] + 4m_t(p \cdot s_1)[(p, p_2)_{\mu\nu} + m_b(p, s_2)_{\mu\nu}] + 2m_t[2(p \cdot p_2) - M_H^2 - 2m_t^2] \times$$
$$\times [(s_1, p_2)_{\mu\nu} + m_b(s_1, s_2)_{\mu\nu}] + 8m_t(p \cdot p_1)[(p_2, s_1)_{\mu\nu} + m_b(s_2, p_1)_{\mu\nu}];$$

In the decay of $A \to t + \bar{b} + W^-$

$$I_{\mu\nu}(A \to t\bar{b}W^-) = 4(p \cdot p_1)[(p, p_2)_{\mu\nu} + m_b(p, s_2)_{\mu\nu}] - 2M_A^2[(p_1, p_2)_{\mu\nu} + m_b(p_1, s_2)_{\mu\nu}] +$$

$$+ 4m_t(p \cdot s_1)[(p, p_2)_{\mu\nu} + m_b(p, s_2)_{\mu\nu}] + +4m_t^3[(s_1, p_2)_{\mu\nu} + m_b(s_1, s_2)_{\mu\nu}].$$

We note that $(b, c)_{\mu\nu}$ denotes a brief notation of the tensor

$$(b, c)_{\mu\nu} = b_\mu c_\nu + c_\mu b_\nu - (b \cdot c) g_{\mu\nu},$$

where $b$ and $c$ are arbitrary 4-particle vectors.

**APPENDIX *B***

Consider the product of the tensor $G_{\mu\nu}=-g_{\mu\nu}+\dfrac{k_\mu k_\nu}{M_w^2}$ on the tenzor

$$(p,p_2)_{\mu\nu}=p_\mu p_{2\nu}+p_\nu p_{2\mu}-(p\cdot p_2)g_{\mu\nu}:$$

$$(-g_{\mu\nu}+\frac{k_\mu k_\nu}{M_w^2})\cdot[p_\mu p_{2\nu}+p_{2\mu}p_\nu-(p\cdot p_2)g_{\mu\nu}]=-(p\cdot p_2)-(p_2\cdot p)+4(p\cdot p_2)+$$

$$\frac{1}{M_w^2}[(p\cdot k)(p_2\cdot k)+(p_2\cdot k)(p\cdot k)-k^2(p\cdot p_2)]=2(p\cdot p_2)+\frac{2}{M_w^2}(p\cdot k)(p_2\cdot k)-(p\cdot p_2)=$$

$$=(p\cdot p_2)+\frac{2}{M_w^2}(p\cdot k)(p_2\cdot k).$$

As a result, for the product of $G_{\mu\nu}\,I_{\mu\nu}(H\to t\bar{b}W^-)$ tensors in the decay $H\to t+\bar{b}+W^-$ we obtain :

$$G_{\mu\nu}\,I_{\mu\nu}(H\to t\bar{b}W^-)=4[(p\cdot p_1)-2m_t^2]\cdot[(p\cdot p_2)+m_b(p\cdot s_2)]+2(4m_t^2-M_H^2)\times$$

$$\times[(p_1\cdot p_2)+m_b(p_1\cdot s_2)]+2m_t[2(p\cdot p_1)-M_H^2-2m_t^2]\cdot[(p_2\cdot s_1)+m_b(s_2\cdot s_1)]+$$

$$+8m_t(p\cdot p_1)[(p_2\cdot s_2)+m_b(s_2\cdot s_1)]+\frac{2}{M_w^2}\{4[(p\cdot p_1)-2m_t^2](k\cdot p)+2(4m_t^2-M_H^2)(k\cdot p_1)+$$

$$+4m_t(p\cdot s_1)(k\cdot p)+2m_t[2(p\cdot p_1)-M_H^2-2m_t^2](k\cdot s_1)+8m_t(p\cdot p_1)(k\cdot s_1)\}\cdot[(k\cdot p_2)+m_b(k\cdot s_2)];$$

In the decay of a pseudoscalar $A-$ boson the product of these tensors is given by:

$$G_{\mu\nu}\,I_{\mu\nu}(A\to t\bar{b}W^-)=4(p\cdot p_1)\cdot[(p\cdot p_2)+m_b(p\cdot s_2)]-2M_H^2[(p_1\cdot p_2)+m_b(p_1\cdot s_2)]+$$

$$+4m_t(p\cdot s_1)[(p\cdot p_2)+m_b(p\cdot s_2)]+4m_t^3[(s_1\cdot p_2)+m_b(s_1\cdot s_2)]+\frac{2}{M_w^2}[4(p\cdot p_1)(k\cdot p)-2M_H^2(k\cdot p_1)+$$

$$+4m_t(p\cdot s_1)(k\cdot p)+4m_t^3(k\cdot s_1)]\cdot[(k\cdot p_2)+m_b(k\cdot s_2)].$$

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