THE PRODUCTION OF A CHARGINO PAIR IN POLARIZED LEPTON-ANTILEPTON COLLISIONS (II)

S.K. ABDULLAYEV, M.Sh. GOJAYEV, A.K. GULAYEVA
Baku State University, Azerbaijan, AZ 1148,
Baku, st. Z. Khalilova, 23, m_qocayev@mail.ru

Within the framework of the Minimal Supersymmetric Standard Model, the process of annihilation of a lepton-antilepton pair into a pair of charginos is considered: $\ell^- + \ell^+ \to \tilde{\chi}_i^- + \tilde{\chi}_j^+$. Taking into account the polarization states of the lepton-antilepton pair and the chargino, an analytical expression is obtained for the effective cross section of the process. Diagrams with the exchange of Higgs bosons H, h, A and scalar neutrinos $\tilde{\nu}_L$ are considered in detail. The longitudinal and transverse spin asymmetries caused by the polarizations of the lepton and antilepton, as well as the degrees of the longitudinal and transverse polarization of the chargino, are determined. It is found that the longitudinal spin asymmetry arising from the interaction of polarized leptons with unpolarized antileptons is equal to the longitudinal spin asymmetry arising from the interaction of polarized antileptons with unpolarized leptons.

Keywords: Minimal Supersymmetric Standard Model, Higgs boson, lepton-antilepton pair, chargino, longitudinal spin asymmetry, transverse spin asymmetry.
PACS: 12.10.−g, 12.15.-y, 12.60.−i, 14.80.Ly, 14.70.Bh, 14.70.Hp

1. INTRODUCTION

With the discovery of the Higgs boson H_{SM} at the Large Hadron Collider (LHC) by the ATLAS and CMS collaborations in 2012 [1, 2] (see also reviews [3-5]), a new era in elementary particle physics began. The Standard Model (CM) of fundamental interactions received its logical conclusion and acquired the status of a standard theory. According to SM, there are six leptons and six quarks in nature, making up three generations and three types of interactions: electromagnetic, weak and strong, which are transported by a photon, $W^{\pm}$, Z -bosons and gluons (gravitational interaction is still described by Einstein's general theory of relativity). Now they are supplemented by the Yukawa interaction carried by the Higgs boson H_{SM}. Based on the SM, one can calculate Feynman diagrams of various processes and compare them with the corresponding experimental data. The agreement between standard theory and empirical evidence is convincing.

Despite the success of SM, this theory has its own difficulties. One of the difficulties is related to the renormalization of the Higgs boson mass. The fact is that for all SM particles, the mass renormalization works well, and in the case of the Higgs boson H_{SM} a problem arises: the vacuum has a strong effect on the mass of the Higgs boson, its mass increases trillions of times, and such a particle can no longer play the role of the Higgs boson. Note that there is no restraining factor inside the SM that stops the growth of the Higgs boson mass due to virtual particles. Here such a way out of the difficult situation is possible. If there are some other particles in nature that are absent in the SM, then in virtual form they can compensate for the increase in the Higgs boson mass. In the Minimal Supersymmetric Standard Model (MSSM), the compensation of the Higgs boson masses arises by itself by the construction of the theory.

The MSSM introduces two doublets of the scalar field with hypercharges –1 and +1 [6-10]:

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

To obtain physical Higgs bosonic fields φ_1 and φ_2 are written 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 and P_2^0 are the fields describing the excitations of the system with respect to vacuum states $<\varphi_1>=\frac{1}{\sqrt{2}}\upsilon_1$ and $<\varphi_2>=\frac{1}{\sqrt{2}}\upsilon_2$.

By mixing the fields H_1^0 and H_2^0, one obtains CP-even Higgs bosons H and h (mixing angle α):

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

Similarly, the fields P_1^0 and P_2^0 are mixed, as well as $H_1^{\pm}$ and $H_2^{\pm}$ and get the Goldston bosons G^0 and the CP-odd Higgs boson A, Goldston bosons $G^{\pm}$ and charged Higgs bosons $H^{\pm}$ (mixing angle β):

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

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

Thus, five Higgs bosons appear in the MSSM:

131, H.Javid ave, AZ-1143, Baku
ANAS, Institute of Physics
E-mail: jophphysics@gmail

CP-even H and h bosons, CP-odd A-boson and charged $H^{\pm}$-bosons. In this model, the Higgs sector is characterized by mass parameters M_H, M_h, M_A, $M_{H^{\pm}}$ and angular parameters α and β. Of these, only two parameters are considered free: mass M_A and angle $\mathrm{tg}\beta$. The rest of the parameters are expressed through them:

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

$$M^2_{H^{\pm}} = M^2_A + M^2_Z,$$

$$\mathrm{tg}2\alpha = \mathrm{tg}2\beta \frac{M^2_A + M^2_Z}{M^2_A - M^2_Z}, \quad \left(-\frac{\pi}{2} \le \alpha < 0\right),$$

M_Z and M_W – masses of gauge Z- and $W^{\pm}$-bosons.

Wine $\widetilde{W}^{\pm}$ and higgsino $\widetilde{H}^{\pm}$ are superpartners of gauge $W^{\pm}$- and charged Higgs $H^{\pm}$-bosons. The mass matrix of wine $\widetilde{W}^{\pm}$ and higgsino $\widetilde{H}^{\pm}$ is nondiagonal, which results in mixing of these spinor fields. The resulting new particles are called charjions $\widetilde{\chi}^{\pm}_{1,2}$. The masses and constants of interaction with Higgs bosons are determined by the mass matrix [6, 10]

$$M_C = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin\beta \\ \sqrt{2}M_W \cos\beta & \mu \end{pmatrix},$$

where M_2 and μ – are the mass parameters of wine $\widetilde{W}^{\pm}$ and higgsino $\widetilde{H}^{\pm}$. The matrix M_C is diagonalized by two real two-row matrices U and V. After diagonalizing the matrix M_C, new chargino states with masses are obtained

$$m^2_{\widetilde{\chi}^{\pm}_{1,2}} = \frac{1}{2}\{M^2_2 + \mu^2 + 2M^2_W \mp \sqrt{(M^2_2 - \mu^2)^2 + 4M^2_W(M^2_W \cos^2 2\beta + M^2_2 + \mu^2 + 2M_2\mu \sin 2\beta)}\}.$$

With a very large value of the parameter $|\mu|$ ($|\mu| \to \infty$), light chargino corresponds to the state of wine with mass $m_{\widetilde{\chi}^{\pm}_1} \approx M_2$, and heavy chargino corresponds to the state of higgsino with mass $m_{\widetilde{\chi}^{\pm}_2} \approx |\mu|$. However, when $M_2 >> |\mu|$ and $|\mu| \sim M_Z$ both chargino $\widetilde{\chi}^{\pm}_1$ and $\widetilde{\chi}^{\pm}_2$ exchange roles: $m_{\widetilde{\chi}^{\pm}_1} \approx |\mu|$, $m_{\widetilde{\chi}^{\pm}_2} \approx M_2$.

Supersymmetric (SUSY) particles can be produced in the LHC in the decays of squarks and gluinos: $\widetilde{g} \to q + \widetilde{q}$, $\widetilde{q} \to q + \widetilde{\chi}_i$. One of the main sources of pair production of charginos is high-energy lepton-antilepton (electron-positron and muon-antimuon) colliders of the new generation [11, 12].

In a number of works, the processes of production of a pair of charginos and neutralinos in electron-positron collisions have been considered [14-16].

In the present work, we study the process of creation of a chargino pair upon annihilation of an arbitrarily polarized lepton-antilepton pair:

$$\ell^- + \ell^+ \to \widetilde{\chi}^-_i + \widetilde{\chi}^+_j. \tag{1}$$

Taking into account the polarization states of the lepton-antilepton pair and the chargino, an analytical expression is obtained for the effective cross section of reaction (1).

The longitudinal and transverse spin asymmetries caused by the polarizations of the lepton-antilepton pair, as well as the degrees of the longitudinal and transverse polarization of the chargino, have been determined. The dependence of these characteristics and the cross section of reaction (1) was studied depending on the energy of the lepton-antilepton pair and the angle θ.

2. AMPLITUDE AND WIDTH OF DECAY $\ell^-\ell^+ \to \widetilde{\chi}^-_i \widetilde{\chi}^+_j$

The annihilation of a lepton-antilepton pair into a chargino pair is described by the Feynman diagrams shown in Fig. 1 a), b) and c) (4-momenta and polarization vectors of particles are written in brackets). Diagram 1a) corresponds to the exchange of a photon and a neutral Z-boson between a lepton-antilepton pair and a chargino pair. This diagram was studied in detail in the first work (I) [13].

The second diagram corresponds to the exchange of a virtual Higgs boson Φ^* (H^*, h^* or A^*). From this diagram for the matrix element of the process $\ell^- + \ell^+ \to \widetilde{\chi}^-_i + \widetilde{\chi}^+_j$, we obtain the following expression (we assume that the intermediate Φ^*-boson interacting with the lepton-antilepton pair simultaneously possesses CP-even and CP-odd components):

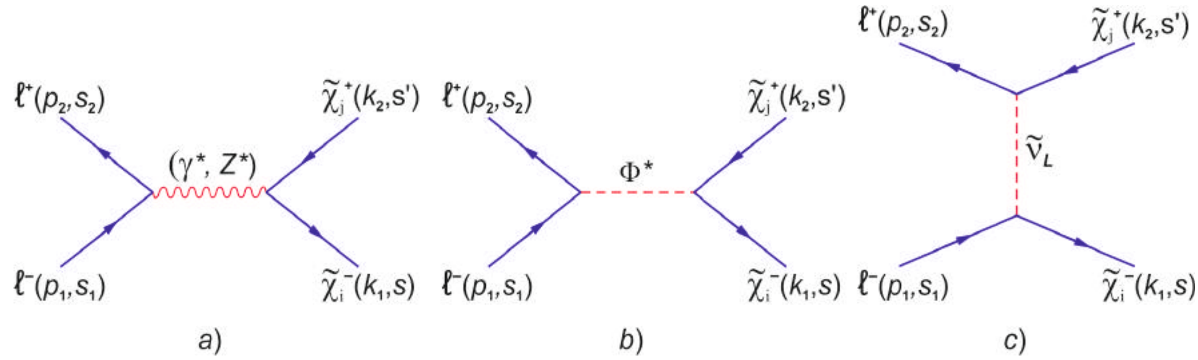

Fig. 1. Feynman diagrams of process $\ell^-\ell^+ \to \tilde{\chi}_i^-\tilde{\chi}_j^+$.

$$M_{i\to f} = ig_{\Phi\ell\ell}[\overline{\upsilon}(p_2,s_2)(a+b\gamma_5)u(p_1,s_1)]\cdot\frac{1}{s-M_\Phi^2+i\Gamma_\Phi M_\Phi}\times$$
$$\times g[\overline{u}(k_1,s)(g_{ijk}^L P_L + g_{ijk}^R P_R)\upsilon(k_2,s')]. \quad (2)$$

Here $g_{\Phi\ell\ell}$ – is the constant of interaction of a Φ-boson with a lepton-antilepton pair; a and b – are some constants, and at a=1 and b=0 the Φ-boson is CP-even (like the bosons H, h), and at a=0 and b=1 we obtain the CP-odd A-boson; $\frac{1}{s-M_\Phi^2+i\Gamma_\Phi M_\Phi}$ – Φ-boson propagator; M_Φ and Γ_Φ – its mass and overall width; g – is the constant that determines the mass of the calibration $W^\pm$-boson

$$M_W^2 = \frac{1}{2}g^2(\upsilon_1^2+\upsilon_2^2);$$

$P_{L,R} = \frac{1}{2}(1\pm\gamma_5)$ – chirality matrices; $g_{ijk}^L = G_L$ and $g_{ijk}^R = G_R$ – Higgs boson coupling constants H_k ($k=1,2,3$ for H, h, A bosons) with a chargino pair [6-8]:

$$G_L = \frac{1}{\sqrt{2}\sin\theta_W}[U_{i2}V_{j1}e_k - U_{i1}V_{j2}d_k],$$
$$G_R = \frac{1}{\sqrt{2}\sin\theta_W}[V_{i1}U_{j2}e_k - V_{i2}U_{j1}d_k]\varepsilon_k; \quad (3)$$

θ_W – Weinberg angle; $\varepsilon_1=\varepsilon_2=1$, $\varepsilon_3=-1$; coefficients e_k and d_k are equal:

$$e_1=+\cos\alpha,\quad e_2=-\sin\alpha,\quad e_3=-\sin\beta,$$
$$d_1=-\sin\alpha,\quad d_2=-\cos\alpha,\quad d_3=+\cos\beta.$$

In a standard way, for the square of the amplitude, we find:

$$\left|M_{i\to f}\right|^2 = \frac{g_{\Phi\ell\ell}^2 g^2}{(s-M_\Phi^2)^2+\Gamma_\Phi^2 M_\Phi^2}\cdot\frac{1}{2}\{[|a|^2+|b|^2][(p_1\cdot p_2)+m_\ell^2(s_1\cdot s_2)]+[|a|^2-|b|^2]\times$$
$$\times[-m_\ell^2-(s_1\cdot s_2)(p_1\cdot p_2)+(p_1\cdot s_2)(p_2\cdot s_1)]-2\operatorname{Re}(ab^*)m_\ell[(p_1\cdot s_2)+(p_2\cdot p_1)]-$$
$$-2\operatorname{Im}(ab^*)p_{1\mu}p_{2\nu}s_{1\rho}s_{2\sigma}\varepsilon_{\mu\nu\rho\sigma}\}\times\{(G_L^2+G_R^2)[(k_1\cdot k_2)+m_{\tilde{\chi}_i^-}m_{\tilde{\chi}_j^+}(s\cdot s')]+$$
$$+(G_L^2-G_R^2)[m_{\tilde{\chi}_i^-}(k_2\cdot s)+m_{\tilde{\chi}_j^+}(k_1\cdot s')]+2G_LG_R[-m_{\tilde{\chi}_i^-}m_{\tilde{\chi}_j^+}-(k_1\cdot k_2)(s\cdot s')+(k_1\cdot s')(k_2\cdot s)]\},$$

where m_ℓ – is the lepton mass

Let us find the effective cross section for reaction (1) in the case when the lepton-antilepton pair is polarized arbitrarily, and the chargino pair is polarized longitudinally:

$$\sigma = \frac{g_{\Phi\ell\ell}^2 g^2 s}{2^7[(s-M_\Phi^2)^2+\Gamma_\Phi^2 M_\Phi^2]}\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\cdot\{[|a|^2+|b|^2][1-(\vec{n}\vec{\xi}_1)(\vec{n}\vec{\xi}_2)]+[|a|^2-|b|^2]\times$$
$$\times[(\vec{\xi}_1\vec{\xi}_2)-(\vec{n}\vec{\xi}_1)(\vec{n}\vec{\xi}_2)]+2\operatorname{Re}(ab^*)[(\vec{n}\vec{\xi}_2)-(\vec{n}\vec{\xi}_1)]-2\operatorname{Im}(ab^*)(\vec{n}[\vec{\xi}_1\vec{\xi}_2])\}\{(G_L^2+G_R^2)\times$$
$$\times(1-r_{\chi_i}-r_{\chi_j})(1+h_1h_2)+(G_L^2-G_R^2)(h_1+h_2)\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}-4G_LG_R(1+h_1h_2)\sqrt{r_{\chi_i}\cdot r_{\chi_j}}\}. \quad (4)$$

Here $\vec{n}$ – is the unit vector directed along the lepton momentum; $\vec{\xi}_1$ and $\vec{\xi}_2$ – are unit vectors directed along the spins of the lepton and antilepton in the rest systems of each of these particles, respectively; h_1 and h_2 – helicity of chargino $\tilde{\chi}_i^-$ and $\tilde{\chi}_j^+$; $s=(p_1+p_2)^2$ – the square of the total energy of a lepton-antilepton pair in their center-of-mass system; $\lambda(r_{\chi_i}, r_{\chi_j})$ – is the known kinematic function of the two-particle phase volume:

$$\lambda(r_{\chi_i}, r_{\chi_j}) = (1-r_{\chi_i}-r_{\chi_j})^2 - 4r_{\chi_i}r_{\chi_j},$$

where the notation:

$$r_{\chi_i} = \left(\frac{m_{\tilde{\chi}_1^-}}{\sqrt{s}}\right)^2, \quad r_{\chi_j} = \left(\frac{m_{\tilde{\chi}_2^+}}{\sqrt{s}}\right)^2.$$

Let us consider some special cases of the effective cross section (4). First, assume that the lepton-antilepton pair is longitudinally polarized:

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

where λ_1 and λ_2 – are the helicities of the lepton and antilepton. In this case, the effective section (4) takes the form

$$\sigma = \frac{g^2_{\Phi\ell\ell}g^2 s}{2^7[(s-M_\Phi^2)^2+\Gamma_\Phi^2 M_\Phi^2]}\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\cdot\{[|a|^2+|b|^2](1+\lambda_1\lambda_2)-2\,\mathrm{Re}(ab^*)(\lambda_1+\lambda_2)\}\cdot\{(G_L^2+G_R^2)\times$$

$$\times(1+h_1h_2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R(1+h_1h_2)\sqrt{r_{\chi_i}\cdot r_{\chi_j}}+(G_L^2-G_R^2)(h_1+h_2)\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\}. \quad (5)$$

As can be seen from this section, the lepton and antilepton, as well as the charginos $\tilde{\chi}_i^-$ and $\tilde{\chi}_j^+$ separately, must have the same helicities: $\lambda_1 = -\lambda_2 = \pm 1$, $h_1 = h_2 = \pm 1$. Consequently, diagram b) in Fig. 1 corresponds to four spiral sections:lepton-antilepton pair and chargino $\tilde{\chi}_i^-$ and $\tilde{\chi}_j^+$ polarized right ($\lambda_1 = \lambda_2 = h_1 = h_2 = +1$):

$$\sigma_{RRRR} \sim |a-b|^2\{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}r_{\chi_j}}+(G_L^2-G_R^2)\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\}; \quad (6)$$

lepton-antilepton pair and chargino $\tilde{\chi}_i^-$, $\tilde{\chi}_j^+$ polarized to the left ($\lambda_1 = \lambda_2 = h_1 = h_2 = -1$):

$$\sigma_{LLLL} \sim |a+b|^2\{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}r_{\chi_j}}-(G_L^2-G_R^2)\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\}; \quad (7)$$

the lepton-antilepton pair is polarized to the right, and the chargino $\tilde{\chi}_i^-$ and $\tilde{\chi}_j^+$ – to the left

$$\sigma_{RRLL} \sim |a-b|^2\{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}r_{\chi_j}}-(G_L^2-G_R^2)\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\}; \quad (8)$$

the lepton-antilepton pair is polarized to the left, and the chargino $\tilde{\chi}_i^-$ and $\tilde{\chi}_j^+$ – to the right:

$$\sigma_{LLRR} \sim |a+b|^2\{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}r_{\chi_j}}-(G_L^2-G_R^2)\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}\}. \quad (9)$$

In these cases, the directions of momenta and particle spins are shown in Fig. 2. As can be seen from the figure, the directions of the spins of the lepton-antilepton pair and the chargino $\tilde{\chi}_i^-$, $\tilde{\chi}_j^+$ are oriented oppositely, therefore, the sum of their spins is equal to zero, the spin of the intermediate Φ-boson is also equal to zero. As noted in the previous work (I), due to the conservation of helicity of particles in the process $\ell^- + \ell^+ \to (\gamma^*;\, Z^*) \to \tilde{\chi}_i^- + \tilde{\chi}_j^+$, the lepton-antilepton pair (also the chargino pair) should have opposite helicities $\lambda_1 = -\lambda_2 = \pm 1$, $h_1 = -h_2 = \pm 1$:

$$\ell_L^- + \ell_R^+ \to \tilde{\chi}_{iL}^- + \tilde{\chi}_{jR}^+;\ \ell_L^- + \ell_R^+ \to \tilde{\chi}_{iR}^- + \tilde{\chi}_{jL}^+;\ \ell_R^- + \ell_L^+ \to \tilde{\chi}_{iL}^- + \tilde{\chi}_{jR}^+;\ \ell_R^- + \ell_L^+ \to \tilde{\chi}_{iR}^- + \tilde{\chi}_{jL}^+.$$

The directions of momenta and particle spins in these spiral processes are shown in Fig. 3. As you can see, in all cases the directions of the spins of the initial (final) particles are parallel to each other, their sum is equal to 1 (in units $\hbar$). That is how it should be, since the photon and Z-boson carrying the interaction have spin 1.

From the above considerations it follows that using left- or right-handed lepton-antilepton beams, it is possible to separate the contribution to the cross section of the diagram b) from the contribution of the diagram a) in Fig. 1.

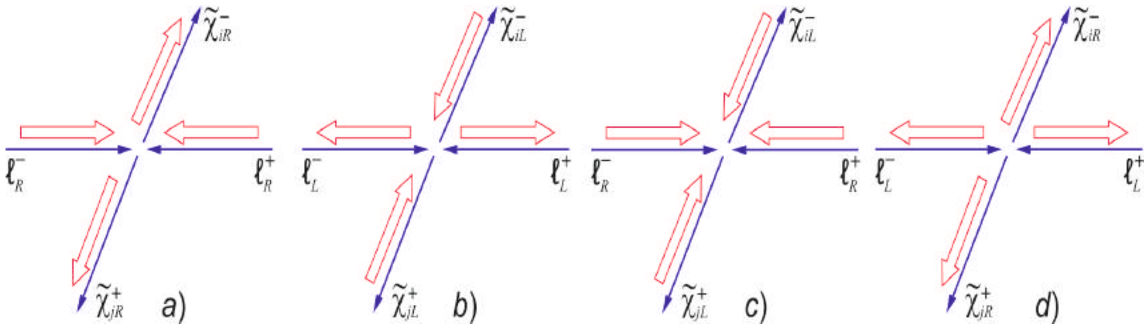

Fig. 2. Directions of momenta and particle spins in the process $\ell^-\ell^+ \to (\Phi^*) \to \tilde{\chi}_i^-\tilde{\chi}_j^+$.

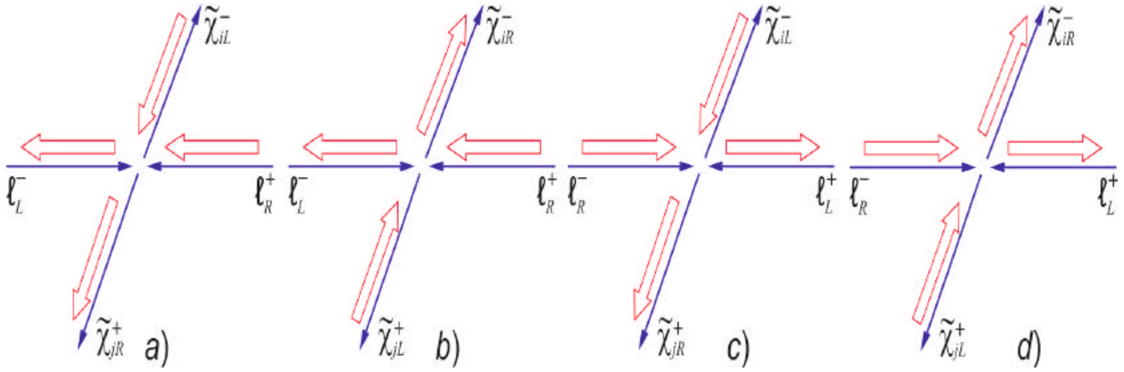

Fig. 3. Directions of momenta and particle spins in the reaction $\ell^-\ell^+ \to (\gamma^*; Z^*) \to \tilde{\chi}_i^-\tilde{\chi}_j^+$.

Summing over the chargino polarizations in (5), we represent the resulting expression in the form:

$$\sigma(\lambda_1,\lambda_2) = \frac{g^2_{\Phi\ell\ell}g^2 s}{32[(s-M^2_\Phi)^2+\Gamma^2\Phi^2]}\sqrt{\lambda(r_{\chi_i},\, r_{\chi_j})}\cdot\{[|a|^2+|b|^2](1+\lambda_1\lambda_2)-2\,\mathrm{Re}(ab^*)(\lambda_1+\lambda_2)\}\times$$
$$\times\{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}\cdot r_{\chi_j}}\}. \quad (10)$$

Let us determine the longitudinal spin asymmetries due to the polarizations of the lepton and antilepton:

$$A_{\ell^-} = \frac{1}{\lambda_1}\frac{\sigma(\lambda_1,0)-\sigma(-\lambda_1,0)}{\sigma(\lambda_1,0)+\sigma(-\lambda_1,0)} = -\frac{2\,\mathrm{Re}(ab^*)}{|a|^2+|b|^2},$$
$$A_{\ell^+} = \frac{1}{\lambda_2}\frac{\sigma(0,\lambda_2)-\sigma(0,-\lambda_2)}{\sigma(0,\lambda_2)+\sigma(0,-\lambda_2)} = -\frac{2\,\mathrm{Re}(ab^*)}{|a|^2+|b|^2}. \quad (11)$$

Here $\sigma(\lambda_1,0)$ ($\sigma(0,\lambda_2)$) – is the annihilation cross section for the interaction of a longitudinally polarized lepton with an unpolarized antilepton (an unpolarized lepton with a polarized antilepton). From expressions (11) it follows that the longitudinal spin asymmetries A_{ℓ^-} and A_{ℓ^+} are equal to each other. This means that the longitudinal spin asymmetry arising from the interaction of polarized leptons with unpolarized antileptons is equal to the longitudinal spin asymmetry arising from the interaction of polarized antileptons with unpolarized leptons.

Note that the study of longitudinal spin asymmetries can provide valuable information about the CP-even or odd nature of the Higgs boson Φ. If the Φ-boson is a CP-even particle (like the bosons H, h) or a CP-odd particle (like a A-boson), then the experiments will not reveal longitudinal spin asymmetry.

Now suppose the lepton-antilepton pair is transversely polarized. Wherein

$$(\vec{n}\vec{\xi}_1) = (\vec{n}\vec{\eta}_1) = 0,\ (\vec{n}\vec{\xi}_2) = (\vec{n}\vec{\eta}_2) = 0,\ (\vec{\xi}_1\vec{\xi}_2) = (\vec{\eta}_1\vec{\eta}_2) = \eta_1\eta_2\cos\phi,$$

where $\vec{\eta}_1$ and $\vec{\eta}_2$ – are the transverse components of the spin vectors of the lepton and antilepton (at full transverse polarization $\eta_1 = \eta_1 = 1$), φ – is the angle between these vectors. In this case, for the effective section of the process $\ell^- + \ell^+ \to \tilde{\chi}_i^- + \tilde{\chi}_j^+$, the expression is obtained:

$$\sigma(\eta_1,\eta_2) = \frac{g^2_{\Phi\ell\ell}g^2 s}{32[(s-M^2_\Phi)^2+\Gamma^2_\Phi\Phi^2_\Phi]}\sqrt{\lambda(r_{\chi_i},\, r_{\chi_j})}\cdot\{|a|^2+|b|^2+[|a|^2-|b|^2]\eta_1\eta_2\cos\phi -$$

$$-2\,\mathrm{Im}(ab^*)\eta_1\eta_2\sin\phi\}[(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}\cdot r_{\chi_j}}\,]. \quad (12)$$

This effective cross section leads to the following transverse spin asymmetries associated with the polarizations of the lepton-antilepton pair:

$$A_1=\frac{\sigma(\phi=0)-\sigma(\phi=\pi)}{\sigma(\phi=0)+\sigma(\phi=\pi)}=\frac{|a|^2-|b|^2}{|a|^2+|b|^2}\eta_1\eta_2, \quad (13)$$

$$A_2=\frac{\sigma(\phi=-\pi/2)-\sigma(\phi=\pi/2)}{\sigma(\phi=-\pi/2)+\sigma(\phi=\pi/2)}=\frac{2\,\mathrm{Im}(ab^*)}{|a|^2+|b|^2}\eta_1\eta_2. \quad (14)$$

For a complete transversely polarized lepton-antilepton pair ($\eta_1=\eta_1=1$), we have $A_1=1$, if the intermediate Φ-boson is a CP-even boson H or h ($a=1$, $b=0$). For an odd CP $\Phi=A$ boson, the transverse spin asymmetry is $A_1=-1$ ($a=0$, $b=1$). Hence, by measuring the transverse spin asymmetry A_1, one can obtain information about the nature of the Higgs boson.

The nonzero transverse spin asymmetry also indicates CP-parity violation in the reaction $\ell^-+\ell^+\to(\Phi^*)\to\tilde{\chi}_i^-+\tilde{\chi}_j^+$.

The effective cross section of the reaction with allowance for the longitudinal polarizations of the chargino can be represented as:

$$\sigma(h_1,h_2)=\frac{1}{4}\sigma_0[1+h_1h_2+(h_1+h_2)P_{\parallel}], \quad (15)$$

where

$$\sigma_0=\frac{g_{\Phi\ell\ell}^2g^2\cdot s\sqrt{\lambda(r_{\chi_i},\,r_{\chi_j})}}{32[(s-M_\Phi^2)^2+\Gamma_\Phi^2\Phi_\Phi^2]}\cdot[|a|^2+|b|^2][(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}\cdot r_{\chi_j}}\,] \quad (16)$$

– the effective cross section of the considered process in the case of unpolarized particles, and $P_{\parallel}$ the degree of longitudinal polarization of the chargino

$$P_{\parallel}=\frac{(G_L^2-G_R^2)\sqrt{\lambda(r_{\chi_i},\,r_{\chi_j})}}{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}\cdot r_{\chi_j}}}. \quad (17)$$

If the charginos are transversely polarized, then the cross section of the process under consideration can be represented in the following form:

$$\sigma(\eta,\eta')=\frac{1}{4}\sigma_0(1+\eta\eta'P_{\perp}), \quad (18)$$

where

$$P_{\perp}=\frac{2\cos\varphi\cdot[G_LG_R(1-r_{\chi_i}-r_{\chi_j})-(G_L^2+G_R^2)\sqrt{r_{\chi_i}\cdot r_{\chi_j}}\,]}{(G_L^2+G_R^2)(1-r_{\chi_i}-r_{\chi_j})-4G_LG_R\sqrt{r_{\chi_i}\cdot r_{\chi_j}}} \quad (19)$$

– is the degree of transverse polarization of the chargino due to the polarizations η and η', φ – is the angle between the spin vectors of the chargino $\vec{\eta}$ and $\vec{\eta}'$.

Let us estimate the degree of longitudinal and transverse polarization of the chargino in the processes $\ell^-+\ell^+\to\tilde{\chi}_1^-+\tilde{\chi}_1^+$, $\ell^-+\ell^+\to\tilde{\chi}_2^-+\tilde{\chi}_2^+$, $\ell^-+\ell^+\to\tilde{\chi}_1^-+\tilde{\chi}_2^+$ and $\ell^-+\ell^+\to\tilde{\chi}_2^-+\tilde{\chi}_1^+$. Calculations show that in all these processes the constants of the interaction of the chargino with the Higgs bosons $\Phi=H,h$ and A $G_L=G_R$, because of this, the degree of longitudinal polarization of the chargino $P_{\parallel}$ vanishes, and the degree of transverse polarization of the chargino $P_{\perp}$ is equal to the cosine of the angle φ between the spin vectors $\vec{\eta}$ and $\vec{\eta}'$:

$$P_{\perp}=\cos\varphi. \quad (20)$$

In Fig. 4 shows the dependence of the degree of transverse polarization of the chargino $P_{\perp}$ on the angle φ. When $\varphi=0$ the degree of transverse polarization is maximum and is 1, with an increase in the angle φ, the degree of transverse polarization of the chargino decreases and vanishes at $\varphi=90°$. Then the sign changes and becomes negative at the end of the angular spectrum at $\varphi=180°$ $P_{\perp}=-1$.

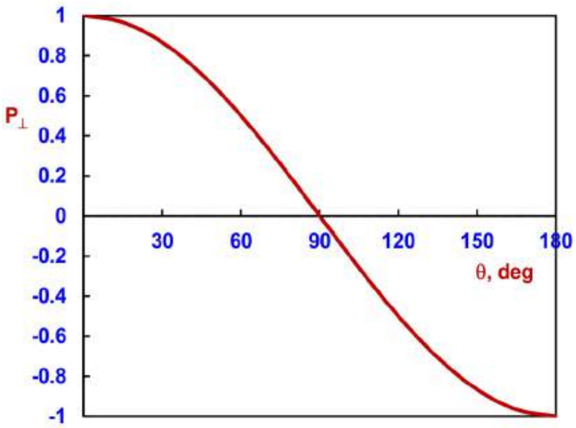

Fig. 4. Dependence of the degree of transverse polarization on the angle φ .

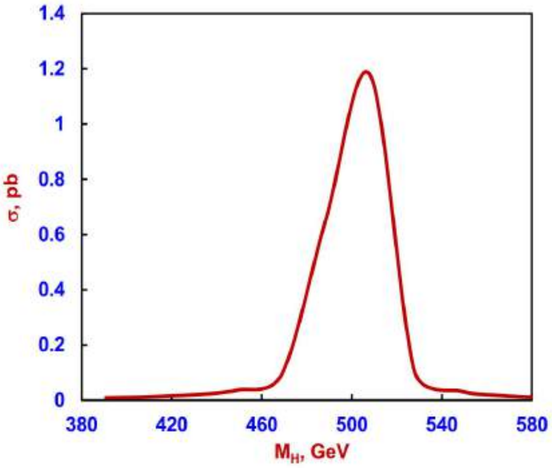

Fig. 5. Dependence of the reaction $\mu^-\mu^+ \to (H^*) \to \tilde{\chi}_1^-\tilde{\chi}_2^+$ cross section on the Higgs boson mass.

In Fig. 5 shows the dependence of the cross section of the process $\mu^- + \mu^+ \to \tilde{\chi}_1^- + \tilde{\chi}_2^+$ at an energy of colliding muon-antimuon beams of $\sqrt{s} = 500$ GeV on the Higgs boson M_H mass. Chargino masses $m_{\tilde{\chi}_1^-}$ and $m_{\tilde{\chi}_2^+}$ are determined at parameter values of $\mathrm{tg}\beta = 1$, $M_2 = 150$ GeV, $\mu = 200$ GeV. The total width of the Higgs boson decay was chosen to be $\Gamma_H = 4$ GeV, and the Weinberg parameter was $x_W = 0.2315$. With an increase in the Higgs boson mass, the effective cross section increases and at $M_H = \sqrt{s}$ =500 GeV reaches its maximum value. Further increase in mass leads to a decrease in the cross section.

Fig. 6 illustrates the dependence of the effective cross section of the process $\mu^- + \mu^+ \to (H^*) \to \tilde{\chi}_1^- + \tilde{\chi}_2^+$ on the energy $\sqrt{s}$ of muon-antimuon beams at the same values of the parameters as in Fig. 5. The mass of the Higgs boson is chosen to be $M_H = 600$ GeV. With increasing energy, the cross section increases and reaches its maximum value at $\sqrt{s} = M_H = 600$ GeV.

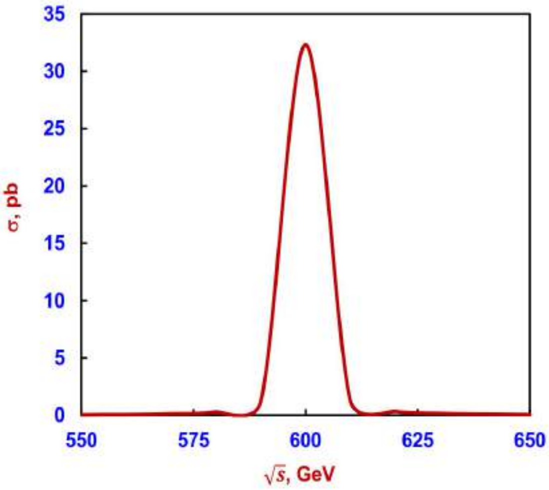

Fig. 6. Energy dependence of the reaction $\mu^-\mu^+ \to (H^*) \to \tilde{\chi}_1^-\tilde{\chi}_2^+$ cross section at $M_H = 600$ GeV, $\Gamma_H = 4$ GeV.

3. AMPLITUDE AND CROSS SECTION OF THE REACTION $\ell^-\ell^+ \to (\tilde{\nu}_L) \to \tilde{\chi}_i^-\tilde{\chi}_j^+$

Now we turn to the calculation of the diagram c) Fig. 1 with scalar neutrino $\tilde{\nu}_L$ exchange. The amplitude corresponding to this diagram can be written as

$$M_{i\to f} = ie^2 g^2_{\tilde{\chi}\ell\tilde{\nu}_L}[\bar{u}_i(k_1,s)P_L u_\ell(p_1,s_1)]\cdot\frac{1}{(k_1-p_1)^2 - m^2_{\tilde{\nu}_L}}[\bar{\upsilon}_\ell(p_2,s_2)P_L\upsilon_j(k_2,s')], \quad (21)$$

where $g^2_{\tilde{\chi}\ell\tilde{\nu}_L} = G^2 = \frac{(V_{i1})^2}{x_W}$ – is the constant of interaction of the chargino with the lepton and the sneutrino [6]; $\frac{1}{(k_1-p_1)^2 - m^2_{\tilde{\nu}_L}}$ – scalar neutrino propagator.

We define the square of the modulus of the matrix element (21) in the standard way:

$$\left|M_{i\to f}\right|^2=\frac{e^4G^4}{[(k_1-p_1)^2-m_{\tilde{\nu}_L}^2]}\cdot\frac{1}{4}[(p_1\cdot k_1)-m_\ell m_{\tilde{\chi}_i}(s\cdot s_1)-m_\ell(s_1\cdot k_1)+m_{\tilde{\chi}_i}(s\cdot p_1)]\times$$
$$\times[(p_2\cdot k_2)-m_\ell m_{\tilde{\chi}_j}(s_2\cdot s')-m_\ell(s_2\cdot k_2)+m_{\tilde{\chi}_j}(p_2\cdot s')]. \quad (22)$$

Using (22), for the cross section of the process under consideration in the case of longitudinally polarized lepton-antilepton pairs, we find the following expression:

$$\frac{d\sigma}{d(\cos\theta)}=\frac{\pi\alpha^2G^4s}{32[(k_1-p_1)^2-m_{\tilde{\nu}_L}^2]^2}\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cdot(1-\lambda_1)(1-\lambda_2)\times$$
$$\times[1+r_{\tilde{\chi}_i}-r_{\tilde{\chi}_j}-\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cos\theta][1-r_{\chi_i}+r_{\chi_j}-\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cos\theta], \quad (23)$$

here (the lepton mass is neglected in comparison with the energy $\sqrt{s}$)

$$(k_1-p_1)^2=\frac{s}{2}[r_{\chi_i}+r_{\chi_j}-1+\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cos\theta].$$

As seen from the differential effective cross section (23), the lepton and antilepton should have left-handed helicities $\lambda_1=\lambda_2=-1$. At $\lambda_1=+1$ or $\lambda_2=+1$, the process is prohibited by the law of conservation of the total moment at the vertex $\ell^-\to\tilde{\nu}_\ell+\tilde{\chi}_i^-$ ($\ell^+\to\tilde{\nu}_\ell+\tilde{\chi}_j^+$). This means that there is no interference between diagrams a) and c) at $\lambda_1=\lambda_2=-1$.

Now we assume that the lepton-antilepton pair is unpolarized and the chargino $\tilde{\chi}_i^-$ is longitudinally polarized. In this case, the differential cross section of the process under consideration is determined by the following expression:

$$\frac{d\sigma}{d(\cos\theta)}=\frac{1}{2}\frac{d\sigma_0}{d(\cos\theta)}(1+h_1P_\parallel), \quad (24)$$

where

$$\frac{d\sigma_0}{d(\cos\theta)}=\frac{\pi\alpha^2G^4s}{32[(k_1-p_1)^2-m_{\tilde{\nu}_L}^2]^2}\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cdot[1+r_{\chi_i}-r_{\chi_j}-\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cos\theta]\times$$
$$\times[1-r_{\chi_i}+r_{\chi_j}-\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cos\theta] \quad (25)$$

is the differential cross section of the reaction in the case of unpolarized particles, and $P_\parallel$ – is the degree of longitudinal polarization of the chargino:

$$P_\parallel=\frac{\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}-(1+r_{\chi_i}-r_{\chi_j})\cos\theta}{1+r_{\chi_i}-r_{\chi_j}-\sqrt{\lambda(r_{\chi_i},r_{\chi_j})}\cos\theta}. \quad (26)$$

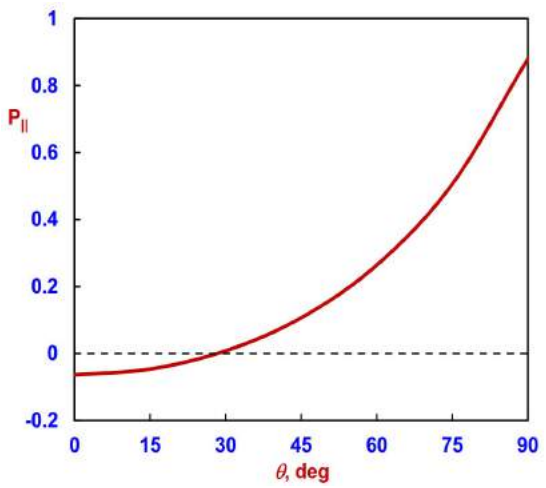

Fig. 7. Angular dependence of the $P_\parallel$ on the angle θ.

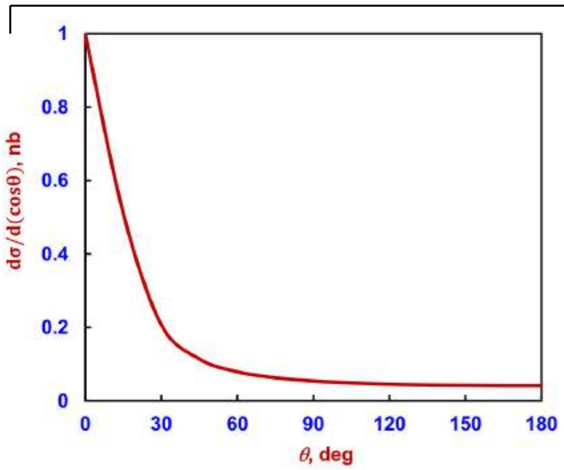

Fig. 8. Angular dependence of the cross section in the reaction $e^-e^+\to(\tilde{\nu}_L^*)\to\tilde{\chi}_1^-\tilde{\chi}_2^+$.

In Fig. 7 shows the dependence of the degree of longitudinal polarization of the chargino on the angle θ at energy $\sqrt{s}$ =500 GeV, M_2=150 GeV, μ=200 GeV, M_W=80.385 GeV. At the beginning of the angular spectrum ($0°\le\theta\le 90°$), the degree of longitudinal polarization is negative and with an increase in the emission angle θ it increases.

The dependence of the effective cross section on the angle θ is illustrated in Fig. 8 at $\sqrt{s}$ =500 GeV, x_W =0.2315, M_2 =150 GeV, μ =200 GeV, $m_{\tilde{\nu}_L}$ =40 GeV. As follows from the figure, with an increase in the angle θ, the effective cross section at the beginning of the angular spectrum ($0° \leq \theta \leq 90°$) decreases, and at $\theta > 90°$ it no changes.

CONCLUSION

We discussed the creation of a chargino pair in the annihilation of an arbitrarily polarized lepton-antilepton pair $\ell^- + \ell^+ \to \tilde{\chi}_i^- + \tilde{\chi}_j^+$. The contribution to the cross section of the diagram with the exchange of the Higgs bosons H, h and A, as well as the scalar neutrino $\tilde{\nu}_L$ is studied in detail.

The longitudinal and transverse spin asymmetries caused by the polarizations of the lepton-antilepton pair, as well as the degrees of the longitudinal and transverse polarization of the chargino, have been determined. The angular and energy dependences of these characteristics, as well as the cross section of the considered reaction, are investigated in detail. The calculation results are illustrated with graphs.

---

[1] ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector of the LHC Phys. Letters, 2012, B 716, p. 1-29.

[2] CMS Collaboration. Observation of a new boson at mass of 125 GeV with the CMS experiment at the LHC Phys. Letters, 2012, B 716, p. 30-60.

[3] *V.A. Rubakov.* On Large Hadron Colliders discovery of a new particle with Higgs Boson properties UFN, 2012, V.182, No 10, p.1017-1025 (in Russian).

[4] *A.V. Lanev.* CMS Collaboration results: Higgs boson and search for new physics UFN, 2014, V. 184, No 9, p. 996-1004 (In Russian).

[5] *D.I. Kazakov.* The Higgs boson is found: what is next? UFN, 2014, V. 184, No 9, p. 1004-1017 (In Russian).

[6] *A. Djouadi.* The Anatomy of Electro-Weak Symmetry Breaking. Tome II: The Higgs boson in the Minimal Supersymmetric Standard Model. arXiv: hep-ph/0503172v2, 2003; DOI: 10.1016/j.physrep.2007.10.004.

[7] *M. Spira.* QCD effects in Higgs Physics. arXiv: hep-ph / 9705337v2, 1997.

[8] *J.F. Gunion, H.E. Haber.* Higgs bosons in Supersymmetric Phys. Rev., 2003, D 67, p. 0750.19.

[9] *H.E. Haber, G. Kane.* The search for supersymmetry: Probing physics beyond the Standard Model Phys. Rep., 1985, C 117, No 2-4, p. 75-263.

[10] *D.I. Kazakov.* Beyond the Standart Model (in search of Supersymmetry). arXiv: hep-ph/0012288.2000, 80p.

[11] *V.D. Shiltsev.* High energy particle colliders: past 20 years, next 20 years and beyond UFN, 2012, V. 182, No 10, p. 1033-1046 (in Russian).

[12] *K. Peters.* Prospects for beyond Standard Model Higgs boson searches at future LHC runs and other machines. arXive: 1701.05124v2 [hep-ex], 2007, 8p.

[13] S.*K. Abdullayev, M.Sh. Gojayev, A.K. Gulayeva.* The production of a chargino pair in polarized lepton-antilepton collisions (I) AJP, Fizika, 2020, V. XXVI, No 3, p. 20-30.

[14] *A. Bartl, H. Fraas, W. Majerotto.* Signatures of chargino production in e^+e^- collisions. Z. Phys., 1986, B 30, p. 441-449.

[15] *A. Bartl, H. Fraas, W. Majerotto.* Production and decay of neutralinos in e^+e^--collisions. J. Nucl. Phys., 1986, B 278, p. 1-25

[16] *A. Djouadi, J. Kalinowski, P. Ohmann, P.M. Zerwas.* Heavy SUSY Higgs bosons at e^-e^+ linear colliders. Z. Phys., 1997, C 74, p. 93-111.

Received:17.11.2020