

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

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In the framework of the Minimal Supersymmetric Standard Model, the processes of annihilation of an arbitrarily polarized lepton-antilepton pair into a pair of charginos are considered: $\ell^- + \ell^+ \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_j^+$. A general expression is obtained for the cross section of the process in the case of arbitrarily polarized initial particles. The angular and polarization characteristics of the process have been studied in detail. In particular, it is shown that the asymmetry arising in the interaction of longitudinally polarized electrons with unpolarized positrons is equal in magnitude and opposite in sign of the asymmetry arising in the interaction of polarized positrons with unpolarized electrons.

Keywords: Minimal Supersymmetric Standard Model, Standard Model, lepton-antilepton pair, chargino, longitudinal polarization, transverse polarization.

PACS: 12.10.-g, 12.15.-y, 12.60.-i, 14.80.Ly, 14.70.Bh, 14.70.Hp.

1. INTRODUCTION

The discovery of the Higgs boson H_{SM} at the Large Hadron Collider (LHC) by the ATLAS and CMS collaborations [1, 2] (see also reviews [3-5]) began a new chapter in the history of elementary particle physics. The mechanism of the generation of masses of fundamental particles - the mechanism of spontaneous breaking of the Braut – Englert – Higgs symmetry [6, 7] was experimentally confirmed. Thus, the Standard Model (SM) of fundamental interactions received its logical conclusion and acquired the status of a standard theory.

According to the SM, there are six quarks and six leptons in nature, making up three generations and three types of interactions: strong, electromagnetic and weak, which are transported by gluons, photons and W^\pm, Z -bosons. Now a fourth, the Yukawa interaction, carried by the Higgs boson, has been added to them. Based on the CM, one can accurately calculate Feynman diagrams of various processes and compare them with the corresponding experimental data. The agreement between CM and experience is strikingly good.

Despite the successes of SM, this theory has its own difficulties. Many of them are related to the fact that this theory describes a lot, but does not explain where it came from, does not allow it to be derived from deeper principles. One of the mysteries of the SM is the very large spread of masses of fundamental fermions - quarks and leptons. The mass of the electron is the smallest ($m_e = 5 \cdot 10^{-4}$ GeV), and the mass of the top quark is the largest ($m_t = 173.2$ GeV). Their masses differ hundreds of thousands of times. The masses of all SM particles are scattered over a very wide range (see Fig. 1).

This situation looks abnormal. Physicists are trying to figure out if there is some mechanism that naturally leads to such a spread of masses. Within the framework of the SM, such a hierarchy of masses does not receive a satisfactory explanation; however, in

some non-standard models a similar hierarchy of masses may arise.

In quantum field theory, it turns out that the vacuum is not an absolute emptiness, but a ceaselessly seething sea of virtual particles. These virtual particles of various kinds appear for a short moment and then disappear. However, if there is some real particle in a vacuum, then virtual particles envelop it and change its properties. All the particles of our world are particles dressed in a virtual fur coat. Masses, charges and all other characteristics of the observed particles these are the characteristics of the particles dressed in a fur coat.

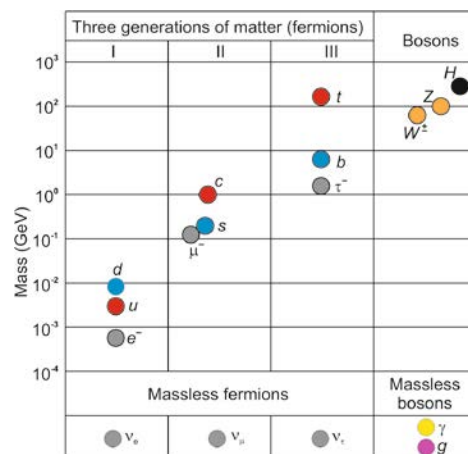


Fig. 1. Particle masses of the Standard Model.

This phenomenon is taken into account by a mathematical procedure called renormalization. For all SM particles, renormalization works well, but in the case of the Higgs boson, a problem arises: the effect of virtual particles on the Higgs boson mass is too large, the boson mass increases by a factor of trillions, and such a particle can no longer play the role of the Higgs boson. Inside the SM, there is no restraining factor that stops the growth of the Higgs boson mass due to virtual particles. This difficulty is called the hierarchy problem. 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 effect on the Higgs boson mass. The most important thing here is that in models of physics outside the SM, for example, in the Minimal Supersymmetric Standard Model (MSSM), such compensation itself arises from the construction of the theory.

The absence of dark matter particles in the SM is also one of the difficulties of this theory. In astrophysics, it is believed that in the Universe, in addition to ordinary matter in the form of planets, stars, black holes, gas and dust clouds, neutrinos, etc., there are also particles of a completely different nature. These particles practically do not interact with ordinary matter and radiation. There is not a single particle in the SM that is suitable for this role. However, in the MSSM there are new particles called neutralino, sneutrino, gluino, gravitino, which can be candidates for dark matter.

All the above facts and a number of other reasons indicate the need to go beyond the SM. At the same time, special attention is paid to the MSSM. In this model, two doublets of the scalar field are introduced and after spontaneous symmetry breaking, five Higgs bosons appear: CP-even H^- and h^- -bosons, CP-odd A^- -boson and charged H^\pm -bosons. The Higgs sector is characterized by the parameters $M_H, M_h, M_A, M_{H^\pm}, \alpha$ and β (α and β are the mixing angles of the scalar fields). Of these, the parameters M_A and $\text{tg}\beta = \frac{v_2}{v_1}$ are assumed to be free

(v_1 and v_2 are the vacuum values of the neutral scalar fields). The rest of the parameters are expressed through M_A and β :

$$M_{H(h)}^2 = \frac{1}{2}[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2M_Z^2 \cos^2 2\beta}],$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2,$$

$$\text{tg}2\alpha = \text{tg}2\beta \cdot \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \left(-\frac{\pi}{2} \leq \alpha \leq 0 \right).$$

Here M_Z and M_W are the masses of gauge Z^- and W^\pm -bosons.

The supersymmetric (SUSY) partners of gauge W^\pm -bosons and Higgs H^\pm -bosons are calibrino \tilde{W}^\pm and Higgsino \tilde{H}^\pm . These spinor fields mix and create new mass states called charginos $\tilde{\chi}_{1,2}^\pm$. Chargino's mass matrix depends on the mass parameters of wine and Higgsino, as well as on the parameter M_2 and μ [8, 9, 11]:

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

This matrix is diagonalized by two real two-row matrices U and V :

$$UM_C V^{-1} \Rightarrow U = R_-, V = \begin{cases} R_+, & \text{if } \det M_C > 0 \\ \sigma_3 R_+, & \text{if } \det M_C < 0 \end{cases},$$

where σ_3 – is the Pauli matrix making the chargino mass positive R_+ and R_- – the rotation matrix with angles θ_+ and θ_- :

$$\text{tg}2\theta_+ = \frac{2\sqrt{2}M_W(M_2 \sin\beta + \mu \cos\beta)}{M_2^2 - \mu^2 + 2M_W^2 \cos\beta},$$

$$\text{tg}2\theta_- = \frac{2\sqrt{2}M_W(M_2 \cos\beta + \mu \sin\beta)}{M_2^2 - \mu^2 - 2M_W^2 \cos\beta}.$$

This leads to two mass states of charginos:

$$m_{\tilde{\chi}_{1,2}^\pm}^2 = \frac{1}{2}\{M_2^2 + \mu^2 + 2M_W^2 \mp [(M_2^2 - \mu^2)^2 + 4M_W^2(M_2^2 \cos^2 2\beta + M_2^2 + \mu^2 + 2M_2\mu \sin 2\beta)]^{1/2}\}.$$

When $|\mu| \rightarrow \infty$ we have:

$$m_{\tilde{\chi}_1^\pm} \approx M_2, \quad m_{\tilde{\chi}_2^\pm} \approx |\mu|,$$

this means that a light chargino corresponds to a wino state, and a heavy chargino corresponds to a Higgsino state. In the case $M_2 \gg |\mu|$, M_W – of light and heavy charginos, they exchange roles:

$$m_{\tilde{\chi}_i^\pm} \approx |\mu|, \quad m_{\tilde{\chi}_2^\pm} \approx M_2.$$

The neutral analogs of the charginos are called neutralino, there are four of them: $\tilde{\chi}_j^0$ ($j = 1, 2, 3, 4$).

They arise from the mixing of bino \tilde{B}^0 , wino \tilde{W}_3^0 and Higgsino \tilde{H}_1^0 and \tilde{H}_2^0 .

Charginos and neutralinos can be born in the LHC in the decays of squarks and gluinos: $\tilde{g} \rightarrow q + \tilde{q}$ and $\tilde{q} \rightarrow q + \tilde{\chi}_i$. The joint production of a pair of neutralinos in quark-antiquark collisions in hadron colliders $q + \bar{q} \rightarrow \tilde{\chi}_i^0 + \tilde{\chi}_j^0$ was considered in [12]. The process of production of a pair of different neutralinos in the collision of polarized electrons and positrons has been studied in a number of works [13-18].

In this paper, we consider the production of a pair of charginos in arbitrarily polarized lepton-antilepton (electron-positron or muon-antimuon) collisions ($\ell^- \ell^+ \rightarrow e^- e^+, \mu^- \mu^+$):

$$\ell^- + \ell^+ \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_j^+, \quad (1)$$

Cases of annihilation of a longitudinally and transversely polarized lepton-antilepton pair are considered separately. The degrees of longitudinal and transverse polarization of the chargino were also determined during the annihilation of a longitudinally polarized lepton and an unpolarized antilepton.

2. THE AMPLITUDE AND CROSS SECTION OF THE PROCESS $\ell^- \ell^+ \rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$

Within the framework of the MSSM, the process of annihilation of a lepton-antilepton pair into a chargino pair is described by the Feynman diagrams shown in Fig. 2: a) s-channel diagrams with the exchange of a photon and a Z-boson; b) s-channel diagrams with the exchange of Higgs bosons H, h or A ; c) t -channel diagram with scalar neutrino $\tilde{\nu}_L$ exchange.

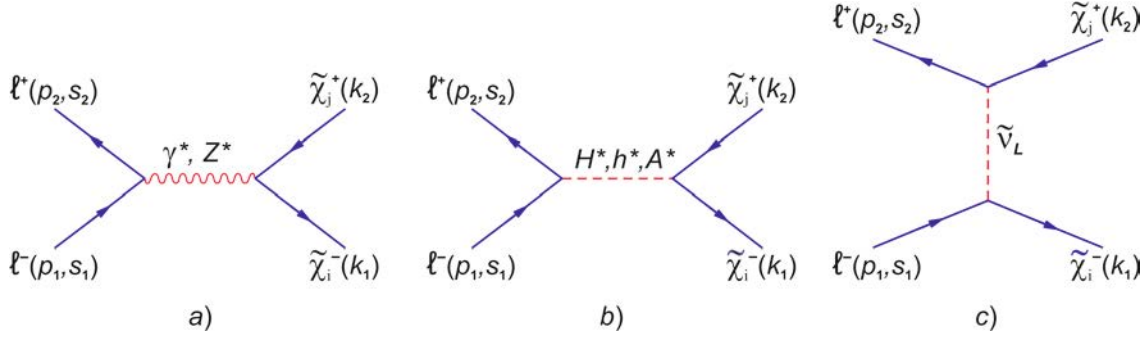


Fig. 2. Feynman diagrams for reaction $\ell^- \ell^+ \rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$.

Consider the diagram a) with the exchange of a photon and a Z-boson. The amplitude corresponding to these diagrams can be represented as:

$$M_{i \rightarrow f} = M^{(\gamma)} + M^{(Z)},$$

$$M^{(\gamma)} = i \frac{e^2}{s} [\bar{v}_e(p_2, s_2) \gamma_\mu u_e(p_1, s_1)] [\bar{u}_{\chi_i}(k_1) \gamma_\mu v_{\chi_j}(k_2)], \quad (2)$$

$$M^{(Z)} = \frac{ig_Z^2}{(s - M_Z^2 + iM_Z \Gamma_Z)} \{ \bar{v}_e(p_2, s_2) \gamma_\mu [g_L(1 + \gamma_5) + g_R(1 - \gamma_5)] u_e(p_1, s_1) \} \times [\bar{u}_{\chi_i}(k_1) \gamma_\mu (g_{\tilde{\chi}_i^- \tilde{\chi}_j^+ Z}^L P_L + g_{\tilde{\chi}_i^- \tilde{\chi}_j^+ Z}^R P_R) v_{\chi_j}(k_2)], \quad (3)$$

where $s = (p_1 + p_2)^2 = (k_1 + k_2)^2$ – is the square of the total energy of the lepton-antilepton pair in the center of mass system; $p_1(s_1)$ and $p_2(s_2)$ – 4-vectors of the momentum (polarization) of the lepton and antilepton; g_Z – weak coupling constant

$$g_Z^2 = \frac{e^2}{4x_W(1-x_W)}; \quad (4)$$

$x_W = \sin^2 \theta_W$ – Weinberg parameter; g_L and g_R – are the left and right constants of interaction of a lepton with a Z-boson

$$g_L = -\frac{1}{2} + x_W, \quad g_R = x_W; \quad (5)$$

$P_{L(R)} = (1 \pm \gamma_5)/2$ – chirality matrices; $g_{\tilde{\chi}_i^- \tilde{\chi}_j^+ Z}^L = G_L$

and $g_{\tilde{\chi}_i^- \tilde{\chi}_j^+ Z}^R = G_R$ – are the left and right constants of interaction of the chargino with the vector -boson (they are given [8]):

$$G_L = \frac{1}{\cos \theta_W} \left[\delta_{ij} \sin^2 \theta_W - \frac{1}{2} V_{i2} V_{j1} + V_{i1} V_{j1} \right], \quad (6)$$

$$G_R = \frac{1}{\cos \theta_W} \left[\delta_{ij} \sin^2 \theta_W - \frac{1}{2} U_{i2} U_{j1} - U_{i1} U_{j1} \right].$$

The square of the process amplitude is:

$$|M_{i \rightarrow f}|^2 = |M^{(\gamma)}|^2 + |M^{(Z)}|^2 + M^{+(\gamma)} M^{(Z)} + M^{+(Z)} M^{(\gamma)}, \quad (7)$$

here $|M^{(\gamma)}|^2$ and $|M^{(Z)}|^2$ – are the contributions of the diagrams with the exchange of a photon and Z-boson,

$(M^{+(\gamma)}M^{(Z)} + M^{+(Z)}M^{(\gamma)})$ – is the interference of these diagrams. The expressions for these quantities are given in the Appendix.

The differential effective cross section of the reaction is expressed by the formula

$$d\sigma = \frac{1}{2s} |M_{i \rightarrow f}|^2 (2\pi)^4 \delta(p_1 + p_2 - k_1 - k_2) \frac{dk_1}{(2\pi)^3 \cdot 2\varepsilon_1} \frac{dk_2}{(2\pi)^3 \cdot 2\varepsilon_2}, \quad (8)$$

where $\varepsilon_1(\vec{k}_1)$ and $\varepsilon_2(\vec{k}_2)$ – are the energies (impulses) of the chargino $\tilde{\chi}_i^-$ and $\tilde{\chi}_j^+$. After integrating over the chargino $\tilde{\chi}_j^+$ impulses and over the chargino $\tilde{\chi}_i^-$ energy, we obtain the following expression for the differential cross section of the considered reaction in the center of mass system

$$\frac{d\sigma}{d\Omega} = \frac{|M_{i \rightarrow f}|^2}{64\pi^2 s} \cdot \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}, \quad (9)$$

Here $d\Omega = \sin\theta d\theta d\phi$ – is the solid angle of departure of the chargino $\tilde{\chi}_i^-$; θ – the polar angle between the directions of the lepton and chargino $\tilde{\chi}_i^-$ pulses, ϕ – the azimuthal angle of departure of the

chargino; $\lambda(r_{\chi_i}, r_{\chi_j})$ – is the known kinematic function of the two-particle phase volume

$$\lambda(r_{\chi_i}, r_{\chi_j}) = (1 - r_{\chi_i} - r_{\chi_j})^2 - 4r_{\chi_i} r_{\chi_j}, \quad (10)$$

where the notation are introduced:

$$r_{\chi_i} = \left(\frac{m_{\chi_i}}{\sqrt{s}} \right)^2, \quad r_{\chi_j} = \left(\frac{m_{\chi_j}}{\sqrt{s}} \right)^2.$$

Using the expressions $|M^{(\gamma)}|^2$, $|M^{(Z)}|^2$ and

$(M^{+(\gamma)}M^{(Z)} + M^{+(Z)}M^{(\gamma)})$ given in the Appendix, we obtain the following expressions for the differential cross sections of the process $\ell^- + \ell^+ \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_j^+$:

$$\begin{aligned} \frac{d\sigma^{(\gamma)}}{d\Omega} = & \frac{\alpha_{\text{QED}}^2}{16s} \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \{ (1 - \lambda_1 \lambda_2) [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta + 8\sqrt{r_{\chi_i} r_{\chi_j}}] + \\ & + \lambda(r_{\chi_i}, r_{\chi_j}) \sin^2 \theta \cos(2\phi - \phi) \cdot \eta_1 \eta_2 \}, \end{aligned} \quad (11)$$

$$\begin{aligned} \frac{d\sigma^{(Z)}}{d\Omega} = & \frac{\alpha_{\text{QED}}^2 \cdot s}{32[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \frac{\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}}{x_W^2 (1 - x_W)^2} \times \\ & \times \{ (G_L^2 + G_R^2) [g_L^2 (1 - \lambda_1)(1 + \lambda_2) + g_R^2 (1 + \lambda_1)(1 - \lambda_2)] [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + \\ & + g_L g_R \lambda(r_{\chi_i}, r_{\chi_j}) \sin^2 \theta \cos(2\phi - \phi) \cdot \eta_1 \eta_2 \} + 2(G_L^2 - G_R^2) [g_L^2 (1 - \lambda_1)(1 + \lambda_2) - g_R^2 (1 + \lambda_1)(1 - \lambda_2)] \times \\ & \times \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \cos \theta + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} [g_L^2 (1 - \lambda_1)(1 + \lambda_2) + g_R^2 (1 + \lambda_1)(1 - \lambda_2)]. \end{aligned} \quad (12)$$

$$\begin{aligned} \frac{d\sigma^{(I)}}{d\Omega} = & \frac{\alpha_{\text{QED}}^2}{16x_W (1 - x_W)} \frac{s - M_Z^2}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \times \\ & \times \{ (G_L + G_R) [g_L (1 - \lambda_1)(1 + \lambda_2) + g_R (1 + \lambda_1)(1 - \lambda_2)] [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \\ & + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta + 8\sqrt{r_{\chi_i} r_{\chi_j}}] + \lambda(r_{\chi_i}, r_{\chi_j}) \sin^2 \theta \cos(2\phi - \phi) \cdot \eta_1 \eta_2 \} + \\ & + 2(G_L - G_R) [g_L (1 - \lambda_1)(1 + \lambda_2) - g_R (1 + \lambda_1)(1 - \lambda_2)] \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \cos \theta. \end{aligned} \quad (13)$$

Here λ_1 and λ_2 – are the helicities of the lepton and antilepton, $\vec{\eta}_1$ and $\vec{\eta}_2$ – are the transverse components of their spin vectors, ϕ – the angle between the transverse spin vectors of the lepton $\vec{\eta}_1$ and antilepton $\vec{\eta}_2$, and Γ_Z – the total width of the Z -boson decay. At high energies of lepton-antilepton beams ($s \gg M_Z^2$), the contribution of the diagram with Z -boson exchange prevails over the contribution

of the electromagnetic mechanism. In this regard, let us analyze the cross section of the Z -boson mechanism (12) in various cases of particle polarizations.

3. THE CASE OF LONGITUDINAL POLARIZATION OF PARTICLES

Differential cross section (12) in the case of longitudinally polarized lepton-antilepton beams has the following form:

$$\frac{d\sigma(\lambda_1, \lambda_2)}{d\Omega} = \frac{\alpha_{\text{QED}}^2 \cdot s}{32[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \frac{\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}}{x_W^2 (1 - x_W)^2} \times$$

$$\times \{ [g_L^2(1-\lambda_1)(1+\lambda_2) + g_R^2(1+\lambda_1)(1-\lambda_2)] [(G_L^2 + G_R^2)(1+r_{\chi_i} - r_{\chi_j})(1-r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} \} + 2 [g_L^2(1-\lambda_1)(1+\lambda_2) - g_R^2(1+\lambda_1)(1-\lambda_2)] (G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j}) \cos \theta}. \quad (14)$$



Fig.3. Directions of impulses and spins $\ell^- \ell^+$ -pair.

As follows from this expression, during annihilation the lepton and antilepton should have opposite helicities ($\lambda_1 = -\lambda_2 = \pm 1$). If the lepton is polarized to the left ($\lambda_1 = -1$; ℓ_L^-), then the antilepton must have a right-handed helicity ($\lambda_2 = +1$; ℓ_R^+) and vice versa, in the annihilation of an right-polarized lepton ($\lambda_1 = +1$; ℓ_R^-), the antilepton must have a left-handed helicity ($\lambda_2 = -1$; ℓ_L^+) (see Fig. 3, where the momenta and spin vectors of the lepton-antilepton pair are shown).

This is due to the preservation of the full moment in the transition $\ell^- + \ell^+ \rightarrow Z$. Indeed, let us consider this transition in the center-of-mass system of a lepton-antilepton pair. In this system, the momenta of the lepton and antilepton are equal in magnitude, but opposite in direction. In fig. 3a), the helicity of the lepton is equal -1 , and the helicity of the antilepton is $+1$. Thus, the projection of the total angular momentum of the lepton-antilepton pair onto the

direction of the lepton momentum -1 . The spin of the Z -boson is equal to 1, which means that the total moment is conserved in the transition $\ell^- + \ell^+ \rightarrow Z$.

Based on the differential effective cross section (14), we determine the longitudinal spin asymmetry due to the polarization of the lepton (antilepton):

$$A_1(\theta) = \frac{1}{\lambda_1} \frac{d\sigma(\lambda_1, 0)/d\Omega - d\sigma(-\lambda_1, 0)/d\Omega}{d\sigma(\lambda_1, 0)/d\Omega + d\sigma(-\lambda_1, 0)/d\Omega}, \quad (15)$$

$$A_2(\theta) = \frac{1}{\lambda_2} \frac{d\sigma(0, \lambda_2)/d\Omega - d\sigma(0, -\lambda_2)/d\Omega}{d\sigma(0, \lambda_2)/d\Omega + d\sigma(0, -\lambda_2)/d\Omega}, \quad (16)$$

where $\frac{d\sigma(\lambda_1, 0)}{d\Omega} \left(\frac{d\sigma(0, \lambda_2)}{d\Omega} \right)$ – the differential cross section of process (1) in the annihilation of a longitudinally polarized lepton and an unpolarized antilepton (an unpolarized lepton and a longitudinally polarized antilepton)

Taking into account (14) in (15) and (16). We have

$$A_2(\theta) = -A_1(\theta) = \{ (g_L^2 - g_R^2) [(G_L^2 + G_R^2)(1+r_{\chi_i} - r_{\chi_j})(1-r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} \} + 2 (g_L^2 + g_R^2) (G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j}) \cos \theta} \times \{ (g_L^2 + g_R^2) [(G_L^2 + G_R^2)(1+r_{\chi_i} - r_{\chi_j})(1-r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} \} + 2 (g_L^2 - g_R^2) (G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j}) \cos \theta} \}^{-1}. \quad (17)$$

Hence it follows that the longitudinal spin asymmetry $A_2(\theta)$ arising in the process of annihilation of polarized antileptons with unpolarized leptons is equal in magnitude and opposite in sign to the longitudinal spin asymmetry $A_1(\theta)$ arising in the interaction of longitudinally polarized leptons with

unpolarized antileptons.

The differential cross section for the reaction $\ell^- + \ell^+ \rightarrow Z^* \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_j^+$ in the case of unpolarized particles has the form

$$\frac{d\sigma_0(\theta)}{d\Omega} = \frac{\alpha_{\text{QED}}^2 \cdot s}{32[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \frac{\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}}{x_W^2 (1 - x_W)^2} \times \{ (g_L^2 + g_R^2) [(G_L^2 + G_R^2)(1+r_{\chi_i} - r_{\chi_j})(1-r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} \} + 2 (g_L^2 + g_R^2) (G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j}) \cos \theta}. \quad (18)$$

Differential cross section (18) of the process under consideration does not have symmetry upon replacement $\theta \rightarrow \pi - \theta$. Consequently, the angular distribution of the charginos is asymmetric.

Expression for the angular asymmetry of the forward-backward chargino obtained on the basis of (18) according to the definition

$$A_{FB}(\theta) = \frac{d\sigma_0(\theta)/d(\cos\theta) - d\sigma_0(\pi - \theta)/d(\cos\theta)}{d\sigma_0(\theta)/d(\cos\theta) + d\sigma_0(\pi - \theta)/d(\cos\theta)}, \quad (19)$$

has the following

$$A_{FB}(\theta) = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} \frac{2(G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \cos\theta}{(G_L^2 + G_R^2)[(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2\theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}} \quad (20)$$

The measurement of the longitudinal spin asymmetries $A_1(\theta)$, $A_2(\theta)$ and the angular asymmetry forward-backward $A_{FB}(\theta)$ in the experiment allows, in principle, to obtain information about the constants of the interaction of the chargino with the vector Z -boson G_L and G_R .

Expressions for the integral characteristics of the process (1) can also be obtained from (14) and (18). For this purpose, we define as follows the total cross section for the production of a pair of charginos:

$$\begin{aligned} \sigma(\lambda_1, \lambda_2) &= 2\pi \int_0^\pi \frac{d\sigma(\lambda_1, \lambda_2)}{d(\cos\theta)} d(\cos\theta) = \\ &= \frac{\pi \alpha_{\text{QED}}^2 \cdot s}{8[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \frac{\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}}{x_W^2 (1 - x_W)^2} [g_L^2 (1 - \lambda_1)(1 + \lambda_2) + g_R^2 (1 + \lambda_1)(1 - \lambda_2)] \times \\ &\quad \times \left\{ (G_L^2 + G_R^2) \left[(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \frac{1}{3} \lambda(r_{\chi_i}, r_{\chi_j}) \right] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} \right\}, \quad (21) \end{aligned}$$

and cross-sections of the birth of chargino $\tilde{\chi}_i^-$ in the front (F) and back (B) hemispheres:

$$\begin{aligned} \sigma_F &= 2\pi \int_0^1 \frac{d\sigma}{dx} dx, \\ \sigma_B &= 2\pi \int_{-1}^0 \frac{d\sigma}{dx} dx. \end{aligned} \quad (22)$$

From the formula for the effective cross section (21) for the integral longitudinal spin asymmetry, we obtain:

$$\begin{aligned} A_{FB} &= \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \\ &= \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} \frac{(G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}}{(G_L^2 + G_R^2) \left[(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \frac{1}{3} \lambda(r_{\chi_i}, r_{\chi_j}) \right] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}}. \quad (24) \end{aligned}$$

Let's assess the above asymmetries in the processes $e^- e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$, $e^- e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_2^+$, $e^- e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$ and $e^- e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+$ at the value of the parameter $\tan\beta = 1$. In this case, the matrices V_{ij} and U_{ij} are defined as [10]

$$V_{ij} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, \quad U_{ij} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}. \quad (25)$$

Using the elements of these matrices for the left and right constants of the interaction of the chargino with the Z -boson, we obtain the expressions:

1) in process

$$e^- e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+ \quad G_L = G_R = \frac{1}{\cos\theta_W} \left[x_W - \frac{1}{4} \right];$$

2) in process

$$A_2 = -A_1 = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}. \quad (23)$$

This asymmetry is only a function of the Weinberg parameter x_W and at $x_W = 0.2315$ $A_2 = 14.7\%$.

For the integral asymmetry forward-backward, the expression is:

$$e^- e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_2^+ \quad G_L = G_R = \frac{1}{\cos\theta_W} \left[x_W - \frac{1}{4} \right];$$

3) in process

$$e^- e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+ \quad G_L = -G_R = -\frac{3}{4 \cos\theta_W};$$

4) in process e

$$e^- e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+ \quad G_L = -G_R = -\frac{1}{4 \cos\theta_W}.$$

As can be seen, in all four processes $G_L^2 = G_R^2$, because of this condition, the asymmetry $A_{FB}(\theta)$ and integral angular asymmetry (24) become zero. As for the longitudinal spin asymmetries $A_2(\theta)$, $A_1(\theta)$, and also the integral spin asymmetries A_2 and A_1 , they are the same in all processes and depend only on the Weinberg parameter x_W :

$$A_2(\theta) = -A_1(\theta) = A_2 = -A_1 \frac{\frac{1}{4} - x_W}{\frac{1}{4} - x_W + 2x_W^2}.$$

As noted above, for the Weinberg parameter $x_W = 0.2315$, these asymmetries are $\pm 14.7\%$.

4. CASE OF TRANSVERSE POLARIZATION OF BEAMS

It is known that electrons and positrons moving in storage rings acquire predominantly transverse polarization due to synchrotron radiation. In the case when the initial particles are transversely polarized,

$$A_{\perp}(\theta, \varphi) = -g_L g_R (G_L^2 + G_R^2) \lambda(r_{\chi_i}, r_{\chi_j}) \sin^2 \theta \cos 2\varphi \times \\ \times \{ (g_L^2 + g_R^2) [(G_L^2 + G_R^2) [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}] + \\ + 2(g_L^2 - g_R^2)(G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j}) \cos \theta} \}^{-1}. \quad (27)$$

This asymmetry is maximum at the azimuthal angle of departure of the chargino $\varphi = 0$ and π .

In fig. 4 shows the angular dependence of the transverse spin asymmetry $A_{\perp}(\theta)$ in the reactions $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$ (curve 1), $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_2^+$ (curve 2), $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$ (or $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+$) (curve 3) at $\sqrt{s} = 500$ GeV and parameter values of $M_2 = 150$ GeV, $\mu = 200$ GeV, $x_W = 0.2315$, $M_W = 80.385$ GeV.

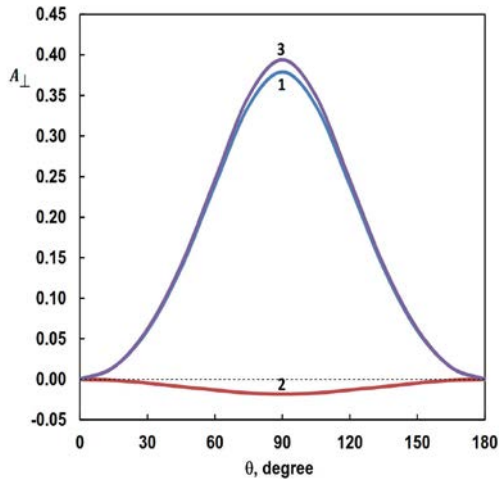


Fig. 4. Transverse spin asymmetry $A_{\perp}(\theta)$ as a function of angle θ .

As can be seen from the figure, in the processes $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$, $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$ (or $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+$) the transverse spin asymmetry is positive and with an increase in the angle θ it reaches a maximum at $\theta = 90^\circ$, and with a further

the differential cross section of process (1) has the form:

$$\frac{d\sigma(\eta_1, \eta_2)}{d\Omega} = \frac{d\sigma_0(\theta)}{d\Omega} [1 + \eta_1 \eta_2 A_{\perp}(\theta, \varphi)], \quad (26)$$

where $\frac{d\sigma_0(\theta)}{d\Omega}$ – the differential cross section of process (1) in the case of unpolarized particles (formula (18)), $A_{\perp}(\theta, \varphi)$ – the transverse spin asymmetry due to the transverse polarizations of the lepton and antilepton (the angle between the vectors $\vec{\eta}_1$ and $\vec{\eta}_2$ is taken $\phi = \pi$):

increase in the angle, this asymmetry decreases and approaches zero at the end of the angular spectrum.

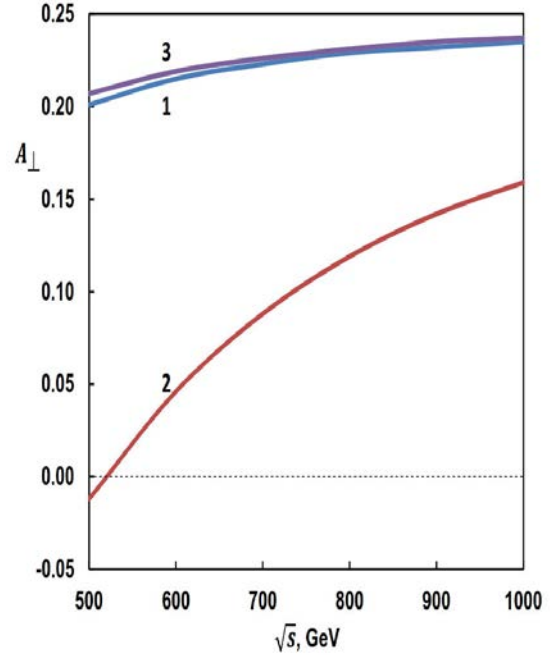


Fig. 5. Energy dependence of transverse spin asymmetry \sqrt{s} .

As for the transverse spin asymmetry $A_{\perp}(\theta)$ in the reaction $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_2^+$, we note that it is negative and at an angle of $\theta = 90^\circ$ reaches a minimum (at this point, the asymmetry $A_{\perp}(\theta) = -1.8\%$).

We also present an expression for the transverse spin asymmetry $A_{\perp}(\sqrt{s}, \varphi)$ integrated over the polar angle θ of the chargino emission:

$$A_{\perp}(\sqrt{s}, \varphi) = -\frac{2}{3} g_L g_R (G_L^2 + G_R^2) \lambda(r_{\chi_i}, r_{\chi_j}) \cos 2\varphi \times \left\{ (g_L^2 + g_R^2) [(G_L^2 + G_R^2) \left[(1+r_{\chi_i} - r_{\chi_j})(1-r_{\chi_i} + r_{\chi_j}) + \frac{1}{3} \lambda(r_{\chi_i}, r_{\chi_j}) \right] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}] \right\}^{-1}. \quad (28)$$

In fig. 5 shows the energy dependence of the transverse spin asymmetry $A_{\perp}(\sqrt{s})$ integrated over the polar angle θ in the reactions $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$ (curve 1), $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_2^+$ (curve 2) and $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$ (or $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+$) (curve 3) at the same values of the parameters as in Figure 3. In all processes, the transverse spin asymmetry is positive and with increasing energy of colliding electron-positron beams, the asymmetry is increasing.

5. DEGREES OF LONGITUDINAL AND TRANSVERSE POLARIZATION OF CHARGINO

So far, we have been interested in the polarization states of the lepton and antilepton. We have determined the longitudinal and transverse spin asymmetries caused by the polarizations of the lepton

and antilepton. Note that the study of the degrees of longitudinal and transverse polarizations of the charginos is also of certain interest. They can provide valuable information about the constants of interaction of a chargino with a gauge Z -boson G_L and G_R . In this regard, we turn to the study of the polarization characteristics of the chargino.

Let us consider the differential cross section of process (1) taking into account the longitudinal polarization of the chargino:

$$\frac{d\sigma(h)}{d\Omega} = \frac{1}{2} \frac{d\sigma_0}{d\Omega} [1 + hP_{\parallel}(\theta)]. \quad (29)$$

Here, $\frac{d\sigma_0}{d\Omega}$ – the differential effective cross section for reaction (1) in the case of unpolarized particles, a $P_{\parallel}(\theta)$ – the degree of longitudinal polarization of the chargino $\tilde{\chi}_i^-$:

$$P_{\parallel}(\theta) = \{ (g_L^2 + g_R^2)(G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} [1 - r_{\chi_i} + r_{\chi_j} + (1 + r_{\chi_i} - r_{\chi_j}) \cos^2 \theta] - 2(g_L^2 - g_R^2) [(G_L^2 + G_R^2)(1 - r_{\chi_i} - r_{\chi_j}) + 4G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}] \} \times \{ (g_L^2 + g_R^2) [(G_L^2 + G_R^2) [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}] + 2(g_L^2 - g_R^2)(G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \cos \theta \}^{-1}. \quad (30)$$

If the chargino is transversely polarized in the plane of production, then the differential cross section of process (1) takes the form (the lepton is longitudinally polarized):

$$\frac{d\sigma(\lambda_1, \eta)}{d\Omega} = \frac{1}{2} \frac{d\sigma(\lambda_1)}{d\Omega} [1 + \eta P_{\perp}(\theta, \sqrt{s})], \quad (31)$$

Where $\frac{d\sigma(\lambda_1)}{d\Omega}$ – the differential effective cross section for reaction (1) upon annihilation of a longitudinally polarized lepton and an unpolarized antilepton:

$$\frac{d\sigma(\lambda_1)}{d\Omega} = \frac{\alpha_{\text{QED}}^2 \cdot s}{32[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2] x_W^2 (1 - x_W)^2} \times \{ [g_L^2(1 - \lambda_1) + g_R^2(1 + \lambda_1)] [(G_L^2 + G_R^2) [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}] + 2[g_L^2(1 - \lambda_1) - g_R^2(1 + \lambda_1)] (G_L^2 - G_R^2) \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \cos \theta \}, \quad (32)$$

η – the transverse component of the spin vector of the chargino, and $P_{\perp}(\theta, \sqrt{s})$ – the degree of transverse polarization of the chargino, determined by the expression:

$$P_{\perp}(\theta, \sqrt{s}) = \sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \sin 2\theta \{ [g_L^2(1 - \lambda_1) + g_R^2(1 + \lambda_1)] (G_L^2 - G_R^2) \sqrt{r_{\chi_i}} + [g_L^2(1 - \lambda_1) - g_R^2(1 + \lambda_1)] [-(G_L^2 + G_R^2) \sqrt{r_{\chi_i}} + 8G_L G_R \sqrt{r_{\chi_j}}] \} \cdot \{ [g_L^2(1 - \lambda_1) + g_R^2(1 + \lambda_1)] \times [(G_L^2 + G_R^2) [(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \lambda(r_{\chi_i}, r_{\chi_j}) \cos^2 \theta] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}}] +$$

$$+ 2[g_L^2(1-\lambda_1) - g_R^2(1+\lambda_1)](G_L^2 - G_R^2)\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})} \cos \theta\}^{-1}. \quad (33)$$

In fig. 6 illustrates the angular dependence of the degree of longitudinal polarization of the chargino in the processes $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$ (curve 1), $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_2^+$ (curve 2) and $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$ (or $e^- + e^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+$) (curve 3). It is seen that in all processes the degree of longitudinal polarization of the chargino is negative, with an increase in the emission angle θ it slowly decreases, reaches a minimum at an angle of $\theta = 90^\circ$, and a further increase in the angle leads to an increase in the degree of longitudinal polarization of the chargino.

The angular dependence of the degree of transverse polarization $P_\perp(\theta, \sqrt{s})$ of the chargino in the reaction $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$ is shown in fig. 7

$$\sigma_0(\lambda_1) = \frac{\alpha_{\text{КЭД}}^2 \cdot s}{8[(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \frac{\sqrt{\lambda(r_{\chi_i}, r_{\chi_j})}}{x_W^2 (1 - x_W)^2} [g_L^2(1 - \lambda_1) + g_R^2(1 + \lambda_1)] \times \left\{ (G_L^2 + G_R^2)^2 \left[(1 + r_{\chi_i} - r_{\chi_j})(1 - r_{\chi_i} + r_{\chi_j}) + \frac{1}{3} \lambda(r_{\chi_i}, r_{\chi_j}) \right] + 8G_L G_R \sqrt{r_{\chi_i} r_{\chi_j}} \right\}. \quad (34)$$

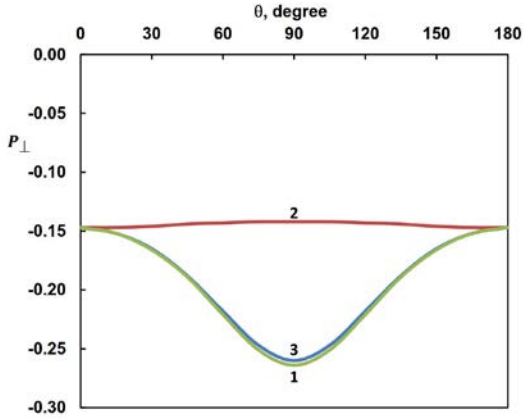


Fig. 6. Angular dependence of the degree of longitudinal polarization of the chargino in the processes $e^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^+$ (curve 1), $e^- e^+ \rightarrow \tilde{\chi}_2^- \tilde{\chi}_2^+$ (curve 2) and $e^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_2^+$ (or $e^- e^+ \rightarrow \tilde{\chi}_2^- \tilde{\chi}_1^+$) (curve 3).

In fig. 8 illustrates the energy dependence of the cross section in the reaction $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$ in three cases: a) when the electron is right-handed ($\lambda_1 = 1$, $e_R^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$); b) when the electron has left helicity ($\lambda_1 = -1$, $e_L^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$); c) when particles are unpolarized ($e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+$).

As can be seen from the figure, there is the following relationship between these sections:

for the helicity of the lepton $\lambda_1 = 1$ (curve 1), $\lambda_1 = -1$ (curve 2) and for an unpolarized electron (curve 3). It follows from the figure that in the interaction of a left (right) polarized electron with an unpolarized positron, the degree of transverse polarization of the chargino in the reaction $e^- + e^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+$ first increases (decreases) and reaches a maximum (minimum) at 60° , and then decreases (increases) becomes zero, and changes sign repeats numerical values with opposite sign. In the annihilation of an unpolarized electron-positron pair, the degree of transverse polarization of the chargino is only a few percent (at $\theta = 45^\circ$ $P_\perp = 4.8\%$).

The total cross section for reaction (1), obtained by integrating over the angles θ and φ , has the form:

$$\sigma_1(e_R^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_2^+) < \sigma_3(e^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_2^+) < \sigma_2(e_L^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_2^+)$$

This is due to the fact that the left-hand coupling constant of the electron with the Z -boson g_L^2 is numerically ahead of the right-hand coupling constant g_R^2 ($g_L^2 > g_R^2$).

The study of the contribution of s-channel diagrams with the exchange of Higgs bosons H , h and A , as well as the t-channel diagram with exchange of sneutrino $\tilde{\nu}_{eL}$, was outlined in another work.

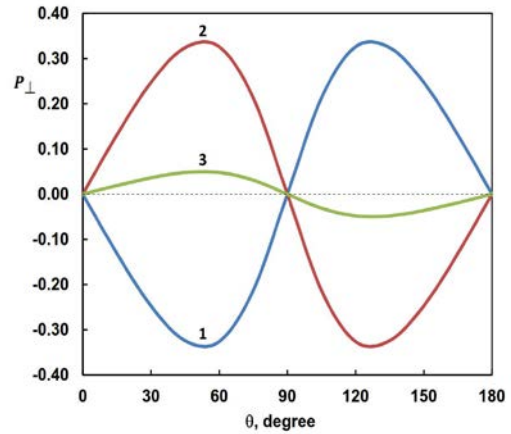


Fig. 7. Angular dependence of the degree of transverse polarization of the chargino in the process $e^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^+$: $\lambda_1 = 1$ (curve 1), $\lambda_1 = -1$ (curve 2) and for an unpolarized electron (curve 3).

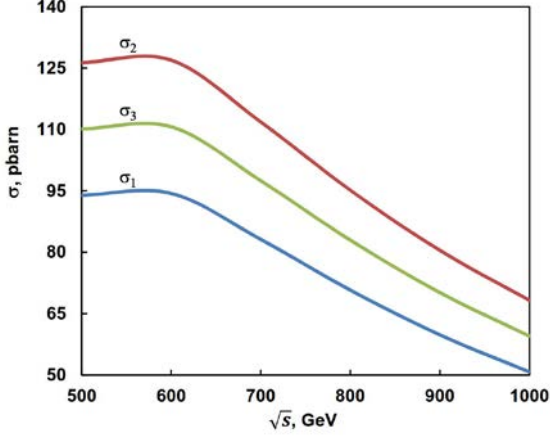


Fig. 8. The energy dependence of the cross section of the reaction $e^-e^+ \rightarrow \tilde{\chi}_1^-\tilde{\chi}_2^+$ in the cases $\lambda_1 = 1$ (curve 1), $\lambda_1 = -1$ (curve 2) and when unpolarized electron (curve 3).

CONCLUSION

We have discussed the annihilation process of an arbitrarily polarized lepton-antilepton pair (e^-e^+ - or $\mu^-\mu^+$ -pair) into a chargino pair $\ell^- + \ell^+ \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_j^+$. The diagram with the exchange of a neutral Z -boson is studied in detail in the case of a longitudinally and transversely polarized lepton-antilepton pair. The longitudinal and transverse spin asymmetries caused by the polarizations of the lepton-antilepton pair, the forward-backward angular asymmetry A_{FB} , as well as the degrees of the longitudinal and transverse polarization of the chargino are determined. The angular and energy dependences of these characteristics, as well as the total cross section of the reaction under consideration, are studied in detail. Research results are illustrated with graphs.

APPENDIX

Here we give the expressions for the squared amplitudes $|M^{(\gamma)}|^2$, $|M^{(Z)}|^2$ and $(M^{+(\gamma)}M^{(Z)} + M^{+(Z)}M^{(\gamma)})$:

$$\begin{aligned}
 |M^{(\gamma)}|^2 &= \frac{8(4\pi\alpha_{\text{QED}})^2}{s^2} \times \\
 &\times \{ (k_1 \cdot p_1)(k_2 \cdot p_2) + (k_1 \cdot p_2)(k_2 \cdot p_1) - m_e^2 [(k_1 \cdot s_1)(k_2 \cdot s_2) + (k_1 \cdot s_2)(k_2 \cdot s_1)] - \\
 &- (s_1 \cdot s_2) [(k_1 \cdot p_1)(k_2 \cdot p_2) + (k_1 \cdot p_2)(k_2 \cdot p_1) - (p_1 \cdot p_2) [(k_1 \cdot s_1)(k_2 \cdot s_2) + (k_1 \cdot s_2)(k_2 \cdot s_1) - \\
 &- (k_1 \cdot k_2)(s_1 \cdot s_2)] + (p_1 \cdot s_2) [(k_1 \cdot s_1)(p_2 \cdot k_2) + (k_2 \cdot s_1)(k_1 \cdot p_2) - (k_1 \cdot k_2)(p_2 \cdot s_1)] + \\
 &+ (p_2 \cdot s_1) [(k_1 \cdot p_1)(k_2 \cdot s_2) + (k_2 \cdot p_1)(k_1 \cdot s_2)] + m_{\chi_i} m_{\chi_j} [(p_1 \cdot p_2) - m_e^2 (s_1 \cdot s_2)] \}; \\
 |M^{(Z)}|^2 &= \left(\frac{\pi\alpha_{\text{QED}}}{x_W(1-x_W)} \right)^2 \frac{8}{(s-M_Z^2)^2 + \Gamma_Z^2 M_Z^2} \times \\
 &\times \{ [(g_{\chi_i \chi_j Z}^L)^2 + (g_{\chi_i \chi_j Z}^R)^2] [(g_L^2 + g_R^2) [(k_1 \cdot p_1)(k_2 \cdot p_2) + (k_1 \cdot p_2)(k_2 \cdot p_1) - m_e^2 [(k_1 \cdot s_1)(k_2 \cdot s_2) + \\
 &+ (k_1 \cdot s_2)(k_2 \cdot s_1)]] + (g_L^2 - g_R^2) m_e [(k_1 \cdot p_1)(k_2 \cdot s_2) + (k_2 \cdot p_1)(k_1 \cdot s_2) - (k_1 \cdot p_2)(k_2 \cdot s_1) - \\
 &- (p_1 \cdot k_2)(k_1 \cdot s_1)] + 2g_L g_R [- (s_1 \cdot s_2) [(k_1 \cdot p_1)(k_2 \cdot p_2) + (k_1 \cdot p_2)(k_2 \cdot p_1)] - \\
 &- (p_1 \cdot p_2) [(k_1 \cdot s_1)(k_2 \cdot s_2) + (k_1 \cdot s_2)(k_2 \cdot s_1) - (p_1 \cdot p_2)(k_1 \cdot k_2)] + (p_1 \cdot s_2) [(k_1 \cdot s_1)(k_2 \cdot p_2) + \\
 &+ (k_2 \cdot s_1)(k_1 \cdot p_2) - (k_1 \cdot k_2)(p_1 \cdot s_2)] + (p_2 \cdot s_1) [(k_1 \cdot p_1)(k_2 \cdot s_2) + (k_1 \cdot s_2)(k_2 \cdot p_1)]] \} + \\
 &+ [(g_{\chi_i \chi_j Z}^L)^2 - (g_{\chi_i \chi_j Z}^R)^2] [(g_L^2 + g_R^2) m_e [(p_1 \cdot k_2)(k_1 \cdot s_2) - (p_1 \cdot k_1)(k_2 \cdot s_2) + (k_1 \cdot s_1)(k_2 \cdot p_2) - \\
 &- (k_1 \cdot p_2)(k_2 \cdot s_1)] + (g_L^2 - g_R^2) [(k_1 \cdot p_2)(k_2 \cdot p_1) - (k_1 \cdot p_1)(k_2 \cdot p_2) + m_e^2 [(k_1 \cdot s_1)(k_2 \cdot s_2) - \\
 &- (k_1 \cdot s_2)(k_2 \cdot s_1)]] + g_R g_L m_e [(k_2 \cdot p_2)(k_1 \cdot s_2) - (k_1 \cdot p_2)(k_2 \cdot s_2) + (k_1 \cdot p_1)(k_2 \cdot s_1) - (k_2 \cdot p_1)(k_1 \cdot s_1)] \} + \\
 &+ 2g_{\chi_i \chi_j Z}^L g_{\chi_i \chi_j Z}^R m_{\chi_i} m_{\chi_j} [(g_L^2 + g_R^2) [(p_1 \cdot p_2) - m_e^2 (s_1 \cdot s_2)] + (g_L^2 - g_R^2) m_e [(p_1 \cdot s_2) - (p_2 \cdot s_1)]] \}; \\
 M^{+(\gamma)}M^{(Z)} + M^{+(Z)}M^{(\gamma)} &= \left(\frac{4\pi\alpha_{\text{QED}}}{x_W(1-x_W)} \right)^2 \frac{2(s-M_Z^2)}{s[(s-M_Z^2)^2 + \Gamma_Z^2 M_Z^2]} \times \\
 &\times \{ (g_{\chi_i \chi_j Z}^L + g_{\chi_i \chi_j Z}^R) [(g_L + g_R) [(p_1 \cdot k_1)(p_2 \cdot k_2) + (p_1 \cdot k_2)(p_2 \cdot k_1) - m_e^2 [(k_1 \cdot s_1)(k_2 \cdot s_2) +
 \end{aligned}$$

$$\begin{aligned}
 & + (k_1 \cdot s_2)(k_2 \cdot s_1)] - (s_1 \cdot s_2)[(k_1 \cdot p_1)(k_2 \cdot p_2) + (k_1 \cdot p_2)(k_2 \cdot p_1)] - (p_1 \cdot p_2)[(k_1 \cdot s_1)(k_2 \cdot p_2) + \\
 & + (k_1 \cdot s_2)(k_2 \cdot s_1) - (k_1 \cdot k_2)(s_1 \cdot s_2)] + (p_1 \cdot s_2)[(k_1 \cdot s_1)(k_2 \cdot p_2) + (k_2 \cdot s_1)(k_1 \cdot p_2) - (k_1 \cdot k_2)(p_2 \cdot s_1)] + \\
 & + (p_2 \cdot s_1)[(k_1 \cdot s_2)(k_2 \cdot p_1) + (k_2 \cdot s_2)(k_1 \cdot p_1)] + (g_L - g_R)m_e[(k_1 \cdot s_2)(k_2 \cdot p_1) + (k_1 \cdot p_1)(k_2 \cdot s_1) - \\
 & - (k_1 \cdot p_2)(k_2 \cdot s_1) - (k_2 \cdot p_2)(k_1 \cdot s_1) + m_{\chi_i} m_{\chi_j} [(p_1 \cdot s_2) - (p_2 \cdot s_1)]] + (g_{\chi_i \chi_j Z}^L - g_{\chi_i \chi_j Z}^R)m_e[(g_L + g_R) \times \\
 & \times [(k_1 \cdot p_1)(k_2 \cdot s_2) - (k_2 \cdot p_1)(k_1 \cdot s_2) + (k_1 \cdot p_2)(k_2 \cdot s_2) - (k_2 \cdot p_2)(k_1 \cdot s_1) + (k_1 \cdot p_2)(k_2 \cdot s_2) - \\
 & - (k_2 \cdot p_2)(k_1 \cdot s_2) + (k_1 \cdot p_1)(k_2 \cdot s_1) - (k_2 \cdot p_1)(k_1 \cdot s_1)] - (g_L - g_R)[(k_1 \cdot p_1)(k_2 \cdot p_2) - \\
 & - (k_1 \cdot p_2)(k_2 \cdot p_1) - m_e^2[(k_1 \cdot s_1)(k_2 \cdot s_2) - (k_1 \cdot s_2)(k_2 \cdot s_1)]]].
 \end{aligned}$$

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Received:19.10.2020