THE PRODUCTİON OF THE HIGGS BOSON AND $t\bar{t}$-PAIR İN POLARIZED $e^{-}e^{+}$-BEAMS

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In the framework of the Standard (Minimal Supersymmetric Standard) model the process of the Higgs boson and heavy $t\bar{t}$-pair production in arbitrarily polarized colliding electron-positron beams $e^{-}e^{+} \to H_{SM}t\bar{t}$ ($e^{-}e^{+} \to Ht\bar{t}$, $e^{-}e^{+} \to ht\bar{t}$) is considered. The characteristic features in the behavior of cross sections and polarization characteristics (left-right spin asymmetry, transverse spin asymmetry) are investigated and revealed, depending on the Higgs boson energy and the invariant quark mass.

Keywords: Standard model, Higgs boson, quark pair, left and right coupling constants, Weinberg parameters.
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1. INTRODUCTION

The Standard model (SM), based on the local gauge symmetry group $SU_C(3)\times SU_L(2)\times U_Y(1)$ describes well the physics of strong, electromagnetic and weak interactions between leptons and quarks [1-3]. A doublet of scalar fields $\varphi = \begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix}$ is introduced into the model, the neutral component of which has a vacuum value different from zero. As a result of spontaneous symmetry breaking due to quantum excitations of the scalar field, a new particle appears – the scalar Higgs boson H_{SM}, and due to interaction with this field gauge bosons, quarks and charged leptons acquire mass. Recently a scalar Higgs boson has been discovered at the LHC collider by the ATLAS and CMS collaborations [4, 5] (see also the reviews [6-8]). In this connection, the theoretical interest in the various channels for the production and decay of the Higgs boson has greatly increased [9-15].

Along with SM, the Minimal Supersymmetric Standard Model (MSSM) is widely discussed in the literature [16]. Here two doublets of the scalar field are introduced and after spontaneous symmetry breaking there appear five Higgs particles: CP-even *H* and *h* bosons, CP-odd *A*-boson and charged H^{+}, H^{-} bosons.

In recent papers [10, 13], we studied the production of the Higgs boson and the light fermion pair $f\bar{f}$ ($f\bar{f} = \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, \mu^{-}\mu^{+}, \tau^{-}\tau^{+}, d\bar{d}, s\bar{s}, c\bar{c}, b\bar{b}$) under the collision of an arbitrarily polarized $e^{-}e^{+}$-pair. In the present paper, we investigate the process of the Higgs boson $H_{SM}(H,h)$ and heavy quark pair $t\bar{t}$ production in annihilation of an arbitrarily polarized electron-positron pair:

$$\begin{aligned} e^{-}+e^{+} &\Rightarrow H_{SM}+t+\bar{t}, \\ e^{-}+e^{+} &\Rightarrow H+t+\bar{t}, \\ e^{-}+e^{+} &\Rightarrow h+t+\bar{t}. \end{aligned} \tag{1}$$

2. THE RADIATION OF HIGGS BOSON BY A VECTOR Z-BOSON

Due to a rather strong connection with the vector Z-boson, the main source of the production of scalar bosons is their emission by the Z-boson, which is produced in colliding electron-positron beams. This process is described by the Feynman diagram shown in Fig. 1, where four-dimensional momenta of the particles are written in the parentheses and also the four-dimensional electron (s_1) and the positron (s_2) spins.

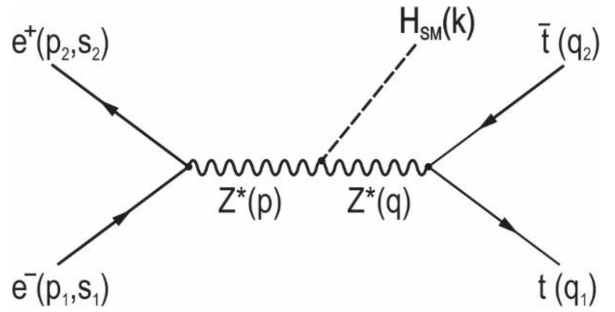

Fig. 1. The Feynman diagram of the reaction $e^{-}e^{+} \to H_{SM}t\bar{t}$.

It is known that the interaction Lagrangians $e^{-}e^{+}$ ($t\bar{t}$) with the Z-boson and the Z-bosons with the scalar Higgs boson H_{SM} are written in the form [1-3]

$$L_{eeZ} = \frac{e}{2\sin\theta_W\cos\theta_W}[g_L(e)\bar{e}\gamma_\mu(1+\gamma_5)e + g_R(e)\bar{e}\gamma_\mu(1-\gamma_5)e]Z_\mu,$$

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$$L_{t\bar{t}Z} = \frac{e}{2\sin\theta_W \cos\theta_W}[g_L(t)\bar{t}\gamma_\mu(1+\gamma_5)t + g_R(t)\bar{t}\gamma_\mu(1-\gamma_5)t]Z_\mu, \quad (2)$$

$$L_{ZZh} = \frac{e}{\sin\theta_W \cos\theta_W} M_Z Z_\mu Z_\rho g_{\mu\rho} H(k).$$

Here M_Z is the mass of the Z^0-boson,

$$g_L(e) = -\frac{1}{2} + \sin^2\theta_W, \quad g_R(e) = \sin^2\theta_W,$$
$$g_L(t) = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W, \quad g_R(t) = -\frac{2}{3}\sin^2\theta_W \quad (3)$$

are left and right coupling constants of an electron and a t-quark with a Z^0-boson, θ_W is the Weinberg angle

On the basis of the Lagrangians (2) we write the matrix element corresponding to the diagram in Fig. 1:

$$M = -i\left(\frac{e}{2\sin\theta_W \cos\theta_W}\right)^3 2M_Z D_Z(s) D_Z(xs)\times$$

$$\times[\bar{\upsilon}(p_2,s_2)\gamma_\mu(g_L(e)(1+\gamma_5) + g_R(e)(1-\gamma_5))u(p_1,s_1)]\times$$

$$\times[\bar{u}(q_1)\gamma_\mu(g_L(t)(1+\gamma_5) + g_R(t)(1-\gamma_5))\upsilon(q_2)], \quad (4)$$

where

$$D_Z(s) = \frac{1}{s - M_Z^2}, \; D_Z(xs) = \frac{1}{xs - M_Z^2}, \quad (5)$$

$s = (p_1 + p_2)^2$ is the square of the total energy of the electron and positron in the center of mass system, x is the invariant mass of the t-quark pair in units of s

$$x = \frac{(q_1 + q_2)^2}{s} = 1 - \frac{2E_H}{\sqrt{s}} + \frac{M_H^2}{s}, \quad (6)$$

E_H and M_H are energy and mass of a scalar boson H_{SM}.

The square of the matrix element (4) is given by:

$$|M|^2 = \left(\frac{e^2}{4x_w(1-x_w)}\right)^3 \cdot 4M_Z^2 D_Z^2(s) D_Z^2(xs) \cdot T_{\mu\nu}^{(1)} \cdot T_{\mu\nu}^{(2)}, \quad (7)$$

where $x_W = \sin^2\theta_W$ is Weinberg parameter, $T_{\mu\nu}^{(1)}$ and $T_{\mu\nu}^{(2)}$ are tensors of electron-positron and t-quark pair determined by the expressions:

$$T_{\mu\nu}^{(1)} = Sp[\upsilon(p_2,s_2)\bar{\upsilon}(p_2,s_2)\gamma_\mu(g_L(e)(1+\gamma_5) + g_R(e)(1-\gamma_5))\times$$

$$\times u(p_1,s_1)\bar{u}(p_1,s_1)\gamma_\nu(g_L(e)(1+\gamma_5) + g_R(e)(1-\gamma_5))] =$$

$$= Sp\left[\frac{1}{2}(\hat{p}_2 - m)(1-\gamma_5\hat{s}_2)\gamma_\mu(g_L(e)(1+\gamma_5)+g_R(e)(1-\gamma_5))\times\right.$$

$$\left.\times\frac{1}{2}(\hat{p}_1+m)(1-\gamma_5\hat{s}_1)\gamma_\nu(g_L(e)(1+\gamma_5)+g_R(e)(1-\gamma_5)\right] = 2[g_L^2(e)+g_R^2(e)]\times$$

$$\times[p_{2\mu}p_{1\nu}+p_{1\mu}p_{2\nu}-(p_1p_2)g_{\mu\nu}-m^2(s_{2\mu}s_{1\nu}+s_{1\mu}s_{2\nu}-(s_1s_2)g_{\mu\nu})-$$

$$-im\varepsilon_{\mu\nu\rho\sigma}(p_{2\rho}s_{1\sigma}+p_{1\rho}s_{2\sigma})]+2[g_L^2(e)-g_R^2(e)][m(s_{2\mu}p_{1\nu}+p_{1\mu}s_{2\nu}-(p_1s_2)g_{\mu\nu}-$$

$$-p_{2\mu}s_{1\nu}-s_{1\mu}p_{2\nu}+(p_2s_1)g_{\mu\nu})-i\varepsilon_{\mu\nu\rho\sigma}(p_{1\rho}p_{2\sigma}-m^2s_{1\rho}s_{2\sigma})]+4g_L(e)g_R(e)]\times$$

$$\times[-(p_1p_2)(s_{1\mu}s_{2\nu}+s_{2\mu}s_{1\nu}-(s_1s_2)g_{\mu\nu}-(s_1s_2)(p_{2\mu}p_{1\nu}+p_{1\mu}p_{2\nu})+(p_2s_1)(s_{2\mu}p_{1\nu}+$$

$$+p_{1\mu}s_{2\nu}-(s_2p_1)g_{\mu\nu})+(p_1s_2)(s_{1\mu}p_{2\nu}+p_{2\mu}s_{1\nu})-im\varepsilon_{\mu\nu\rho\sigma}(p_{1\rho}s_{1\sigma}+p_{2\rho}s_{2\sigma})],$$

$$T_{\mu\nu}^{(2)} = Sp[u(q_1)\overline{u}(q_1)\gamma_\mu(g_L(t)(1+\gamma_5)+g_R(t)(1-\gamma_5))\times$$

$$\times\upsilon(q_2)\overline{\upsilon}(q_2)\gamma_\nu(g_L(t)(1+\gamma_5)+g_R(t)(1-\gamma_5))] =$$

$$= Sp[(\hat{q}_1+m_t)\gamma_\mu(g_L(t)(1+\gamma_5)+g_R(t)(1-\gamma_5))\times$$

$$\times(\hat{q}_2-m_t)\gamma_\nu(g_L(t)(1+\gamma_5)+g_R(t)(1-\gamma_5)] =$$

$$= 8[g_L^2(t)+g_R^2(t)][q_{2\mu}q_{1\nu}+q_{1\mu}q_{2\nu}-(q_1q_2)g_{\mu\nu}]+$$

$$+8i[g_L^2(t)-g_R^2(t)]\varepsilon_{\mu\nu\rho\sigma}q_{1\rho}q_{2\sigma}-16g_L(t)g_R(t)m_t^2g_{\mu\nu}. \quad (9)$$

Here m and m_t are the masses of the electron and *t*-quark.

The product of tensors $T_{\mu\nu}^{(1)}$ and $T_{\mu\nu}^{(2)}$ gives an expression (in the integration over the momenta of the t-quark pair the antisymmetric part of the tensor $T_{\mu\nu}^{(2)}$ vanishes, for this reason this part is not taken into account):

$$T_{\mu\nu}^{(1)}T_{\mu\nu}^{(2)} = 32[g_L^2(e)+g_R^2(e)]\{[g_L^2(t)+g_R^2(t)][(p_1q_1)(p_2q_2)+(p_1q_2)(p_2q_1)-$$

$$-m^2((s_1q_1)(s_2q_2)+(s_1q_2)(s_2q_1))]+2g_L(t)g_R(t)m_t^2[(p_1p_2)-m^2(s_1s_2)]\}+$$

$$+32[g_L^2(e)-g_R^2(e)]m\{[g_L^2(t)+g_R^2(t)][(p_1q_1)(q_2s_2)+(p_1q_2)(q_1s_2)-(p_2q_2)(s_1q_1)-$$

$$-(q_1p_2)(s_1q_2)]-2g_L(t)g_R(t)m_t^2[(p_2s_1)-(p_1s_2)]\}+64g_L(e)g_R(e)[g_L^2(t)+g_R^2(t)]\times$$

$$\times\{-(p_1p_2)[(s_1q_1)(s_2q_2)+(s_1q_2)(s_2q_1)]-(s_1s_2)[(p_1q_1)(p_2q_2)+(p_1q_2)(p_2q_1)-$$

$$-(p_1p_2)(q_1q_2)]+(p_2s_1)[(s_2q_1)(p_1q_2)+(s_2q_2)(p_1q_1)]\}. \quad (10)$$

The integration over the momenta of the t-quark pair is carried out by the invariant method [1, 2, 10].

Integral

$$I_{\mu\nu}=\int q_{1\mu}q_{2\nu}\frac{d\vec{q}_1}{E_1}\frac{d\vec{q}_2}{E_2}\delta(q_1+q_2-q) \tag{11}$$

is a second-rank tensor depending only on the 4-dimensional momentum $q=p-k$:

$$I_{\mu\nu}=Aq^2g_{\mu\nu}+Bq_\mu q_\nu\,, \tag{12}$$

where *A* and *B* are scalar functions. To find them, we multiply expression (11) first by $g_{\mu\nu}$, and then by $q_\mu q_\nu$:

$$\begin{aligned} g_{\mu\nu}I_{\mu\nu}&=(4A+B)q^2,\\ q_\mu q_\nu I_{\mu\nu}&=(A+B)q^4. \end{aligned} \tag{13}$$

Hence we find:

$$A=\frac{1}{3q^2}\left[g_{\mu\nu}I_{\mu\nu}-\frac{1}{q^2}q_\mu q_\nu I_{\mu\nu}\right]. \tag{14}$$

Let us calculate the integrals

$$g_{\mu\nu}I_{\mu\nu}=\int(q_1q_2)\frac{d\vec{q}_1}{E_1}\cdot\frac{d\vec{q}_2}{E_2}\delta(q_1+q_2-q)=(q_1q_2)\cdot I=\left(\frac{1}{2}q^2-m_t^2\right)\cdot I,$$

$$q_\mu q_\nu I_{\mu\nu}=(q\cdot q_1)(q\cdot q_2)\cdot I=\frac{1}{4}q^4I.$$

The resulting integral I is easily calculated in the center of mass system of the quark and antiquark

$$I=\int\frac{d\vec{q}_1}{E_1}\frac{d\vec{q}_2}{E_2}\delta(q_1+q_2-q)=2\pi\sqrt{1-\frac{4m_t^2}{q^2}}\,. \tag{15}$$

For the scalar function *A* we obtain the expression:

$$A=\frac{\pi}{6}\left(1-\frac{4m_t^2}{q^2}\right)^{\frac{3}{2}}. \tag{16}$$

Similarly, the function *B* is calculated*:*

$$B=\frac{1}{q^4}q_\mu q_\nu I_{\mu\nu}-A=\frac{\pi}{3}\sqrt{1-\frac{4m_t^2}{q^2}}\left(1+\frac{2m_t^2}{q^2}\right). \tag{17}$$

When annihilating electron-positron pair is arbitrarily polarized for the angular and energy distributions of the Higgs boson in the reaction $e^-+e^+\Rightarrow H_{SM}+t+\bar{t}$ is obtained expression:

$$d\sigma=\frac{N_C}{24\pi}\left(\frac{\alpha_{KED}}{x_W(1-x_W)}\right)^3M_Z^2sk_HdE_Hd\Omega_HD_Z^2(s)D_Z^2(xs)\times$$

$$\times\sqrt{1-\frac{4m_t^2}{xs}}\Big\{[g_L^2(e)(1-\lambda_1)(1+\lambda_2)+g_R^2(e)(1+\lambda_1)(1-\lambda_2)]\cdot\Big[(g_L^2(t)+g_R^2(t))\left(2\left(x-\frac{m_t^2}{s}\right)+\right.$$

$$+\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{s}\sin^2\theta\right)+12g_L(t)g_R(t)\cdot\frac{m_t^2}{s}\Bigg]+2g_L(e)g_R(e)[(g_L^2(t)+g_R^2(t)]\times$$

$$\times\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{s}\sin^2\theta\cdot\cos2\varphi\cdot\eta_1\eta_2\Bigg\}. \qquad (19)$$

Here $N_C = 3$ is the color factor, λ_1 and λ_2 are the helicity of the electron and positron, η_1 and η_2 are the transverse components of their spin vectors, θ and φ are the polar and azimuth angles of the Higgs boson.

In the case of a longitudinally polarized electron-positron pair the differential cross section of the process can be represented in the form:

$$\frac{d\sigma(\lambda_1,\lambda_2)}{dxd\Omega_H}=\frac{d\sigma_0}{dxd\Omega_H}\;[(1-\lambda_1\lambda_2)+(\lambda_2-\lambda_1)A_{LR}], \qquad (19)$$

where

$$\frac{d\sigma_0}{dxd\Omega_H}=\frac{N_C}{48\pi}\left(\frac{\alpha_{KED}}{x_W(1-x_W)}\right)^3 M_Z^2 s\sqrt{s}k_H D_Z^2(s)D_Z^2(xs)\times$$

$$\times\sqrt{1-\frac{4m_t^2}{xs}}[g_L^2(e)+g_R^2(e)]\cdot\Bigg\{(g_L^2(t)+g_R^2(t))\Bigg[2\left(x-\frac{m_t^2}{s}\right)+$$

$$+\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{s}\sin^2\theta\Bigg]+12g_L(t)g_R(t)\cdot\frac{m_t^2}{s}\Bigg\} \qquad (20)$$

is differential cross section of the process in the case of unpolarized particles and

$$A_{LR}=\frac{g_L^2(e)-g_R^2(e)}{g_L^2(e)+g_R^2(e)}=\frac{\frac{1}{4}-x_W}{\frac{1}{4}-x_W+2x_W^2}. \qquad (21)$$

is left-right spin asymmetry due to longitudinal polarization of the electron. This asymmetry depends only on the Weinberg parameter x_W and at a value of this parameter x_W = 0.232 it is equal to $A_{LR} = 14\%$.

When the electron-positron pair is polarized transversally the cross section is:

$$\frac{d\sigma(\eta_1,\eta_2)}{dxd\Omega_H}=\frac{d\sigma_0}{dxd\Omega_H}\;[1+A(\theta,\varphi)\cdot\eta_1\eta_2], \qquad (22)$$

where

$$A(\theta,\varphi)=\frac{2g_L(e)g_R(e)}{g_L^2(e)+g_R^2(e)}\cdot\frac{\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{s}\sin^2\theta\cdot\cos2\varphi}{2\left(x-\frac{m_t^2}{s}\right)+\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{s}\sin^2\theta+\frac{12g_L(t)g_R(t)}{g_L^2(t)+g_R^2(t)}\cdot\frac{m_t^2}{s}} \qquad (23)$$

is azimuthal angular asymmetry (this asymmetry is also called transverse spin asymmetry, since it is connected by transverse polarizations of the electron and the positron).

Fig. 2 shows the angular dependence of the transverse spin asymmetry $A(\theta,\varphi=0)$ at $\sqrt{s}=1000$ *GeV*,

E_H =440 *GeV*, $M_H = 125$ *GeV* and $x_W = 0{,}232$ (everywhere taken $\sin^2\theta_W = x_W = 0{,}232$).

As can be seen the transverse spin asymmetry is negative, the asymmetry at zero angle of the Higgs boson emission is zero, with an increase in the angle θ the asymmetry decreases and reaches a minimum at an angle of $\theta = 90°$ and then the asymmetry again increases and reaches a zero at the end of the angular spectrum.

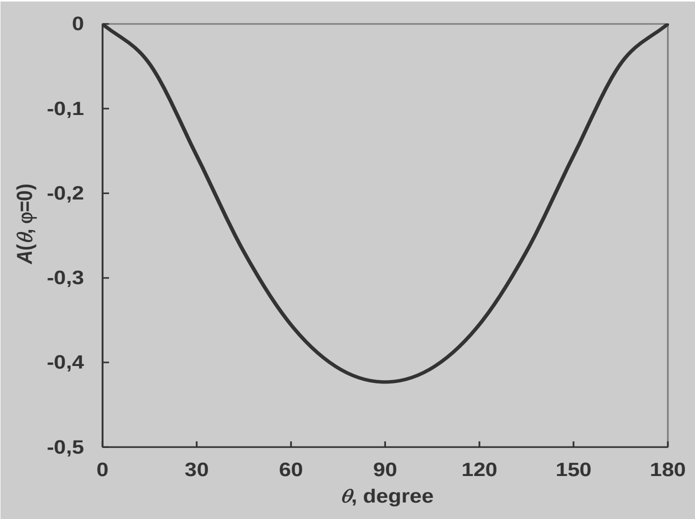

Fig. 2. The angular dependence of the transverse spin asymmetry in the process $e^-e^+ \to H_{SM}t\bar{t}$.

The transverse spin asymmetry integrated over the polar angle θ is expressed by the formula

$$A(\varphi) = \frac{2g_L(e)g_R(e)}{g_L^2(e)+g_R^2(e)} \cdot \frac{\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{3s}\cdot\cos 2\varphi}{x-\frac{m_t^2}{s}+\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{3s}+\frac{6g_L(t)g_R(t)}{g_L^2(t)+g_R^2(t)}\cdot\frac{m_t^2}{s}}. \quad (24)$$

Fig. 3 illustrates the dependence of the transverse spin asymmetry $A(\varphi = 0)$ on the energy of the scalar Higgs boson at $\sqrt{s} = 1000$ *GeV* and $M_H = 125$ *GeV*.

At a minimum Higgs bosons energy of the $E_H = M_H = 125$ *GeV*, the transverse spin asymmetry is zero, from Fig. 3 it follows that the asymmetry is negative and decreases with increasing boson energy, and at the end of the enegy spectrum reaches the value $A(\varphi = 0) = -0{,}79$.

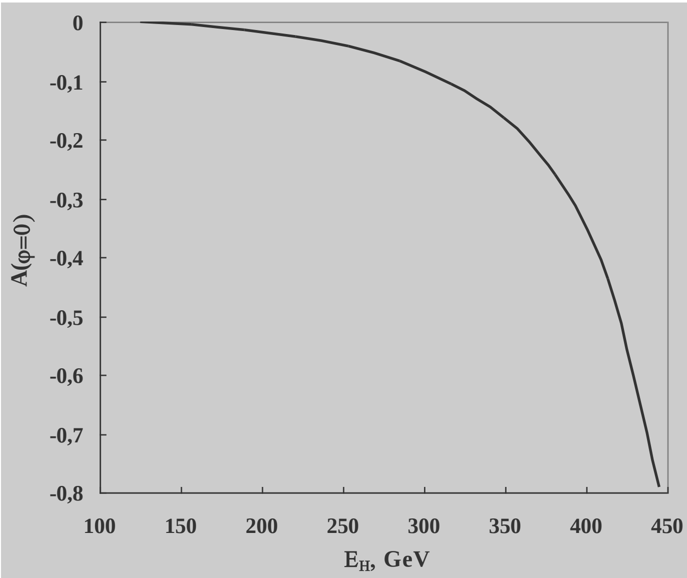

Fig. 3. The energy dependence of the transverse spin asymmetry in the reaction $e^-e^+ \to H_{SM}t\bar{t}$.

Integrating the cross section (20) over the angles of the emission of the Higgs boson, in the case of unpolarized particles we find the following expression for the distribution of $t\bar{t}$ -quark pairs with respect to the invariant mass:

$$\frac{d\sigma_0}{dx} = \frac{N_C}{6}\left(\frac{\alpha_{KED}}{x_W(1-x_W)}\right)^3 M_Z^2 s\sqrt{s}k_H D_Z^2(s)D_Z^2(xs)\sqrt{1-\frac{4m_t^2}{xs}}[g_L^2(e)+g_R^2(e)]\times$$

$$\times\left\{(g_L^2(t)+g_R^2(t))\left[x-\frac{m_t^2}{s}+\left(1+\frac{2m_t^2}{xs}\right)\frac{k_H^2}{3s}\right]+6g_L(t)g_R(t)\cdot\frac{m_t^2}{s}\right\}. \quad (25)$$

Fig. 4 shows the dependence of the cross section of the process $e^- + e^+ \to H_{SM} + t + \bar{t}$ on the invariant mass of *x* at an energy of e^-e^+ -beams $\sqrt{s} = 1000$ GeV and a mass of $M_H = 125$ GeV. According to this figure, with an increase in the invariant mass the cross section decreases monotonically from 2.6 fb to 0.07 fb.

As for the differential cross sections for the processes $e^- + e^+ \to H + t + \bar{t}$ and $e^- + e^+ \to h + t + \bar{t}$, we note that, according to the MSSM, the vertex of the interaction ZZH (ZZh) contains a constant $g_{ZZH}(g_{ZZh})$, where $g_{ZZH} = \frac{eM_Z}{\sin\theta_W\cdot\cos\theta_W}\cdot\cos(\beta-\alpha)$ $\left(g_{ZZh} = \frac{eM_Z}{\sin\theta_W\cdot\cos\theta_W}\cdot\sin(\beta-\alpha)\right)$, where β and α are some parameters of the MSSM [16]. Consequently, the differential cross sections of the processes $e^- + e^+ \to H + t + \bar{t}$ and $e^- + e^+ \to h + t + \bar{t}$ will differ from the cross section of the reaction $e^- + e^+ \to H_{SM} + t + \bar{t}$ by the presence of an additional factor $\cos^2(\beta-\alpha)$ and $\sin^2(\beta-\alpha)$.

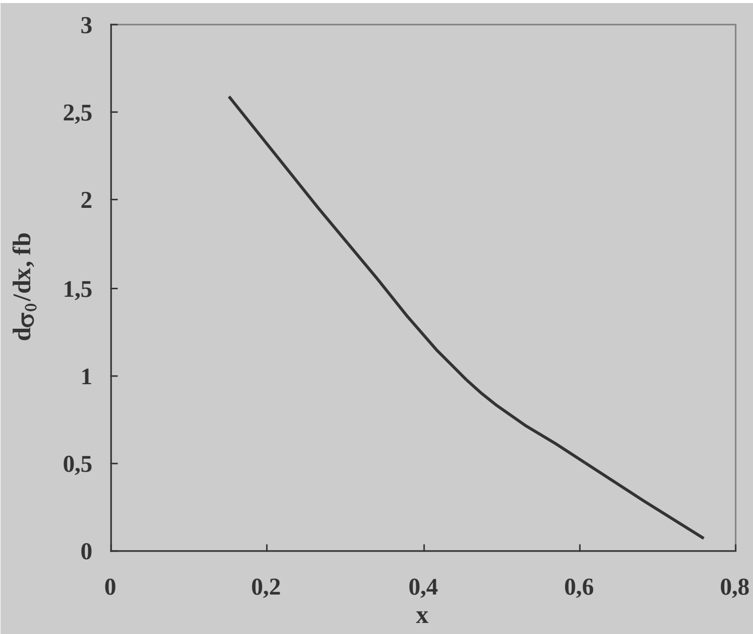

Fig. 4. Dependence of the cross section for the process $e^-e^+ \to H_{SM}t\bar{t}$ on the invariant mass x

We note that in the process $e^- + e^+ \to H_{SM} + t + \bar{t}$ along with the Feynman diagram, shown in Fig. 1, there are other diagrams where the Higgs boson H_{SM} radiation comes from the t -quark or $\bar{t}$ -antiquark line (see Fig. 5). However, the calculation of these diagrams will be given in a separate article.

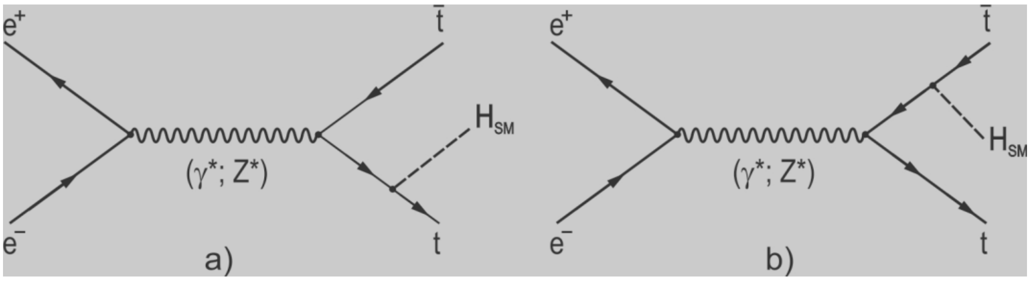

Fig. 5. The Feynman diagrams of the reaction $e^- + e^+ \to H_{SM} + t + \bar{t}$

3. CONCLUSION

Thus, we discussed the processes of the production of a Higgs boson $H_{SM}(H;h)$ and a t-quark pair in the annihilation of an arbitrarily polarized electron-positron pair:

$$e^- + e^+ \to H_{SM} + t + \bar{t}\,,\ e^- + e^+ \to H + t + \bar{t}\,,\ e^- + e^+ \to h + t + \bar{t}\,.$$

Analytic expressions are obtained for differential cross sections, left-right and transverse spin asymmetries. The dependences of the polarization characteristics and cross sections on the emission angle and the energies of the scalar boson, on the invariant mass the t-quark pair, are investigated. The results are presented in the form of graphs.

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