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ABSTRACT

of the submitted dissertation for the degree of Doctor of Philosophy

HIGGS BOSONS DECAYS CHANNELS IN THE MINIMAL SUPERSYMMETRIC STANDARD MODEL

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Field of science: Physics

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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and degree of elaboration. One of the most interesting and rapidly developing areas of modern physics is high-energy elementary particle physics. The Standard Model (SM), based on the local gauge symmetry group $SU_C(3)$ Ч $SU_L(2)$ Ч $U_Y(1)$, describes fundamental particles (quarks, leptons) and the strong, weak, and electromagnetic interactions between them. This model also explains the producing of the scalar Higgs boson field as a result of the spontaneous breaking of the local gauge symmetry $SU_L(2)$ and gaining mass of particles due to the Higgs mechanism.

With the discovery of the Higgs boson with a mass of 125 GeV at the LHC (Large Hadron Collider) by the ATLAS and CMS collaborations, a new page was opened in elementary particle physics and it went down in history as the most brilliant event of recent decades. Therefore, the investigation of the processes involving the Higgs boson in high-energy physics and making measurements more accurate in experiments will remain relevant for the next decades.

The discovery of $W^{\pm}$, Z^0 and H- bosons, whose existence was predicted by SM, was a brilliant victory of this theory. However, despite SM's great achievements in the description of phenomena related to elementary particles, this theory also has its own shortcomings. Irregular distribution of the masses of leptons and quarks in a wide range (the smallest mass electron is 340,000 times lighter than the largest ball quark), the great effect of virtual vacuum particles on the mass of the Higgs boson, the mass of neutrinos and their mixing, the imbalance of matter and antimatter in nature, the absence of any candidates for dark (hidden) matter particles is a drawback of SM. Solving all these issues suggests a new physics behind the SM, and in this regard, the most discussed physical model is the Minimal Supersymmetric Standard Model (MSSM).

The main goal of the LHC and future electron-positron and muon-antimuon colliders (ILC, CLIC, FCC-ee, CEPC, MC) is to detect with great precision $H, h, A, H^{\pm}$ Higgs bosons and their physical characteristics – mass, partial width, full width, to measure the interaction constants between $W^{\pm}$ and Z^0 bosons, leptons and quarks, chargeinos, neutralinos and scalar fermions and them, as well as the interaction constant of the Higgs bosons themselves. It is great interest to study the processes taking place with the participation of Higgs bosons, taking into account the polarization states of particles, in solving such actual issues. Theoretical studing of the degrees of longitudinal and transverse polarization of fermions produced in the decay channels of neutral H, h, A and charged $H^{\pm}$ Higgs bosons, degrees of circular and linear polarization of γ-quanta, as well as distributions of final particles according to energy and angles CP-pair, partial and full decay widths of Higgs bosons, masses and interaction constants with other particles and with each other can be obtained.

Object and subject of research. The processes occurring on the cleavage channels of Higgs bosons H, h, A and $H^{\pm}$ of MSSM were taken as the object of research in the dissertation. The main subject of the study is the spin effects produced in these processes due to the consideration of possible polarization of particles.

The goals and objectives of the dissertation. The main goal of the dissertation is to theoretically study a number of decay channels of neutral H, h, A and charged $H^{\pm}$ Higgs bosons of the MSSM and to analyze various spin effects in these processes.

In order to achieve the goal of the dissertation, the following issues have been put forward:

1. To calculate the differential and full widths of the $H(h, A) \to ff$ and $H^{\pm} \to ff'$ decay processes, taking into account the arbitrary polarization states of the fermion and antifermion, to determine the characteristics that can provide information about the CP-parity of Higgs bosons.

2. To determine the spiral amplitudes, differential and full widths of the $H \to Zff$ and $H^{\pm} \to Wff'$ decay channels, to study the dependence of the full probabilities on the mass of the Higgs boson.

3. To explore the decay channels of H and A bosons $H(A) \to t\bar{t}^* \to t\bar{b}W^-$, $H(A) \to \bar{t}t^* \to \bar{t}bW^+$, to study the dependence of the longitudinal polarization degrees of t- and b-quarks on quark energy.

4. To obtain the formulas of the full probabilities of the decay channels $H \to ZZ^*$, $H \to WW^*$, $H \to AZ^*$, $A \to hZ^*$, $H^{\pm} \to H(h; A)W^{\pm}$ ($Z^* \to ff, W^* \to ff'$) of Higgs bosons, to study the dependence of the probabilities on the masses of Higgs bosons and $tg\beta$parameter.

5. To calculate the t-quark and W-boson loop diagrams that give full widths of the Higgs bosons decay channels $H(h;A)\to\gamma\gamma$, $H(h;A)\to\gamma Z$, $H^{\pm}\to\gamma W^{\pm}$, $H(h;A)\to gg$.

6. To calculate the probabilities of Higgs bosons $H\to hb\bar{b}$, $A\to Zhh$, $H^{\pm}\to W^{\pm}hh$, $H^{\pm}\to W^{\pm}b\bar{b}$ decay channels and to explore their dependence on the mass of Higgs bosons.

7. To calculate the degrees of circular and linear polarization of the γ-quantum in radiation decays of Higgs bosons into fermion-antifermion pairs $H(h;A)\to ff\gamma$.

8. To get the formulas of the probabilities of the Higgs bosons $H(h;A)\to\tilde{\chi}_i^{-}\tilde{\chi}_j^{+}$, $H(h;A)\to\tilde{\chi}_i^{0}\tilde{\chi}_j^{0}$, $H^{\pm}\to\tilde{\chi}_i^{\pm}\tilde{\chi}_j^{0}$ decay channels and to analyze certain spin effects in the processes.

Research methods. Feynman diagram technique, the most reliable research methods of quantum field theory, theoretical and mathematical physics, elementary particle physics tested for many years were used in the dissertation work.

The main scientific provisions are obtained as follows:

1. Decaying of a CP-even (odd) Higgs boson into a transversely polarized fermion-antifermion pair is possible only if their transverse spin vectors are parallel $(\vec{\eta}_1\vec{\eta}_2)=1$ (antiparallel $(\vec{\eta}_1\vec{\eta}_2)=-1$).

2. The fermion and antifermion produced in the $H(h;A)\to ff$ decay must have the same helicity $f_R f_R$ or $f_L f_L$. The degree of longitudinal polarization P_f of the fermion can give some information about the CP-parity of the decaying Higgs boson.

3. The width of the decaying $H(A)\to\tau^{-}\tau^{+}$ increases with the increase of the mass $M_H(M_A)$, but the full width of the decaying $h\to\tau^{-}\tau^{+}$ decreases with the increase of the mass M_h.

4. The full width of the decay channel of the Higgs boson $H\to hh^{*}\to hb\bar{b}$ first increases with the increase in mass M_H and reaches its maximum value at $M_H=144.62$ GeV, with further increase in mass, the width of the decay begins to decrease.

5. The degree of longitudinal polarization of the t-quark in the $H(A)\to t\bar{b}W^{-}$ decay first decreases with an increase in its $x_t=2E_t/M_H$ $(2E_t/M_A)$ energy, and then gradually increases.

6. γ-quantum produced in $H(h;A)\to\gamma\gamma$ decay must be circularly polarized either right ($l_1=l_2=+1$) or left ($l_1=l_2=-1$).

7. The contribution of the t-quark loop diagrams to the $H(A)\to\gamma\gamma$

decay process increases with the increasing of Higgs boson mass. The width of the $H \to \gamma\gamma$ decay is greater than the width of the $A \to \gamma\gamma$ decay. In the $H \to \gamma Z$ process, the probability first decreases weakly with increasing of mass M_H, and starts to increase rapidly after $M_H \sim$ 315 GeV. The width of the $A \to \gamma Z$ decay increases with increasing of mass M_A. The width of the $H^+ \to \gamma W^+$ decay also increases regularly with increasing of mass M_{H^+}.

The widths of $H \to gg$ and $A \to gg$ splittings increase with the increase of the mass of the Higgs boson, at small values of the Higgs boson mass ($M_\Phi < 270$ GeV), $H \to gg$ decay width prevails, and at large values (M_Φ>270 GeV), $A \to gg$ decay width prevails.

8. The degree of circular polarization of the γ-quantum radiated by leptons in $h \to \tau^-\tau^+\gamma$ decay decreases with the increase of the invariant mass of the lepton pair x (with the decrease of the energy of the photon), and the degree of linear polarization increases.

9. The degree of circular polarization of the γ-quantum in the $h \to e^-e^+\gamma$ decay due to the top quark and W-boson loop diagrams is negative, it decreases with the increase in the energy of the e^-e^+-pair (decreasing the energy of the photon) and reaches a minimum when the energy is 80 GeV, the degree of circular polarization increases to zero with the further increasing of energy. The degree of linear polarization of the photon is almost constant and is close to 58%.

10. Charcino pair, neutralino pair and charcino-neutralino pair produced in $H(h;\,A) \to \tilde{\chi}_i^-\tilde{\chi}_j^+$, $H(h;\,A) \to \tilde{\chi}_i^0\tilde{\chi}_j^0$, $H^\pm \to \tilde{\chi}_i^\pm\tilde{\chi}_j^0$ decay channels of Higgs bosons should have either right or left helicities. As the increasing of the Higgs boson mass, the probability of $H(A) \to \tilde{\chi}_1^-\tilde{\chi}_2^+$, $H \to \tilde{\chi}_2^0\tilde{\chi}_3^0$, $A \to \tilde{\chi}_2^0\tilde{\chi}_3^0$ and $H^- \to \tilde{\chi}_2^-\tilde{\chi}_1^0$ decays increases.

The main provisions submitted for protection. The scientific innovations obtained as a result of the research are as follows:

1. For the first time, taking into account the arbitrary polarization of the fermion-antifermion pair, the differential and full widths of the $H(h;A) \to f\bar{f}$, $H^\pm \to f\bar{f}'$ decay processes were calculated,

2. It was established that the degree of longitudinal polarization of the t-quark in the decay of the scalar (peudoscalar) $H(A)$ Higgs boson $H \to t\bar{b}W^-$ $(A \to t\bar{b}W^-)$ is negative (positive) and decreases (increases) with the increase in the energy of the top quark and approaches the value -0.7 (0.95) at the end of the spectrum.

3. The full probability of the charged Higgs boson decay on the $H^+ \to b\bar{b}W^+$ channel was calculated, it was shown that with the increase in the mass of the Higgs boson, the decay width first increases from 5.838 MeV to 6.415 MeV, and then gradually decreases to 0.675 MeV at the end of the spectrum.

4. It has been shown that fermion-antifermion should have opposite spiralities in the $H \to Af\bar{f}$, $A \to hf\bar{f}$, $H^+ \to H(h;A)f\bar{f}'$ decay processes: $h_1 = -h_2 = \pm 1$. As the mass of the Higgs boson increases, the full width of the $H \to AZ^*$ decay decreases, while the full width of the $A \to hZ^*$ decay first decreases, after reaching a minimum, it begins to increase. The full width of the $H^- \to HW^{-*}$ decay first increases, reaches a maximum, and then begins to decrease.

5. Expressions for the full probabilities of the Higgs boson decay channels $H \to hh$, $H \to hh^* \to hb\bar{b}$ have been obtained. It was established that the helicities of b-quark and $\bar{b}$-antiquark in $H \to hb\bar{b}$ decay should be the same: $\lambda_1 = \lambda_2 = \pm 1$. As the mass of the Higgs boson increases, the full width of the decay $H \to hb\bar{b}$ first increases and reaches a maximum at $M_H \cong 148$ GeV, and then begins to decrease, while the full width of the decay process $H \to hh$ gradually decreases.

6. The full decay probabilities of scalar H and pseudoscalar A Higgs bosons along the $H(A) \to H^{+*}W^- \to t\bar{b}W^-$ channel were calculated, and the expression of the degree of longitudinal polarization of the top quark was obtained. It has been shown that with the increasing of the top quark energy, its longitudinal polarization degree first rapidly decreases and then gradually increases.

7. Loop diagrams contributing to $H(h;A) \to \gamma\gamma$, $H(h;A) \to \gamma Z$ and $H^\pm \to \gamma W^\pm$ decays of Higgs bosons were calculated. It was established that in $H(h;A) \to \gamma\gamma$ decay, γ-quantum should be either right ($l_1 = l_2 = +1$) or left ($l_1 = l_2 = -1$) circularly polarized. The $H \to \gamma\gamma$ decay width is larger than $A \to \gamma\gamma$ decay width and both decay widths increases with increasing mass $M_H(M_A)$.

8. Analytical expressions for degrees of circular and linear polarization of the γ-quantum generated in $H(h;A) \to f\bar{f}\gamma$ decays were obtained. It has been shown that with the increasing of the invariant mass of the lepton pair (decreasing of the photon energy) in the $H(h;A) \to$

$\tau^{-}\tau^{+}\gamma$ process, the degree of circular polarization of the γ-quantum decreases, while the degree of linear polarization increases.

Theoretical and practical significance of research. The scientific results of the dissertation work can be used when conducting theoretical research in the physics of high-energy elementary particles, as well as in setting up experiments related to the Higgs boson and discussing the results of the conducted experiments (Baku State University, Institute of Physics of ANAS, Moscow State University, Dubna United Institute of Nuclear Research, at the European Center for Nuclear Research, LHC).

The results obtained in the dissertation may allow to obtain more complete information about the various physical characteristics of the Higgs boson, to verify the provisions of the MSSM in experiments at high energies. In this work, a number of effects in various decay processes of Higgs bosons have been proposed, their study in experiments allows determining the physical parameters of Higgs bosons.

Approbation and application. The main provisions of the dissertation work and the obtained scientific results were widely reported and discussed in the following scientific meetings, seminars and conferences:

–“Problems of Physics and Astronomy” International Scientific Conference of graduate students and young researchers (May 24-25, 2018, Baku);

–International Conference Modern Trends in Physics (01-03 May, 2019, Baku);

–The XIV International Scientific Symposium “A PERSON IN HISTORY” dedicated to the 140th anniversary of the founder of modern Turkey, Mustafa Kemal Ataturk (26 May, 2021, Ankara, Turkey);

–XXIII Republican scientific conference of PHD students and young researchers (03-04 December, 2019, Baku);

–“Problems of Physics and Astronomy” International Scientific Conference of graduate students and young researchers (May 21, 2021, Baku);

–1st International Congress on Natural Sciences (İCNAS – 2021) (10 September, 2021, Erzurum, Turkey);

–Scientific seminars of the Physics faculty of Baku State University.

A total of 23 scientific papers have been published on the topic of the dissertation, including 16 scientific articles (7 of them in journals included in the Web of Science database) and 9 conference materials.

The name of the institution where the dissertation work was performed. The submitted dissertation work was performed at the "Theoretical Physics" department of Baku State University.

Structure and scope of the dissertation. The thesis is composed of an introduction, four chapters, conclusions, appendixes and a list of 120 cited references, and is written on 219 pages. The total volume of the dissertation work contains (excluding pictures, tables, graphs and bibliography) 177 289 (including Introduction – 13758, Chapter I – 28219, Chapter II – 25028, Chapter III – 57633, Chapter IV – 23016, Appendixes – 233, Results – 3212) marks. 103 pictures reflecting the results are given in the dissertation.

CONTENTS OF THE WORK

In the introduction, the relevance of the topic is justified, the main goal, scientific and practical importance of the dissertation work is determined. Publications are indicated and the content of the dissertation is briefly commented.

In **chapter I** of the dissertation, the information is given about the Higgs boson of the Standard Model and its discovery, the difficulties of the Standard Model, as well as the Higgs bosons in the MSSM and the interactions of Higgs bosons with other particles..

The Higgs boson is one of the fundamental objects of SM, which has no smiliar among known particles, and is a particle that occupies an important place in the physical landscape of the modern world. It has already been established in experiments that the Higgs boson is electrically neutral, has no spin, P and C pairs are positive ($J^{PC} = 0^{++}$), is unstable, and decays through different channels. In the experiments carried out at the LHC, it was detected by the processes of decaying into two photons$H_{SM} \to \gamma\gamma$, decaying into two pairs of electron-positron $H_{SM} \to e^-e^+e^-e^+$, $H_{SM} \to e^-e^+\mu^-\mu^+$or $H_{SM} \to \mu^-\mu^+\mu^-\mu^+$ muon-antimuon.

There five Higgs bosons in the MSSM: H, h, A, $H^{\pm}$-bosons.

Supersymmetry is a new type of symmetry that combines fermions with spin $1/2$ and bosons with spin 0, 1. Here it is claimed that each fermion has its own boson and each boson has its own fermion. Unlike SM, two doublet scalar fields are included in MSSM, five Higgs boson fields are created after spontaneous breaking of supersymmetry: CP-even H and h bosons, CP-odd A-boson and charged $H^{\pm}$ bosons.

In MSSM, the Higgs boson sector is characterized by six parameters: the masses of bosons M_H, M_h, M_A, $M_{H^{\pm}}$ and α and β- mixing angles of fields. The masses of H and h Higgs bosons are determined as one-valued according to the β-mixing angle with the masses M_A and M_Z, while the mass of the charged $H^{\pm}$-boson depends on the masses M_A and M_W[1]:

$$M^2_{h(H)} = \frac{1}{2}[M^2_A + M^2_Z \mp \sqrt{(M^2_A + M^2_Z)^2 - 4M^2_A M^2_Z cos^2 2\beta}], \tag{1}$$

$$M^2_{H^{\pm}} = M^2_A + M^2_W.$$

There is also a certain relationship between the mixing angles α and β:

$$\text{tg}2\alpha = \text{tg}2\beta \frac{M^2_A + M^2_Z}{M^2_A - M^2_Z}, \quad (-\frac{\pi}{2} \leq \alpha < 0) \tag{2}$$

Thus, only two of the six parameters defining the Higgs boson sector are free. M_A mass and $tg\beta$ parameter are considered as free parameters.

The $tg\beta$ parameter is equal to the ratio of the vacuum values of Higgs bosons and varies in the range $1 \leq tg\beta \leq m_t/m_b = 35{,}5$ ($tg\beta = v_2/v_1$), where $m_t = 173{,}2$ GeV and $m_b = 4{,}88$ GeV are the masses of t- and b-quarks.

The masses of the Higgs bosons M_H, M_h and $M_{H^{\pm}}$ also satisfy certain conditions:

$$M_H > max(M_A, M_Z), M_h \leq min(M_A, M_Z) \leq M_Z, M_{H^{\pm}} > M_W.$$

The interaction constants of Higgs bosons with intermediate bosons

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[1]Djouadi, A. The Anatomy of Electro-weak Symmetry Breaking. The Higgs boson in the Supersymmetric Model / A. Djouadi. – Tome II. – 2003. – 303 p, arXiv: hep-ph / 0503173v2.

and other particles in MSSM are shown in Table 1.

Table 1. Interaction constants of Higgs bosons with particles in MSSM

Φ	$g_{\Phi uu}$	$g_{\Phi dd}$	$g_{\Phi VV}$	$g_{\Phi AZ}$	$g_{\Phi H^{\pm} W^{\mp}}$
H_{SM}	1	1	1	0	0
H	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$	$\pm\sin(\beta-\alpha)$
h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\mp\cos(\beta-\alpha)$
A	$ctg\beta$	$tg\beta$	0	0	1

Let H, h, A and $H^{\pm}$ Higgs bosons be denoted by $H_k (k = 1, 2, 3, 4)$, then their left and right interaction constants with charcino-neutralino pair can be written as follows:

$$\chi_i^+ \chi_j^- H_k : g_{ijk} = \frac{1}{\sqrt{2}} [V_{i1} U_{j2} e_k - V_{i2} U_{j1} d_k],$$

$$\chi_i^0 \chi_j^0 H_k : g_{ijk} = \frac{1}{2} (Z_{j2} - tan\theta_W Z_{j1})(Z_{i3} e_k + Z_{i4} d_k) + (i \leftrightarrow j),$$

$$\chi_i^{\pm} \chi_j^0 H^{\mp} : g_{ij4} = \cos\beta\, [V_{i1} Z_{j4} + \frac{1}{\sqrt{2}} (Z_{j2} + tg\theta_W Z_{j1})],$$

$$g_{ji4} = \sin\beta\, [U_{i1} Z_{j3} - \frac{1}{\sqrt{2}} (Z_{j2} + tg\theta_W Z_{j1})].$$

Z and U, V are 4×4 and 2×2 matrices, diagonalizing the mass matrices of neutralino and charcino, the coefficients e_k and d_k depend on the mixing angles α and β:

$$e_1 = \cos\alpha\,, e_2 = \sin\alpha\,, e_3 = -\sin\beta,$$

$$d_1 = -\sin\alpha\,, d_2 = \cos\alpha\,, d_3 = \cos\beta.$$

In **Chapter II,** the channels for the decay of Higgs bosons into fermions in the MSSM were studied. The full widths of such decay channels of Higgs bosons have been calculated by several authors without taking into account the polarization states of the fermion pair. Our research shows that taking into account the polarization states of fermions can provide some information about the nature of Higgs bosons. Taking into account arbitrary polarization states of the fermion pair, expressions for the widths of the indicated splitting channels were obtained by us[2].

Thus, in a special case, the matrix element of Higgs bosons decays into ff-pair was written, taking into account the polarization states of the fermion pair, the expressions for the splitting width were obtained. The width of decay is equal to the following expression (β_f is the speed of the fermion):

$$\frac{d\Gamma(\vec{\eta}_1, \vec{\eta}_2)}{d\Omega} = \frac{N_C \beta_f}{64\pi^2 M_\Phi} g^2_{\Phi ff} \times$$

$$\times \{|a|^2 [\frac{1}{2} M^2_\Phi - m^2_f] (1 + \vec{\eta}_1 \vec{\eta}_2) + |b|^2 \frac{1}{2} M^2_\Phi (1 - \vec{\eta}_1 \vec{\eta}_2)\} \quad (3)$$

It can be seen from this that when the transverse polarization vectors of the fermion and antifermion pair are parallel ($\vec{\eta}_1\vec{\eta}_2 = 1$), Φ boson decay can occur as a result of a single CP-even interaction:

$$\frac{d\Gamma(\vec{\eta}_1\vec{\eta}_2 = 1)}{d\Omega} \sim \beta_f |a|^2 (M^2_\Phi - 4m^2_f) \sim \beta^3_f |a|^2. \quad (4)$$

Φ boson decay due to the CP-odd interaction is possible when the transverse polarization vectors of the fermion pair are antiparallel ($\vec{\eta}_1\vec{\eta}_2 = -1$):

$$\frac{d\Gamma(\vec{\eta}_1\vec{\eta}_2 = -1)}{d\Omega} \sim \beta_f |b|^2. \quad (5)$$

If the angle between the transverse polarization vectors $\vec{\eta}_1$ and $\vec{\eta}_2$ of the fermion pair is φ, then for the decay width $\Phi \to f\bar{f}$ the following expression is obtained:

$$\frac{d\Gamma(\varphi)}{d\Omega} = \frac{N_C \beta_f}{128\pi^2} g^2_{\Phi ff} M_\Phi \{|a|^2 \beta^2_f (1 + \eta_1 \eta_2 \cos\varphi) +$$

$$+ |b|^2 (1 - \eta_1 \eta_2 \cos\varphi) + 2\, Im(ab^*) \beta_f \eta_1 \eta_2 \sin\varphi\}. \quad (6)$$

In this case, two types of transverse spin asymmetry arise[2]:

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[2]Abdullayev, S.K., Omarova, E.Sh. Decays of Higgs bosons into fermion-antifermion pair // Russian Physics Journal, – 2018. V 61, №9, – p. 1603-1612

$$A_1 = \frac{\frac{d\Gamma(\varphi = \pi/2)}{d\Omega} - \frac{d\Gamma(\varphi = -\pi/2)}{d\Omega}}{\frac{d\Gamma(\varphi = \pi/2)}{d\Omega} + \frac{d\Gamma(\varphi = -\pi/2)}{d\Omega}} = \eta_1\eta_2 \frac{2\, Im(ab^*)}{|a|^2 + |b|^2}, \quad (7)$$

$$A_2 = \frac{d\Gamma(\varphi = 0)/d\Omega - d\Gamma(\varphi = \pi)/d\Omega}{d\Gamma(\varphi = 0)/d\Omega + d\Gamma(\varphi = \pi)/d\Omega} = \eta_1\eta_2 \frac{|a|^2 - |b|^2}{|a|^2 + |b|^2}. \quad (8)$$

If the Φ-boson consists of a mixture of CP-even and CP-odd states, the asymmetry A_1 is different from zero and this asymmetry can take a value close to unity (if the parameters a and b are of the same order and the fermion pair is fully transversely polarized $\eta_1 = \eta_2 = 1$). In the case of pure CP, one of the parameters a and b is equal to zero, depending on whether the Higgs boson is CP-even or odd, then A_2 asymmetry takes either +1 or –1.

For the full Φ-boson decay width into a pair of longitudinally polarized fermions, the following expression was obtained:

$$\Gamma(h_1, h_2) = \frac{N_C\beta_f}{16\pi M_\Phi} g^2_{\Phi ff} \{[|a|^2 + |b|^2] (\frac{1}{2}M^2_\Phi - m^2_f) (1 + h_1h_2) -$$
$$-[|a|^2 - |b|^2]m^2_f(1 + h_1h_2) + Re(ab^*)M^2_\Phi\beta_f(h_1 + h_2)\}. \quad (9)$$

From this expression, it can be seen that in the $\Phi \to f\bar{f}$ decay, the fermion and antifermion must have the same spirality ($\Phi \to f_R\bar{f}_R$ or $\Phi \to f_L\bar{f}_L$, where f_R and f_L denote the right- and left-polarized fermion). The expression of the degree of longitudinal polarization of the fermion in the $\Phi \to f\bar{f}$ decay can be defined as follows:

$$P_f = \frac{\Gamma(\Phi \to f_R\bar{f}_R) - \Gamma(\Phi \to f_L\bar{f}_L)}{\Gamma(\Phi \to f_R\bar{f}_R) + \Gamma(\Phi \to f_L\bar{f}_L)} \cong \frac{2\, Re(ab^*)}{|a|^2 + |b|^2} \quad (10)$$

and this expression can provide information about the interference of CP-even and CP-odd decay amplitudes of Higgs bosons.

The transverse spin asymmetries A_1 and A_2, as well as, the degree of longitudinal polarization of the fermion P_f, are more convenient to determine in the Higgs boson decay $h(H; A) \to \tau^-\tau^+$, because the angular distribution of the $\pi^-(K^-, \rho^-)$ mesons in the $\tau^- \to \pi^-\nu_\tau$ ($\tau^- \to K^-\nu_\tau$, $\tau^- \to \rho^-\nu_\tau$) decay is sensitive to the spin of the τ^- lepton, which allows us to determine the polarization of the τ lepton experimentally.

Figure 1 shows the dependence of the $\Gamma(H \to t\bar{t})$ and $\Gamma(A \to t\bar{t})$ decay widths on the mass of the Higgs boson. It can be seen from the figure that $A \to t\bar{t}$ decay is more likely than $H \to t\bar{t}$ decay. By measuring the full decay channels widths $H(\mathrm{A}) \to t\bar{t}$ in experiments, both the Higgs bosons masses and the constants $g_{\Phi ff}$ can be accurately determined.

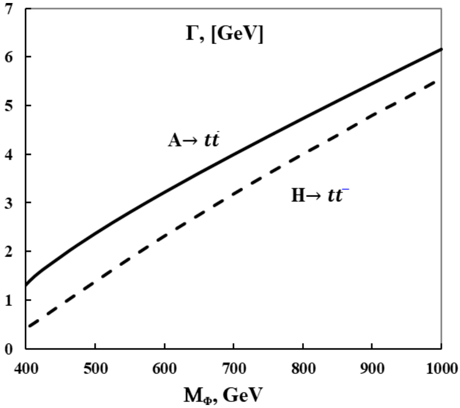

Figure 1. Dependence of the $H \to t\bar{t}$ and $A \to t\bar{t}$ decay widths on the mass of the Higgs boson

It should be noted that in $H^+ \Rightarrow f\bar{f}'$ ($f\bar{f}'$pair can be lepton pair $l^+\nu_l$ or quark pair $q\bar{q}'$) and $H^+ \Rightarrow t\bar{b}$ decays, the transverse spin asymmetry of the fermion pair and the degree of longitudinal polarization have been determined, as well as analytical expressions for the decay widths have been obtained and their dependence on the mass of the Higgs boson graphs are constructed. Here, by measuring these characteristics, the Higgs boson mass M_{H^+} can be determined.

Thus, in the case of a longitudinally polarized fermion pair, the total probability of the decay $H^+ \Rightarrow f + \bar{f}'$ is given by the following expression :

$$\Gamma(\lambda_1,\lambda_2)=\frac{|U_{ff'}|^2 N_C}{32\pi\upsilon^2} M_{H^+} \sqrt{(1-r_f-r_{f'})^2-4r_f r_{f'}}\{[m_f^2 ctg^2\beta+$$

$$+m_{f'}^2 tg^2\beta][1-r_f-r_{f'}+(x_1-2r_f)\lambda_1\lambda_2]+[m_f^2 ctg^2\beta-$$

$$-m_{f'}^2 tg^2\beta]\sqrt{x_1^2-4r_f}(\lambda_1+\lambda_2)-4m_f m_{f'}\sqrt{r_f r_{f'}}-(1-$$

$$-r_f - r_{f'})(x_1 M_{H^+}^2 - 2m_f^2)\lambda_1\lambda_2\}. \quad (11)$$

In the decay process $H^+ \Rightarrow t\bar{b}$, after summing over the polarization states of the $\bar{b}$-antiquark, we can determine the degree of longitudinal polarization of the t-quark :

$$P_f = \frac{\Gamma(\lambda_1=1)-\Gamma(\lambda_1=-1)}{\Gamma(\lambda_1=1)+\Gamma(\lambda_1=-1)} = \frac{[r_t ctg^2\beta - r_b tg^2\beta]\sqrt{(1-r_t-r_b)^2-4r_t r_b}}{[r_t ctg^2\beta + r_b tg^2\beta]\sqrt{(1-r_t-r_b)^2-4r_t r_b}}. \quad (12)$$

Figure 2 shows graphs of the dependence of the decay width $H^+ \to t\bar{b}$ on the Higgs boson mass M_{H^+} when $tg\beta = 3$ and $tg\beta = 30$. As the mass of the Higgs boson increases, the full decay width increases regularly at both values of the $tg\beta$ parameter. The decay width $H^+ \to t\bar{b}$ at the value of the parameter $tg\beta = 30$ is larger[3].

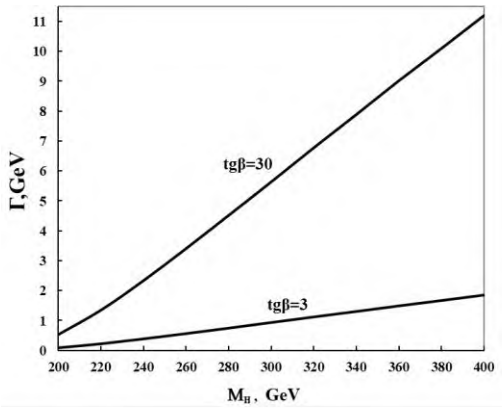

Figure 2. Dependence of the $H^+ \to t\bar{b}$ decay width on the Higgs boson mass

Figure 3 shows the dependence of the transverse spin asymmetry of the top quark A_t and the degree of longitudinal polarization of the b-quark P_b on $tg\beta$ when the charged Higgs boson mass in $H^+ \Rightarrow t\bar{b}$ decay is $M_{H^+} = 125$ GeV and 150 GeV. When $10 \leq tg\beta \leq 30$, the spin asymmetry and the degree of polarization take a negative value and decrease with increasing value of the $tg\beta$ parameter[4].

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[3]Abdullayev, S.K., Omarova, E.Sh. Decays of supersymmetric Higgs bosons into fermions // Azerbaijan Journal of Physics, Fizika, – 2018. V XXIV, №4, – p. 22-34.
[4]Abdullayev S.K., Omarova E.Sh. The decay of a top quark via the channel $t \Rightarrow H^+b$ // Magistrantların və gənc tədqiqatçıların XXI "Fizika və Atronomiya problemləri" ümumrespublika elmi konfransı – Bakı: – 21 may, – 2021, – s. 16-17.

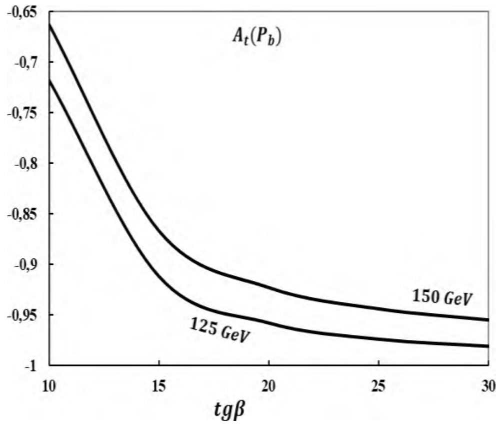


Figure 3. Dependence of A_t spin asymmetry and P_b polarization degree on $tg\beta$ parameter

In **chapter III**, the decay of Higgs bosons into Higgs and vector bosons was studied.

Correspondingly, the $H \Rightarrow Zff$ ($H \rightarrow W\overline{ff'}$) and $H(A) \rightarrow t\bar{b}W^-$ ($H^\pm \rightarrow b\bar{b}W^+$) decay processes were studied and for the decay widths and also for the degree of longitudinal polarization of the t-quark in the $H(A) \rightarrow t\bar{b}W^-$ decay an expression was obtained (Figure 4, 5).

Here the matrix elements of the processes $H(h) \Rightarrow VV$, $H \Rightarrow hh$, $H \Rightarrow hb\bar{b}$, $A \Rightarrow hZ^0$ and $H^\pm \Rightarrow hW^\pm$ are written, and the expression of the decay width for each process is obtained.

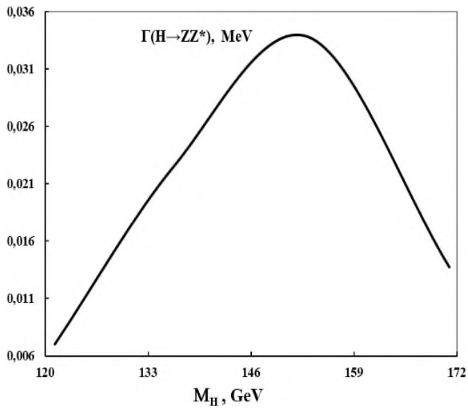


Figure 4. Dependence of the $\Gamma(H \rightarrow ZZ^*)$ decay width on the Higgs boson mass

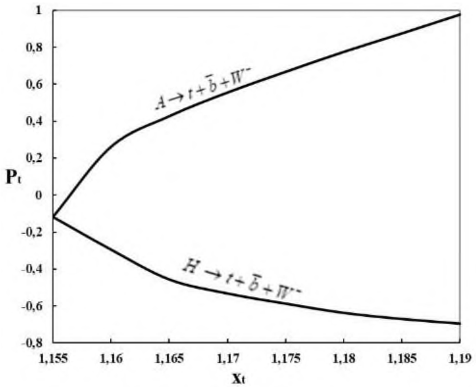
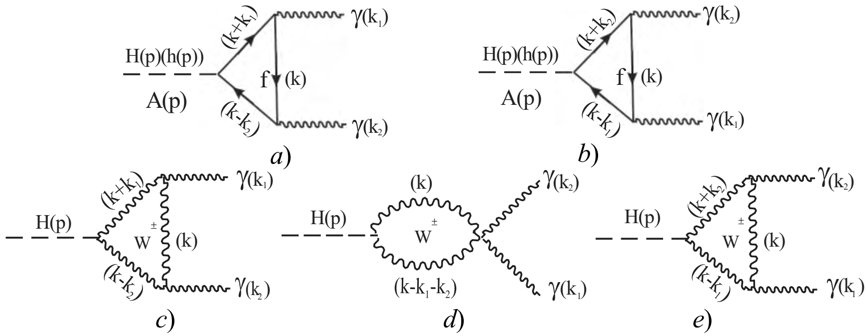


Figure 5. Energy dependence of the degree of longitudinal polarization of the t-quark

I_f the decay width is known from experiments, it is possible to determine both the Higgs boson mass and the $tg\beta$ parameter based on the given formula[5].

Higgs boson decays with loop diagram $H(h;A) \Rightarrow \gamma\gamma(gg)$, $H(h;A) \Rightarrow \gamma Z$, $H^{\pm} \Rightarrow \gamma W^{\pm}$ were considered. Since the photon (gluon) is a massless particle, it does not interact directly with the Higgs boson. Therefore, the Higgs boson decay channels $H(h;A) \Rightarrow \gamma\gamma\ (gg)$, $H(h;A) \Rightarrow \gamma Z$, $H^{\pm} \Rightarrow \gamma W^{\pm}$ are described by loop-particle Feynman diagrams (Figure 6). Loop particles can be heavy fermions (t- and b-quarks, τ^--leptons), $W^{\pm}$-bosons, $H^{\pm}$-Higgs bosons, scalar fermions fЮ, charcinos $\chi^{\pm}_{1,2}$.



[5]Abdullayev, S.K., Omarova, E.Sh. Two- and three-particle decay channels of supersymmetric Higgs bosons // Azerbaijan Journal of Physics, Fizika, – 2019. V. XXV, №4, – p. 29-39.

Figure 6. Feynman loop diagrams of decay $H(h; A) \to \gamma\gamma$

For the $H(h)$ Higgs boson decay width into circularly polarized photons, the following expression was obtained[6]:

$$\Gamma(\Phi \to \gamma\gamma) = \frac{G_F \alpha^2_{KED} M^3_{\boldsymbol{\Phi}}}{512\sqrt{2}\pi^3} \cdot (1 + l_1 l_2) \left|\sum_f N_C Q_f^2 g_{\boldsymbol{\Phi} ff} A^{\boldsymbol{\Phi}}_{1/2}(\tau_f)\right|^2 . \quad (13)$$

In this formula, summarization over loop fermions was performed, $A^{\Phi}_{1/2}(\tau_f)$ is the formfactor of a fermion with $1/2$ spin (Figure 6,*a*,*b*):

$$A^{\boldsymbol{\Phi}}_{1/2}(\tau_f) = \frac{2}{\tau_f^2}[\tau_f + (\tau_f - 1) f(\tau_f)]. \quad (14)$$

It is equal to the $\tau_f = M^2_{\boldsymbol{\Phi}}/4m^2_f$ ratio in the expression of the fermion formfactor.

The $\Phi \Rightarrow \gamma\gamma$ decay width of the corresponding to the $W^{\pm}$-boson loop diagrams (Figure 6,*c*,*d,e*) is given by the formula,

$$\Gamma(\Phi \to \gamma\gamma) = \frac{G_F \alpha^2_{KED} M^3_{\boldsymbol{\Phi}}}{128\sqrt{2}\pi^3} \cdot g^2_{\boldsymbol{\Phi} WW} \cdot |A^{\Phi}_1(\tau_W)|^2, \quad (15)$$

where

$$A^{\Phi}_1(\tau_W) = -\frac{1}{\tau_W^2}[2\tau_W^2 + 3\tau_W + 3(2\tau_W - 1) f(\tau_W)] \quad (16)$$

is the W-boson formfactor, $\tau_W = M^2_{\boldsymbol{\Phi}}/4M^2_W$, $g_{\boldsymbol{\Phi} WW}$ is the interaction constant between the W-boson pair and the Φ-boson, normalized to the decay constant $g_{H_{SM}WW}$.

The charged Higgs boson and Feynman loop diagrams of supersymmetric particles also contribute to $\Phi \Rightarrow \gamma\gamma$ decay. Taking all this into account, the expression of the decay width $\Phi \Rightarrow \gamma\gamma$ in the general case can be shown as follows[6]:

$$\Gamma(\Phi \to \gamma\gamma) = \frac{G_F \alpha^2_{KED} M^3_{\boldsymbol{\Phi}}}{128\sqrt{2}\pi^3} \cdot \left|\sum_f N_C Q_f^2 g_{\boldsymbol{\Phi} ff} A^{\boldsymbol{\Phi}}_{1/2}(\tau_f) + \right.$$

[6]Abdullayev, S.K., Omarova, E.Sh. Decays of $H(h; A)$ Higgs bosons into two photons (gluons) // Russian Physics Journal, – 2020. V. 62, №9, – p. 1623-1634.

$$+\frac{M_Z^2\lambda_{\Phi H^+H^-}}{2M_{H\pm}^2}A_0^{\Phi}(\tau_{H^\pm})+\sum_{f_i}\frac{N_C Q_{f_i}^2}{m_{f_i}}g_{\Phi f_i f_i}A_0^{\Phi}(\tau_{f_i})+$$

$$+g_{\Phi WW}A_1^{\Phi}(\tau_W)+\sum_{\tilde{z}_i^{\pm}}\frac{2M_W}{m_{\tilde{z}_i^{\pm}}}g_{H\tilde{z}_i^+\tilde{z}_i^-}A_{1/2}^{\Phi}(\tau_{\tilde{z}_i^{\pm}})|^2 . \qquad (17)$$

$A \Rightarrow \gamma\gamma$ decay is described by charcino loop diagrams along with fermion loop diagrams. In the general case, the following expression is obtained for the decay width $A \Rightarrow \gamma\gamma$:

$$\Gamma(A \to \gamma\gamma) = \frac{G_F \alpha_{ED}^2 M_{\Phi}^3}{128\sqrt{2}\pi^3}\times$$

$$\times|\sum_f N_C Q_f^2 g_{Aff} A_{1/2}^A(\tau_f)+\sum_{\tilde{z}_i^{\pm}}\frac{2M_W}{m_{\tilde{z}_i^{\pm}}}g_{A\tilde{z}_i^+\tilde{z}_i^-}A_{1/2}^A(\tau_{\tilde{z}_i^{\pm}})|^2 . \qquad (18)$$

In the MSSM, it is also possible for H, h and A-bosons to decay into two gluons described by q-quark or qЮ-scalar quark loop diagrams. An- alytical expressions for the decay widths $\Phi \Rightarrow gg$ $(\Phi = H; h)$ and $A \Rightarrow$
gg are obtained:

$$\Gamma(\Phi \to gg) = \frac{G_F \alpha_s^2 M_{\Phi}^3}{64\sqrt{2}\pi^3}\cdot|\sum_q g_{\Phi qq}\cdot A_{\frac{1}{2}}^{\Phi}(\tau_f)|^2 , \qquad (19)$$

$$\Gamma(A \to gg) = \frac{G_F \alpha_s^2 M_A^3}{64\sqrt{2}\pi^3}\cdot|\sum_a g_{Aqq}\cdot A_{\frac{1}{2}}^{A}(\tau_f)|^2 . \qquad (20)$$

Figure 7 shows the dependence of the decay widths $H \to \gamma\gamma$ and $A \to \gamma\gamma$ on the mass of the Higgs boson when $tg\beta = 3$. It should be noted that in the case of a t-quark loop, $m_t = 173.2$ GeV was taken into account. As it can be seen, as the mass of the Higgs boson M_H increases, the value of the splitting width also increases.

According to the fermion loop diagram, for the decay width of the process Ц $\Rightarrow \gamma + Z$ (Ц $= H; h$) we can write the following expression:

$$\Gamma(\Phi \Rightarrow \gamma Z) = \frac{G_F M_Z^2 \alpha_{KED}}{16\pi^4} M_\Phi^3 \cdot \left(1 - \frac{M_Z^2}{M_\Phi^2}\right)^3 \times$$

$$\times \left|\sum_f g_{\Phi ff} \cdot Q_f \cdot N_C \cdot g_V(f) \cdot A_f^\Phi(\tau_f, \lambda_f)\right|^2, \quad (21)$$

here, $A_f^Ц(\tau_f, \lambda_f)$ denotes the fermion loop form factor:

$$A_f^\Phi(\tau_f, \lambda_f) = F_1(\tau_f, \lambda_f) - F_2(\tau_f, \lambda_f) \quad (22)$$

$$F_1(\tau_f, \lambda_f) = \frac{1}{2(\lambda_f - \tau_f)} + \frac{1}{2(\lambda_f - \tau_f)^2}[f(\tau_f) - f(\lambda_f)] -$$

$$-\frac{1}{(\lambda_f - \tau_f)^2}[g(\tau_f) - g(\lambda_f)], \quad (23)$$

$$F_2(\tau_f, \lambda_f) = -\frac{1}{2(\lambda_f - \tau_f)}[f(\tau_f) - f(\lambda_f)]. \quad (24)$$

The decays of the CP-even H and h bosons into a photon and a Z boson can be represented through the $W^\pm$ and $H^\pm$ boson loop diagrams, as well as via scalar fermion loop diagrams. Apart from the chargino loop diagrams, for all other loop diagrams the decay width of the process $Ц \Rightarrow \gamma + Z$ can be expressed by the following formula :

$$\Gamma(Ц \Rightarrow \gamma Z) = \frac{G_F M_Z^2 \alpha_{KED}}{64\pi^4} M_Ц^3 \cdot \left(1 - \frac{M_Z^2}{M_\Phi^2}\right)^3 \left|\sum_f g_{Цff} \frac{Q_f g_V(f)}{\cos\theta_W} Ч\, N_C A_{\frac{1}{2}}^Ц(\tau_f, \lambda_f) + g_{ЦWW} A_W^Ц(\tau_W, \lambda_W) + \frac{M_W^2 g_{H^\pm}}{2\cos\theta_W M_{H^\pm}^2} \lambda_{ЦH^+H^-} Ч\, A_0^Ц(\tau_{H^\pm}, \lambda_{H^\pm}) + \sum_{fЮ_i} \frac{g_{Цf_i f_i}}{m_{fЮ_i}^2} N_C Q_{fЮ} g_V(f_i) A_0^Ц(\tau_{fЮ}, \lambda_{fЮ})\right|^2. \quad (25)$$

Now, the formula for the decay width of the process A $\Rightarrow \gamma Z$, shown by the fermion loop diagrams, can be written as follows :

$$\Gamma(A \Rightarrow \gamma Z) = \frac{G_F M_Z^2 \alpha_{KED} M_A^3}{4\pi^4} \cdot \left(1 - \frac{M_Z^2}{M_A^2}\right)^3 \times$$

$$\times \left|\sum_f g_{Aff} Q_f N_C g_V(f) A_f^A(\tau_f, \lambda_f)\right|^2, \tag{26}$$

here, $A_f^A(\tau_f, \lambda_f)$ is the fermion form factor, and it is equal to $A_f^A(\tau_f, \lambda_f) = F_2(\tau_f, \lambda_f)$.

Figure 8 shows the graphs of the Higgs boson mass dependence of the decay widths $H \Rightarrow \gamma Z$ and $A \Rightarrow \gamma Z$ when $tg\beta = 3$ and $x_W = 0.2315$, described by means of t-quark loop[7].

One of the decay channels of the Higgs boson is its decay into a photon and $W^\pm$ vector boson. In this case, the decay proceeds through the loop diagrams involving the t- and b-quarks. Based on the t-quark and $\bar{b}$ - antiquark loop diagrams, we obtain the following expression for the decay width of the process $H^+ \Rightarrow t^* + \bar{b}^* + \gamma + W^+$:

$$\Gamma(H^\pm \Rightarrow \gamma W^\pm) = \frac{\alpha_{KED}^3 N_C^2 M_{H^+}^3}{2^8 \cdot 9\pi^2 \cdot M_W^2} \times$$

$$\times \left(1 - \frac{M_W^2}{M_{H^+}^2}\right)^3 x_W \left[ctg^2\beta + \left(\frac{m_b}{m_t} tg\beta\right)^2\right]. \quad (27)$$

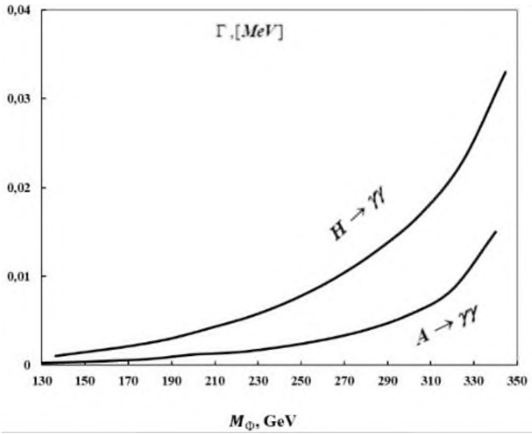


Figure 7. Dependence of the decay widths $H \Rightarrow \gamma\gamma$ and $A \Rightarrow \gamma\gamma$ on the Higgs boson mass (t-quark loop diagram)

[7]Abdullayev, S.K., Omarova, E.Sh. Decays of the Higgs bosons H, h, A and $H^\pm$ into a photon and a gauge boson // Russian Physics Journal, – 2020. V. 63, №3, – p. 372-384.

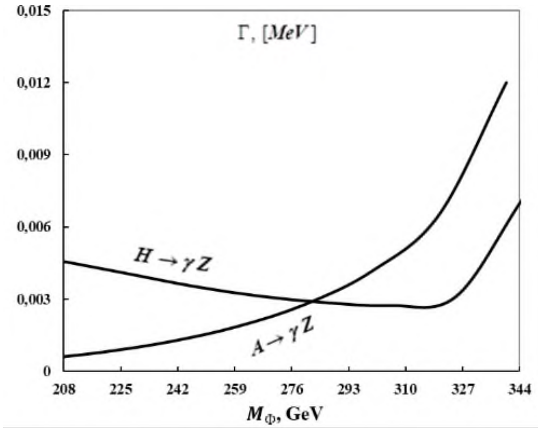


Figure 8. The dependence of $H \Rightarrow \gamma Z$ and $A \Rightarrow \gamma Z$ decay widths on the Higgs boson mass

Figure 9 shows the graph of the dependence of the decay width $H^+ \Rightarrow \gamma W^+$ on the mass of the Higgs boson when $tg\beta = 3$, $x_W = 0.2315$, $M_W = 80{,}385$ GeV, $m_t = 173{,}2$ GeV, $m_b = 4{,}88$ GeV.

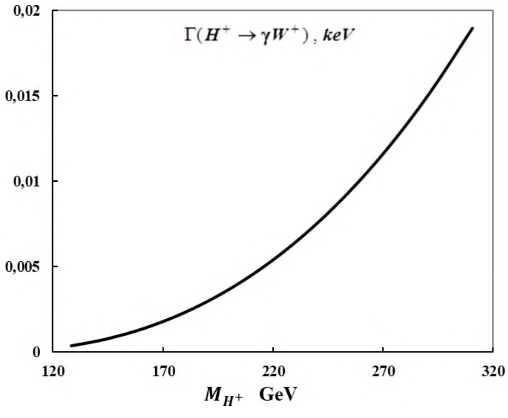


Figure 9. The dependence of decay width $H^+ \Rightarrow \gamma W^+$ on the Higgs boson mass

Also, the $H \Rightarrow Aff$, $A \Rightarrow hff$, $H^\pm \Rightarrow Hff'$ and $H^\pm \Rightarrow h(A)ff'$ decay channels were studied, suitable expressions for the decay widths were obtained, and graphs of the dependence of the decay widths on the mass of the Higgs boson were constructed (Figure 10) [8].

[8]Abdullayev, S.K., Omarova, E.Sh. Three particle decays of the Higgs bosons in the Minimal Supersymmetric Standard Model // Russian Physics Journal, – 2019. V 62, №3, – p. 425-435.

The differential decay width of the process $H \Rightarrow A + f + \bar{f}$ is proportional to the squared matrix element of the decay[8]:

$$\frac{d\Gamma(H \to Af\bar{f})}{dx_1 dx_2} = \frac{N_C |M(H \to Af\bar{f})|^2 M_H}{2^9 \pi^3} = \frac{N_C G_F^2 M_Z^4 M_H}{32\pi^3} \times$$

$$\times \frac{(1 - x_1)(1 - x_2) - r_A}{(1 - x_1 - x_2 - r_A + r_Z)^2 + r_Z \gamma_Z} sin^2(\beta - \alpha) \times$$

$$\times [g_L^2(f)(1 - \lambda_1)(1 + \lambda_2) + g_R^2(f)(1 + \lambda_1)(1 - \lambda_2)]. \qquad (28)$$

From the expression of the differential decay width, it follows that the fermion and antifermion must possess opposite helicities: $\lambda_1 = -\lambda_2 = \pm 1$. When the fermion is a left–handed particle, the antifermion must be right–handed $f_L \bar{f}_R$ or vice versa $f_R \bar{f}_L$. This is a consequence of the conservation of total angular momentum in the $Z^* \to f + \bar{f}$.

In the case where the fermion is left–polarized and the antifermion is right–polarized, expression (28) can be written in the following form:

$$\frac{d\Gamma(H \to Af_L \bar{f}_R)}{dx_1 dx_2} = \frac{N_C G_F^2 M_Z^4 M_H}{8\pi^3} \cdot sin^2(\beta - \alpha) g_L^2(f) \times$$

$$\times \frac{(1 - x_1)(1 - x_2) - r_A}{(1 - x_1 - x_2 - r_A + r_Z)^2 + r_Z \gamma_Z}. \qquad (29)$$

In the opposite case, i.e., when the fermion is right–handed and the antifermion is left–handed, the differential width of the decay $H \to A + f + \bar{f}$ can be expressed as follows:

$$\frac{d\Gamma(H \to Af_R \bar{f}_L)}{dx_1 dx_2} = \frac{N_C G_F^2 M_Z^4 M_H}{8\pi^3} \cdot sin^2(\beta - \alpha) g_R^2(f) \times$$

$$\times \frac{(1 - x_1)(1 - x_2) - r_A}{(1 - x_1 - x_2 - r_A + r_Z)^2 + r_Z \gamma_Z}. \qquad (30)$$

Accordingly, one can write the expression for the degree of longitudinal polarization of the fermion as follows

$$P_f = \frac{g_R^2(f) - g_L^2(f)}{g_R^2(f) + g_L^2(f)}, \tag{31}$$

as can be seen from Eq. (19), the degree of longitudinal polarization of the fermion is determined by the fermion species and the Weinberg parameter x_W.

This chapter also considered the degree of circular (linear) polarization of the γ-quantum in the $H(h; A) \Rightarrow f f \gamma$ decays of Higgs bosons. Analytical expressions for the decay width were calculated and the expression for the degree of circular (linear) polarization of the γ-quantum was obtained. Also graphs of the dependence of the degree of polarization on the output angle of the fermion at different values of energy ($z = cos\ \theta$) have been constructed[9,10,11].

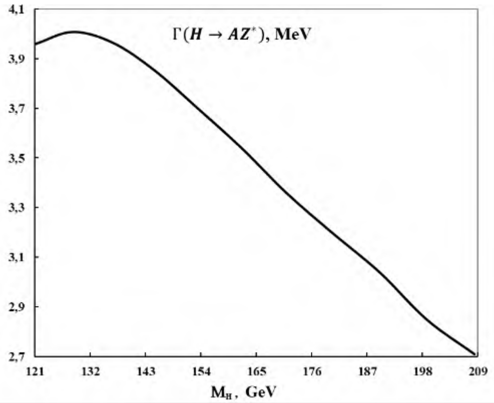


Figure 10. The dependence of the decay width $H \to AZ^*$ on the Higgs boson mass

The decay widths of the processes $H(h;\ A) \Rightarrow \tau^-\tau^+\gamma$ can be expressed as follows:

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[9] Abdullayev, S.K., Omarova, E.Sh. Radiative Higgs boson decay $H(h; A) \Rightarrow f f \gamma$ in MSSM // – Baku: Bakı Universitetinin Xəbərləri, Fizika-riyaziyyat elmləri seriyası, – 2020. №2, – p. 65-80.

[10] Omarova, E.Sh. Radiative Higgs boson decays $H(h; A) \Rightarrow f f \gamma$ in MSSM // – Baku: Journal of Baku Engineering University, Physics, – 2020. V.4, №1, – p.8-17.

[11] Abdullayev, S.K., Omarova, E.Sh. The linear polarization of γ-quanta in the decay $h(H; A) \Rightarrow f f \gamma$ // 1st International Congress on Natural Sciences (ICNAS – 2021), – Erzurum, Turkey: – 10 September, – 2021, – p. 510-513.

$$\frac{d\Gamma}{dxdz} = \frac{A_0^2 M_\Phi \upsilon}{2^{10}\pi^3(1-x)} \cdot \left(\frac{g_{\Phi ff}}{g_{H_{SM}ff}}\right)^2 \frac{N_C}{(1-\upsilon^2 z^2)^2}\{(1+\lambda_1 \times$$

$$\times \lambda_2)(1+x^2)(1-\upsilon^2 z^2) + l(\lambda_1+\lambda_2)(1-x) \times$$

$$\times [2x\upsilon^2(1-z^2) + (1-x)(1-\upsilon^2 z^2)]\}, \qquad (32)$$

In this context, $l = \pm 1$denotes the circular polarization of the photon (where $l = +1$corresponds to a right–circularly polarized photon and $l = -1$corresponds to a left–circularly polarized photon).

The degree of circular polarization of the photon is defined by the following expression :

$$P_\gamma = \frac{d\Gamma(\lambda_1, \mathrm{l} = +1)/\mathrm{dxdz} - \mathrm{d}\Gamma(\lambda_1, \mathrm{l} = -1)/\mathrm{dxdz}}{\mathrm{d}\Gamma(\lambda_1, \mathrm{l} = +1)/\mathrm{dxdz} - \mathrm{d}\Gamma(\lambda_1, \mathrm{l} = -1)/\mathrm{dxdz}} =$$

$$= \lambda_1 \cdot \frac{(1-x)[2x\upsilon^2(1-z^2) + (1-x)(1-\upsilon^2 z^2)]}{(1+x^2)(1-\upsilon^2 z^2)}. \qquad (33)$$

Figure 11 shows graphs of the dependence of the degree of circular polarization of the γ-quantum on the invariant mass of the lepton pair x in $H \Rightarrow \tau^-\tau^+\gamma$ decay when $z = 0$ and $z = 1$. It can be seen from the graph that with the increase of the invariant mass, the value of P_γ decreases regularly.

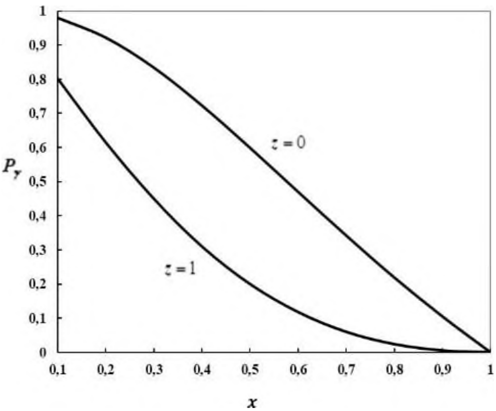

Figure 11. The dependence of P_γ on the invariant mass x

Figure 12 indicates the dependence of the linear polarization degree of γ-quantum on the cosine of θ angle at $h \Rightarrow \tau^-\tau^+\gamma$ decay when $x =$

0.1; 0.5; 0.8. It can be seen that when the value of the degree of linear polarization of the γ-quantum increases (decreases) $-1 \leq \cos\theta \leq -0.5$ $(0.5 \leq \cos\theta \leq 1)$ in $h \Rightarrow \tau^-\tau^+\gamma$ decay, while the value of the degree of linear polarization of the γ-quantum remains constant when $-0.5 \leq \cos\theta \leq 0.5$[10].

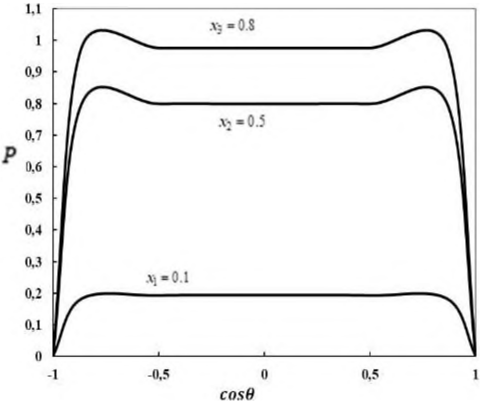

Figure 12. The dependence of the $P(x, \cos\theta)$ on the $\cos\theta$ in the various values of the x at $h \Rightarrow \tau^-\tau^+\gamma$ decay

Chapter IV is devoted to the processes of the supersymmetric particles production in the Higgs boson decays. Examples of supersymmetric particles are charcino, neutralino and scalar fermions.

Supersymmetric partners of gauge $W^{\pm}$ and Higgs bosons $H^{\pm}$ are called as gaugino (vino) $\tilde{W}^{\pm}$ and higgsino $\tilde{H}^{\pm}$. Chargino $\tilde{\chi}^{\pm}_{1,2}$ is 4-com- ponent in the the expression of the mass matrix of these spinor fields. Chargino $\tilde{\chi}^{\pm}_{1,2}$ which is a Dirac fermion, is created when vino $\tilde{W}^{\pm}$ and higgsino $\tilde{H}^{\pm}$ mix with each other.

In the MSSM while neutralino $\tilde{\chi}^0_i (i = 1, 2, 3, 4)$ is created superpozition of neutral vino $\tilde{W}^0$ and bino $\tilde{B}^0$, otherwise $\tilde{H}^0_1$ and $\tilde{H}^0_2$ higgsinos. The neutralino is a Mayaron fermion, and its antiparticle falls on the particle.

Figure 13 shows the dependence of the masses of charginos $m_{\tilde{\chi}^{\pm}_1}$ and $m_{\tilde{\chi}^{\pm}_2}$ on the parameter μ when $tg\beta = 30$ and $M_2 = 150$ GeV. As it can be seen, as the value of the parameter μ increases, the mass of the light (heavy) charginos $m_{\tilde{\chi}^{\pm}_1}$ $(m_{\tilde{\chi}^{\pm}_2})$ also increases regularly and at $\mu = -500$ GeV, $m_{\tilde{\chi}^{\pm}_1} = 147$ GeV $(m_{\tilde{\chi}^{\pm}_2} = 512$ GeV) and at μ

=

1 2

500 GeV, $m_{\tilde{\chi}_1^{\pm}} = 145$ GeV ($m_{\tilde{\chi}_2^{\pm}} = 514$ GeV). At the zero value of the μ parameter, the mass of the charginos also takes a minimum value[12]:

$$m_{\tilde{\chi}_1^{\pm}}(\mu = 0) = 2.696\ \text{GeV},\ m_{\tilde{\chi}_2^{\pm}}(\mu = 0) = 188.192\ \text{GeV}.$$

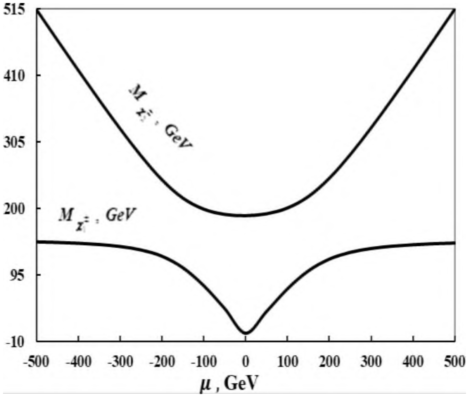

Figure 13. The dependence of the masses of charginos on μ parameter

We get the following expression for the decay width in the case that the chargino is longitudinally polarized in $H_k \Rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$ decay:

$$\Gamma(\lambda_1, \lambda_2) = \frac{1}{4}\Gamma_0(H_k \Rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+)[1 + \lambda_1\lambda_2 + (\lambda_1 + \lambda_2)P]. \quad (34)$$

Here

$$\Gamma_0(H_k \Rightarrow \chi_i^- \chi_j^+) = \frac{G_F M_W^2}{2\sqrt{2}\pi} M_{H_k} \sqrt{(1 - r_i - r_j)^2 - 4 r_i r_j} \times$$

$$\times \{[(g_{ijk}^L)^2 + (g_{ijk}^R)^2](1 - r_i - r_j) - 4 g_{ijk}^L g_{ijk}^R \sqrt{r_i r_j}\} \quad (35)$$

is the decay width of the process when the chargino pair is not polarized, P is the degree of the longitudinal polarization of chargino[12]:

$$P = \frac{[(g_{ijk}^L)^2 - (g_{ijk}^R)^2]\sqrt{(1 - r_i - r_j)^2 - 4 r_i r_j}}{[(g_{ijk}^L)^2 + (g_{ijk}^R)^2](1 - r_i - r_j) - 4 g_{ijk}^L g_{ijk}^R \sqrt{r_i r_j}}. \quad (36)$$

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[12]Abdullayev, S.K., Omarova, E.Sh. Higgs boson decays into a pair of supersymmetric particles // Azerbaijan Journal of Physics, Fizika, – 2020. V. XXVI, №2, – p. 38-50.

From the expression (17), it is clear that in the decay of the Higgs boson $H_k \Rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$, charginos must have the same spirality: $\lambda_1 = \lambda_2 = \pm 1$ ($\tilde{\chi}_{iR}^- \tilde{\chi}_{jR}^+$ or $\tilde{\chi}_{iL}^- \tilde{\chi}_{jL}^+$). This is related to the law of conservation of total momentum in $H_k \Rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$ decay.

The degree of transverse polarization of charginos is given by the following expression:

$$P_\perp = \frac{2 g_{ijk}^L g_{ijk}^R (1 - r_i - r_j) - 4[(g_{ijk}^L)^2 + (g_{ijk}^R)^2]\sqrt{r_i r_j}}{[(g_{ijk}^L)^2 + (g_{ijk}^R)^2](1 - r_i - r_j) - 4 g_{ijk}^L g_{ijk}^R \sqrt{r_i r_j}} \cdot \cos\varphi. \qquad (37)$$

When $tg\beta = 1$, as interaction constants are $g_{ijk}^L = g_{ijk}^R$, the degree of the transverse polarization is equal to only cosine angle between $\vec{\eta}_1$ and $\vec{\eta}_2$ spin vectors:

$$P_\perp = \cos\varphi. \qquad (38)$$

It is shown that, from (21) expression, when φ angle changes from 0° to 180°, the degree of the transverse polarization of the chargino also changes from +1 to –1, the next increasing of the azimutal angle from 180° to 360°, $P_\perp$ enlarges from –1-to +1.

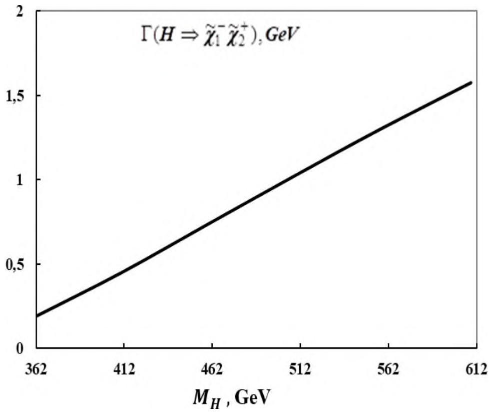

Figure 14. The dependence of decay width $H \Rightarrow \tilde{\chi}_1^- \tilde{\chi}_2^+$ on Higgs boson mass M_H

Figure 14 shows the dependence of the decay width $H \Rightarrow \tilde{\chi}_1^- \tilde{\chi}_2^+$ on Higgs boson mass when $tg\beta = 1$, $M_2 = 150$ GeV, $\mu = 160$ GeV, $M_Z = 91.1875$ GeV, $M_W = 80.385$ GeV. The value of the decay width increases with increasing Higgs boson mass. Chapter IV deals with decay of Higgs bosons into neutralino pair $H(h; A) \Rightarrow \tilde{\chi}^0_i \tilde{\chi}^0_j$, decay of the charged Higgs boson into chargino-neutralino pair $H^{\mp} \Rightarrow \tilde{\chi}^{\mp}_i \tilde{\chi}^0_j$, as well as, decay of charginos into light chargino (neutralino) and Higgs bosons $\tilde{\chi}^{\mp}_2 \Rightarrow \tilde{\chi}^{\mp}_1 H(h; A)$, $\tilde{\chi}^{\mp}_2 \Rightarrow \tilde{\chi}^0_1 H^{\mp}$, $\tilde{\chi}^{\mp}_{3,4} \Rightarrow \tilde{\chi}^0_{1,2}\, h(H; A)$. The matrix element is written, decay widths and the de- gree of the longitudinal and transverse polarizations of particles are obtained for every decay channels[12].

The expression for the decay width of the Higgs bosons into a longitudinally polarized neutralino pair can be written by the following formula:

$$\Gamma(\lambda_1, \lambda_2) = \frac{1}{4} \Gamma_0 (H_k \Rightarrow \tilde{\chi}^0_i \tilde{\chi}^0_j)[1 + \lambda_1 \lambda_2 + (\lambda_1 + \lambda_2) P], \qquad (39)$$

here

$$\Gamma_0(H_k \Rightarrow \chi^0_i \chi^0_j) = \frac{G_F M_W^2}{2\sqrt{2}\pi} M_{H_k} \delta \sqrt{\lambda(r_i, r_j)} \{[(g^L_{ijk})^2 + (g^R_{ijk})^2] \times$$
$$\times (1 - r_i - r_j) - 4\varepsilon_i \varepsilon_j g^L_{ijk} g^R_{ijk} \sqrt{r_i r_j}\}. \qquad (40)$$

denotes the decay width of the process $H_k \Rightarrow \tilde{\chi}^0_i \tilde{\chi}^0_j$ in the case where the neutralino pair is unpolarized, and P represents the degree of longitudinal polarization of the neutralino[12] :

$$P = -\frac{[(g^L_{ijk})^2 - (g^R_{ijk})^2]\sqrt{\lambda(r_i, r_j)}}{[(g^L_{ijk})^2 + (g^R_{ijk})^2](1 - r_i - r_j) - 4\varepsilon_i \varepsilon_j g^L_{ijk} g^R_{ijk} \sqrt{r_i r_j}}, \qquad (41)$$

It should be noted that the neutralino $\tilde{\chi}^0$ is considered the lightest supersymmetric particle. All other supersymmetric particles can decay into a neutralino $\tilde{\chi}^0$ and ordinary SM particles. In Table 4.1.1, the upper bounds of the masses of supersymmetric particles are presented for different values of the parameter $\tan\beta$. In the table, $\tilde{\tau}$ and $\tilde{t}$ are sfermions, namely the stau lepton and the stop quark, respectively.

Table 2. Upper bounds of supersymmetric particle masses

$tan\beta$	$\tilde{\chi}^0$	$\tilde{\chi}^0$	$\tilde{\tau}$	$\tilde{t}$
10	155	280	170	580
15	168	300	185	640

20	220	400	236	812
30	260	470	280	990

Figure 15 indicates the dependence of the decay width $H \Rightarrow \tilde{\chi}_2^0\tilde{\chi}_3^0$ on Higgs boson mass M_H when $tg\beta = 3, sin^2\theta_W = 0.2315$. As can be seen the decay width $H \Rightarrow \tilde{\chi}_2^0\tilde{\chi}_3^0$ enlarges when Higgs boson mass increases.

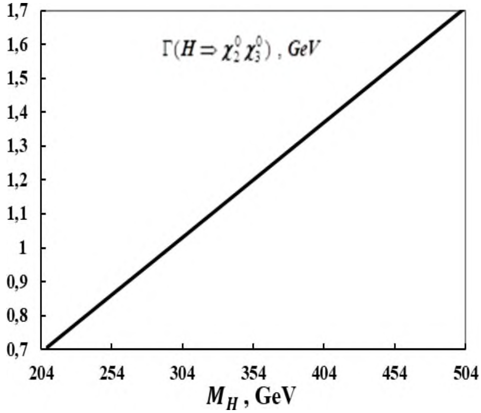

Figure 15. The dependence of the decay width $H \Rightarrow \tilde{\chi}_2^0\tilde{\chi}_3^0$ on Higgs boson mass M_H

Figure 16 shows the dependence of A_{II}– longitudinal spin asymmetry, $A_\perp$– transverse spin asymmetry, and $P_\perp$ – transverse polarization degree on θ angle in $\tilde{\chi}_2^- \Rightarrow \tilde{\chi}_1^0 H^-$ decay. As can be seen in Figure 16, the longitudinal spin asymmetry initially takes positive values, decreases with increasing angle θ, and becomes zero when $\theta = 90^\circ$, and then takes negative values. Longitudinal spin asymmetry takes maximum value when $\theta = 0^\circ$and $A_{II} = 7{,}9\%$. Transverse spin asymmetry $A_\perp$ also takes a positive value. As the value of the angle θ increases, it also increases and when $\theta = 90^\circ$, it takes the maximum value, $A_\perp = 10\%$, then the value of $P_\perp$ decreases with the increase of the angle. The degree of transverse polarization of the neutralino takes a negative value, decreases with the increase of the angle θ and takes the value of –1 when $\theta = 90^\circ$, the value of the degree of transverse polarization also increases with the further increase of the angle.

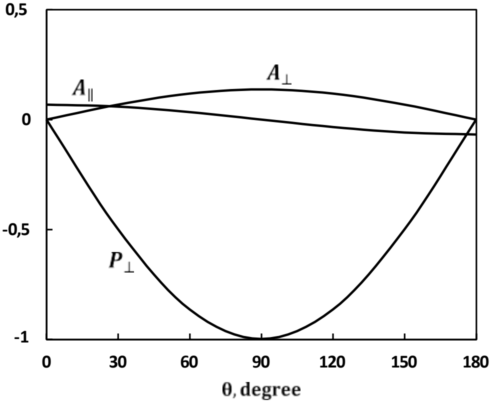

Figure 16. The dependence of the A_{II} and $A_{\perp}$ asimmetries and $P_{\perp}$ the degree of the polarization on θ angle at $\tilde{\chi}_2^- \Rightarrow \tilde{\chi}_1^0 H^-$ decay ($m_{\tilde{\chi}_2^-} =$ 378.303GeV)

RESULTS

1. Taking into account the cases of arbitrary polarization of the fermion-antifermion pair in the MSSM, the differential and complete probabilities of the Higgs bosons decays on $H(h;A) \rightarrow f\bar{f}$ and $H^+ \rightarrow f\bar{f}'$ channels were calculated. It has been shown that when the transverse spin vectors of the fermion-antifermion pair are parallel ($\vec{\eta}_1\vec{\eta}_2 = 1$), the Higgs boson decays along the $H(h;A) \rightarrow f\bar{f}$ channel can occur due to the CP-pair interaction, and when they are antiparallel ($\vec{\eta}_1\vec{\eta}_2 = -1$), the CP-odd interaction can occur.

2. The fermion and antifermion produced by the Higgs bosons decays along the $H(h;A) \rightarrow f\bar{f}$ channel should have the same helicity: $\lambda_1 = \lambda_2 = \pm 1$ ($f_R\bar{f}_R$ or $f_L\bar{f}_L$ helicity cases). P_f the degree of longitudinal polarization of the fermion carries information about the CP-parity of the decaying Higgs boson.

3. P_t the degree of longitudinal polarization of the top quark produced in the decay of the charged Higgs boson along the $H^+ \rightarrow t\bar{b}$ channel is very sensitive to the Higgs boson mass M_{H^+}. Therefore, by measuring the degree of longitudinal polarization of the t-quark in experiments, the Higgs boson mass M_{H^+} can be determined more accurately.

4. Analytical expressions for the differential and full widths of the decay channels $H \rightarrow ZZ^* \rightarrow Zf\bar{f}$, $H \rightarrow WW^* \rightarrow Wf\bar{f}'$ for the heavy Higgs boson into the gauge boson and the longitudinally polarized fundamental fermion-antifermion pair have been obtained. It was determined that the fermion and antifermion formed in the decay processes should have opposite helicities: $\lambda_1 = -\lambda_2 = \pm 1$ ($f_R \bar{f}_L$ or $f_L \bar{f}_R$ helicity cases). The full widths of the $\Gamma(H \to ZZ^*)$ and $\Gamma(H \to WW^*)$ decays are very sensitive to the Higgs boson mass M_H. It is possible to determine the Higgs boson mass by measuring the $H \to ZZ^*$ and $H \to WW^*$ decay widths of in experiments.

5. Using the Feynman technique, the loop diagrams corresponding to the Higgs bosons decay channels $H(h;A) \to \gamma\gamma$, $H(h;A) \to gg$, $H(h;A) \to \gamma Z$, $H^\pm \to \gamma W^\pm$ were calculated and analytical expressions for the full decays widths were obtained. It was established that in $H(h;A) \to \gamma\gamma$ decays gamma quantum should be circularly polarized either right ($l_1 = l_2 = +1$) or left ($l_1 = l_2 = -1$). Right and left circular polarization of one of the photons is forbidden by the law of conservation of total momentum.

6. Analytical formulas for differential probability, degrees of photon circular and linear polarization were obtained taking into account diagrams of radiation of gamma quantum by fermion and antifermion in the Higgs bosons decays $H(h;A) \to f\bar{f}\gamma$ ($f\bar{f}$-heavy fermion-antifermion pair: $f\bar{f} = \tau^-\tau^+$, $c\bar{c}$, $b\bar{b}$) within MSSM. It has been shown that the degree of circular polarization of γ-quantum decreases and the degree of linear polarization increases with the decrease of photon energy in the decay process $H \to \tau^-\tau^+\gamma$.

7. Analytical expressions determining the dependence of the probability on the helicities of both the fermion-antifermion pair and the γ-quantum were obtained by taking into account the top quark and W-boson loop diagrams in the Higgs bosons decays $H(h;A) \to f\bar{f}\gamma$ ($f\bar{f}$-light fermion-antifermion pair: $f\bar{f} = e^-e^+$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$). The degrees of circular and linear polarization of the gamma quantum, and the degree of longitudinal polarization of the fermion were determined, and the dependence of these characteristics on the polar angle θ and the invariant mass x was studied in detail.

8. Given the cases of arbitrary polarization of supersymmetric particles (charcino and neutralino), the expressions of the differential and full probabilities of the Higgs bosons $H(h;A) \to \chi\text{Ю}_i^-\chi\text{Ю}_j^+$, $H(h;A) \to \chi\text{Ю}_i^0\chi\text{Ю}_j^0$ and $H^\pm \to \chi\text{Ю}_i^\pm\chi\text{Ю}_j^0$ fragmentations were obtained, and the longitudinal and transverse polarization degrees of charcino (neutralino) were determined. By measuring these characteristics in experiments, it is possible to obtain certain information about the parameters of the MSSM.

The main provisions of the dissertation work and the results obtained are reflected in the following scientific papers:

1. Abdullayev, S.Q., Ömərova. E.Ş. Skalyar (psevdoskalyar) bozonun fermion cütünə çevrilməsi // Magistrantların və gənc tədqiqatçıların "Fizika və Astronomiya problemləri" beynəlxalq elmi konfransı, – Bakı, Azərbaycan: – 24 – 25 may, – 2018, – s. 45-48.

2. Омарова, Э.Ш. Циркулярная поляризация γ-кванта в радиационном распаде $H \to f f \gamma$ // Doktorantların və gənc tədqiqatçıların XXIII Respublika elmi konfransı, – Bakı, Azərbaycan: – 2019, – s. 39-41.

3. Abdullayev, S.K., Omarova, E.Sh. Decays of Higgs bosons into fermion-antifermion pair // Russian Physics Journal, – 2018. V. 61, №9, – p. 1603-1612.

4. Abdullayev, S.K., Omarova, E.Sh. Decays of Higgs bosons into a gauge boson and a fermion-antifermion pair // Russian Physics Journal, – 2019. V. 62, №1, – p. 30-39.

5. Abdullayev, S.K., Omarova, E.Sh. Three particle decays of the Higgs bosons in the Minimal Supersymmetric Standard Model // Russian Physics Journal, – 2019. V. 62, №3, – p. 425-435.

6. Abdullayev, S.K., Omarova, E.Sh. Decays of $H(h; A)$ Higgs bosons into two photons (gluons) // Russian Physics Journal, – 2020. V. 62, №9, – p. 1623-1634.

7. Abdullayev, S.K., Omarova, E.Sh. Decays of the Higgs bosons H, h, A and $H^{\pm}$ into a photon and a gauge boson // Russian Physics Journal, – 2020. V. 63, №3, – p. 372-384.

8. Abdullayev, S.K., Omarova, E.Sh. Circular polarization of a γ-quantum in the radiative decay $H \Rightarrow f f \gamma$ Part I // Russian Physics Journal, – 2021. V. 64, №2, – p. 228-236.

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10. Abdullayev, S.K., Omarova, E.Sh. Decays of supersymmetric Higgs bosons into fermions // – Baku: Azerbaijan Journal of Physics, Fizika, – 2018. V. XXIV, №4, – p. 22-34.

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12. Abdullayev, S.K., Omarova, E.Sh. Decay channels of Higgs bosons $H(h; A) \Rightarrow \gamma\gamma(gg)$, $H(h; A) \Rightarrow \gamma Z$, $H^{\pm} \Rightarrow \gamma W^{\pm}$ // – Baku: Journal of Baku Engineering University, Physics, – 2019. V. 3, №1, – p. 39-57.

13. Abdullayev, S.K., Omarova, E.Sh. Polarization effects at Higgs boson decay $H \to f\bar{f}\gamma$ // – Baku: Azerbaijan Journal of Physics, Fizika, – 2020. V. XXVI, №1, – p. 3-12.

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15. Abdullayev, S.K., Omarova, E.Sh. Radiative Higgs boson decay $H(h; A) \to ff\gamma$ in MSSM // –Bakı: Bakı Universitetinin Xəbərləri, Fizika-riyaziyyat elmləri seriyası, – 2020. №2, – p. 65-80.

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17. Abdullayev, S.K., Omarova, E.Sh. The decays of $H(h; A)$ Higgs-bosons into two photons // International Conference "Modern trends in Physics", – Baku, Azerbaijan: – 01 – 03 May, – 2019, – p. 96-98.

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20. Abdullayev, S.K., Omarova, E.Sh. The decay of a top quark via the channel $t \Rightarrow H^+b$ // Magistrantların və gənc tədqiqatçıların XXI "Fizika və Astronomiya problemləri" Ümumrespublika elmi konfransı, – Bakı: – 21 may, – 2021, – s. 16-17.

21. Abdullayev, S.K., Omarova, E.Sh. Higgs boson decays into a chargino pair $H(h; A) \Rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$ // Magistrantların və gənc tədqiqatçıların XXI "Fizika və Astronomiya problemləri" ümumrespublika elmi konfransı, – Bakı, Azərbaycan: – 21 may, – 2021, – s. 18-19.

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23. Omarova, E.Sh. The decay channels of Higgs bosons $H(h; A) \Rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+, H(h; A) \Rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ // – Bakı: Bakı Universitetinin Xəbərləri. Fizika-riyaziyyat elmləri seriyası, – 2021. №3, – s. 105-117.

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