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ON THE LIGHTEST SUPERSYMMETRIC PARTICLE IN POLARIZED e^+e^--COLLISIONS

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1. In nearly all supersymmetric (SUSY) theories[1] R -parity is a well defined quantum number. This implies the existence of a lightest SUSY particle (LSP) which should be stable[1] and also colourless and electrically neutral[2]. Its type is uniquely predicted by the accepted scheme of SUSY - breaking (SSB). Knowledge of LSP is of fundamental theoretical importance for understanding the mechanism of SSB.

The plausible candidate in most SUSY models is one of the heavy Majorana fermions, called neutralinos, that inevitably appear in SUSY models. In the minimal SUSY model[1] these are the superpartners $\tilde{\gamma}$ and $\tilde{Z}$ of the neutral gauge bosons and the superpartners $\tilde{H}_{10}$ and $\tilde{H}_{20}$ of the two neutral Higgs scalars. As SUSY is broken the physical (massive) neutralinos χ_i should be a mixture of $S = 1/2$ neutral SUSY partners:

$$\chi_{iL} = N_{ij} \Psi_{jL} , \quad \Psi_j^T = (\tilde{\gamma}, \tilde{Z}, \tilde{H}_{10}, \tilde{H}_{20}) \tag{1}$$

where N_{ij} are elements of the neutralino mixing matrix determined by the SSB mechanism (subscript L denotes l.h. components of the four component spinors).

In this paper the production cross section for two different (massive) neutralinos χ_1 and χ_2 in longitudinally polarized e^+e^- - collisions

$$e^+ + e^- \longrightarrow \chi_1 + \chi_2 \tag{2}$$

is calculated in the minimal SUSY extended standard model in the general case of arbitrary neutralino mising, eq.(1). Process (2) has been considered earlier both for unpolarized[3-8] and polarized[9,10] initial beams. It has been shown that the values of the cross section and the asymmetries strongly depend on the type of produced χ_1 and χ_2.

We assume χ_1 to be LSP. To obtain specific properties of the cross section and the polarization asymmetries in process (2) that reflect the type of LSP, independently of the produced heavier neutralino χ_2, based only on the fundamental assumption of SUSY that every familiar particle of the standard model has the same coupling as its superpartner is the aim of this paper.

We assume process (2) to be identified by observation of a lepton $\ell^+\ell^-$-pair (from the decay $\chi_2 \to \chi_1 + \ell^+ + \ell^-$) and a large amount of "missing" momentum (taken away by χ_1).

Here we show that measurements of the cross section and the longitudinal asymmetry allow us to distinguish between the two characteristic cases of neutralino mixing:

i) when LSP is of gaugino type, i.e. χ_1 is mainly a mixture of $\tilde{\gamma}$ and $\tilde{Z}$ and

ii) when LSP is of higgsino type, i.e. χ_1 is a mixture of $\tilde{H}_{10}$ and $\tilde{H}_{20}$. It is shown also that the longitudinal asymmetry is very sensitive to the selectron mass spectrum.

2. The relevant terms of the interaction Lagrangian in a very general class of $N=1$ SUSY models, introducing four neutralinos, may be written in the form:

$$\mathcal{L} = \frac{-ig}{\cos\theta_W}\left[\bar{e}\gamma_\alpha(c_V + c_A\gamma_5)e - \bar{\chi}_1\gamma_\alpha(g_V + g_A\gamma_5)\chi_2\right]\cdot Z_\alpha + \tag{3}$$
$$+ \frac{ig}{2}\sum_{i=1,2}\left\{\xi_i\, \mathcal{U}_{iL}\, \tilde{e}_L\, \bar{e}\, \chi_{iR} - \mathcal{U}_{iR}\, \tilde{e}_R\, \bar{e}\, \chi_{iL}\right\} + h.c.$$

Here

$$c_V = \frac{1}{4} - \sin^2\theta_W \quad , \quad c_A = \frac{1}{4}$$
$$g_V = O_{12}(1 - \xi_1\xi_2) \quad , \quad g_A = O_{12}(1 + \xi_1\xi_2)$$
$$O_{12} = -\frac{1}{2}N_{13}N_{23} + \frac{1}{2}N_{14}N_{24}$$
$$\mathcal{U}_{iL} = N_{i2} + N_{i1}\, tg\,\theta_W \,,\; N_{iR} = 2N_{i1}\, tg\,\theta_W \,,\; i = 1,2.$$

The $Z^0 e^+e^-$ couplings (c_V and c_A) are given by the standard model and expressed in terms of $\sin^2\theta_W$. The neutralino couplings to Z^0 (g_V and g_A) and to $\tilde{e}_L$ and $\tilde{e}_R$ ($\mathcal{U}_{iL}$ and $\mathcal{U}_{iR}$) are determined by the SSB mechanism and expressed via N_{ij}, which in the considered here case of CP-invariance may be chosen to be real. The factors $\xi_\varkappa$ ($\xi_\varkappa = \pm 1$) in the Majorana condition

$$C\,\bar{\chi}_\varkappa^T(x) = \xi_\varkappa\, \chi_\varkappa(x), \quad \varkappa = 1,\dots 4 \tag{4}$$

(C is the charge conjugate matrix) are related to the CP-parities $\eta_\varkappa^{CP}$ of $\chi_\varkappa$ /11/: $i\eta_\varkappa^{CP} = \xi_\varkappa$, which ensures nonnegative mass spectrum of $\chi_\varkappa$. In eq.(3) and further on we shall refer to $\xi_\varkappa$ as to measurable quantities.

The cross section of process (2) with longitudinally polarized e^+e^- has the general form /12/:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\lambda_1\lambda_2} = \alpha_0\left[(1-\lambda_1\lambda_2)Y_1(\theta) + (\lambda_2 - \lambda_1)Y_2(\theta)\right]. \tag{5}$$

Here λ_1 and λ_2 are longitudinal polarizations of e^- and e^+, θ is the angle between the momenta of e^- and χ_2 in the c.m.s. Both $Y_1(\theta)$ and $Y_2(\theta)$ get contributions from the diagrams with Z^0-exchange, $\tilde{e}_L$, $\tilde{e}_R$-exchange and from Z^0-$\tilde{e}_L$, Z^0-$\tilde{e}_R$ interference:

$$Y_i(\theta) = Y_i^Z(\theta) + Y_i^{\tilde{e}}(\theta) + Y_i^I(\theta), \quad i = 1,2. \tag{6}$$

From eqs.(3) and (4) after long calculations we obtain:

$$\alpha_0 = \frac{4\alpha^2|\vec{p}|^2}{s\sqrt{s}\,\sin^4\theta_W\cos^4\theta_W}, \quad |\vec{p}| = \frac{\lambda(s, m_1^2, m_2^2)}{2\sqrt{s}},$$
$$Y_1^Z(\theta) = \frac{4O_{12}^2(c_V^2 + c_A^2)}{|D_Z(s)|^2}\left\{A + B - \frac{s}{2}\xi_1\xi_2 m_1 m_2\right\},$$
$$Y_2^Z(\theta) = \frac{8O_{12}^2 c_V c_A}{|D_Z(s)|^2}\left\{A + B - \frac{s}{2}\xi_1\xi_2 m_1 m_2\right\}, \tag{7a}$$

$$A = (\ell_1 p_1)(\ell_2 p_2), \quad B = (\ell_1 p_2)(\ell_2 p_1)$$

$$Y_1^{\tilde{e}}(\theta) = \frac{1}{8}\left(\frac{\cos^2\theta_W}{4}\right)^2\left\{\mathcal{U}_{1L}^2\,\mathcal{U}_{2L}^2\left[\frac{A}{D_L^2(p_1)} + \frac{B}{D_L^2(p_2)} - \frac{s}{2}\frac{\xi_1\xi_2 m_1 m_2}{D_L(p_1)D_L(p_2)}\right] + (L \to R)\right\},$$
$$Y_2^{\tilde{e}}(\theta) = \frac{1}{8}\left(\frac{\cos^2\theta_W}{4}\right)^2\left\{\mathcal{U}_{1L}^2\,\mathcal{U}_{2L}^2\left[\frac{A}{D_L^2(p_1)} + \frac{B}{D_L^2(p_2)} - \frac{s}{2}\frac{\xi_1\xi_2 m_1 m_2}{D_L(p_1)D_L(p_2)}\right] - (L \to R)\right\}. \tag{7b}$$

Here s is the c.m. energy squared, $D_Z(s) = -s + m_Z^2 - i m_Z \Gamma_Z$,
$D_L(p_i) = (\ell_2 - p_i)^2 + m_L^2$, $D_R(p_i) = (\ell_2 - p_i)^2 + m_R^2$,

l_1, l_2, p_1, p_2 are the momenta of e^-, e^+, χ_1, χ_2; m_L and m_R are the masses of $\tilde{e}_L$ and $\tilde{e}_R$; m_Z and Γ_Z are the mass and decay width of Z^o. We do not present the explicit expression for $Y_i^I(\theta)$ as it is irrelevant to our further considerations.

3. According to SUSY the couplings of the ordinary particles are identical to those of their superpartners. So Z^o couples $\tilde{H}_{10}$ and $\tilde{H}_{20}$ and does not couple $\tilde{\gamma}$ and $\tilde{Z}$, while $\tilde{e}_L$, $\tilde{e}_R$ (at the considered energies when the electron mass can be neglected) couple only $\tilde{\gamma}$ and $\tilde{Z}$. Thus in the considered process of neutralino production it is only the $\tilde{H}_o$ -components (N_{i3}, N_{i4}) of χ_1 and χ_2 that contribute to $Y_i^Z(\theta)$ and only the gaugino components (N_{i1}, N_{i2}) that contribute to $Y_i^{\tilde{e}}(\theta)$. It is the interference term Y_i^I that gets contributions both from higgsino and gaugino components.

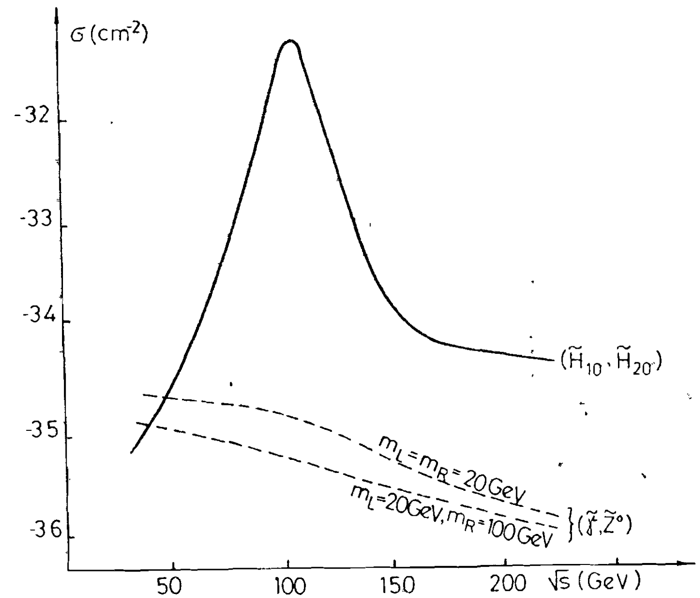
Let us assume that χ_1 is either of gaugino or of $\tilde{H}_o$ -type. In this case $Y_i^I(\theta)$ equals zero, whatever the mixing in χ_2 is. If χ_1 is of higgsino type, process (2) proceeds via Z^o-exchange, i.e. $Y_i(\theta) = Y_i^Z(\theta)$, while if χ_1 is of gaugino type, it occurs via $\tilde{e}_L$, $\tilde{e}_R$ - exchange, i.e. $Y_i = Y_i^{\tilde{e}}(\theta)$. If we propose now that χ_1 is LSP, separating the contributions of Z^o and from $\tilde{e}_L$, $\tilde{e}_R$ -exchange we would be able to distinguish between the two mechanisms of SSB: when LSP is of $\tilde{H}_o$ or gaugino type. If LSP is of gaugino type, three situations characterizing the mass spectrum of $\tilde{e}_L$ and $\tilde{e}_R$ will be discussed: a) the chargino massive states are degenerate, $m_L = m_R$, b) $m_L^2 >> m_R^2$ and c) $m_L^2 << m_R^2$.

If LSP is of $\tilde{H}_o$ -type, due to the Z^o-annihilation diagram a resonance peak of the total cross section $\sigma(s)$ at $\sqrt{s} = m_Z$ is expected, while a flat decreasing behaviour of $\sigma(s)$ is predicted if LSP is of gaugino type. The three considered possibilities for the chargino mass spectrum do not lead to any significant difference in σ, its value being mainly determined by the lighter selectron-exchange diagram. The cross section decreases for larger selectron masses. This is illustrated on fig.1. The cross-section at the Z^o-peak reaches 10^{-31} cm^{-2}.

Let us now consider the longitudinal asymmetry A_{11}:

$$A_{11}(s) = \frac{1}{\lambda_1}\frac{\sigma(\lambda_1,0)-\sigma(-\lambda_1,0)}{\sigma(\lambda_1,0)+\sigma(-\lambda_1,0)} = -\frac{1}{\lambda_2}\frac{\sigma(0,\lambda_2)-\sigma(0,-\lambda_2)}{\sigma(0,\lambda_2)+\sigma(0,-\lambda_2)}, \quad (8)$$

where $\sigma(\lambda,0)(\sigma(0,\lambda))$ denotes the total cross section of process (2) when the electron (positron) beam has longitudinal polarization λ.



F i g. 1. The total cross section $\sigma(s)$ for LSP of higgsino (full line, m_1 = 1 GeV, m_2 = 30 GeV) and gaugino (dotted line, m_1 = 1.9 GeV, m_2 = 33 GeV) type. The neutralino mixing matrix of ref./1/ is used.

From eqs. (5) and (8) we obtain

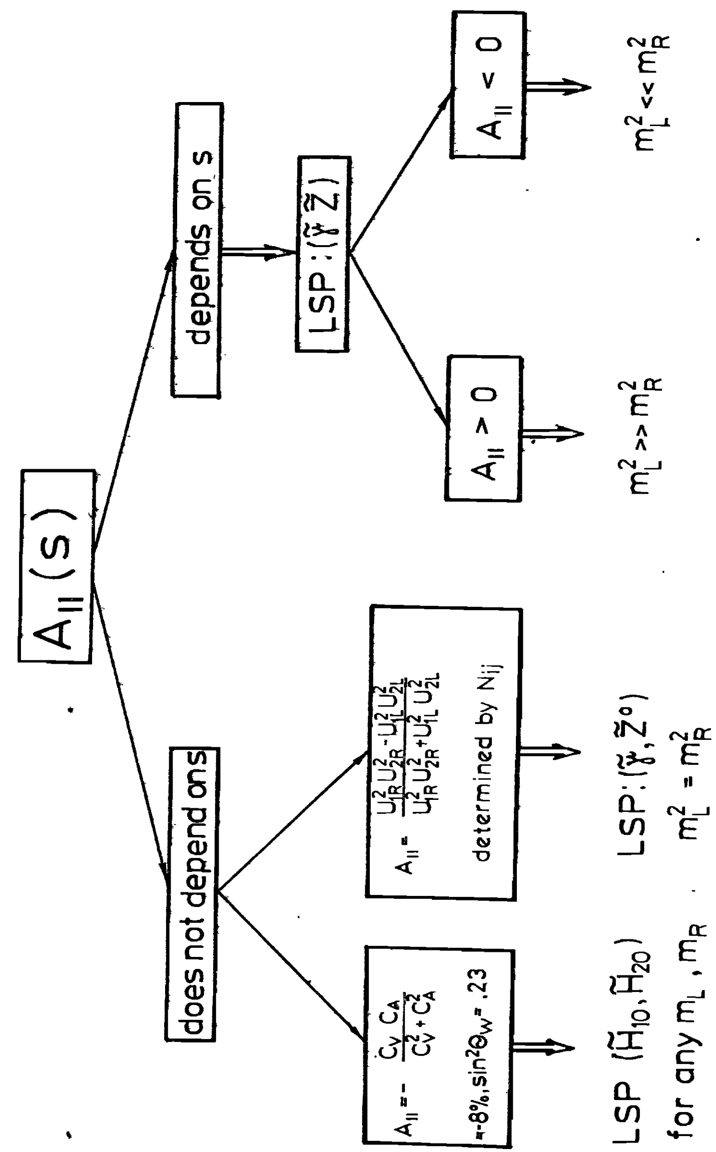
$$A_{11}(s) = -\int Y_2(\theta)\,d\Omega \Big/ \int Y_1(\theta)\,d\Omega. \quad (9)$$

The calculations show that measurements of A_{11} can provide more refined tests of the theory. The difference of the predictions due to different LSP and chargino mass spectrum are shown on the diagram on fig. 2 and can be formulated as follows:

1) If A_{11} is independent of s, two possibilities exist:

a) LSP is of $\tilde{H}_o$ -type. Then eqs.(7a) and (9) imply $A_{11} = -c_V c_A/(c_V^2 + c_A^2)$ uniquely fixed by $\sin^2\theta_W$ whose value is known with good accuracy from experiment. At $\sin^2\theta_W$ =.23/13/, A_{11} =-8%.

b) LSP is of gaugino type, $m_L = m_R$. In this case from eqs.(7b) and (9) we obtain $A_{11} = (U_{1R}^2 U_{2R}^2 - U_{1L}^2 U_{2L}^2)/(U_{1R}^2 U_{2R}^2 + U_{1L}^2 U_{2L}^2)$, sensitive to the neutralino mixing matrix. The

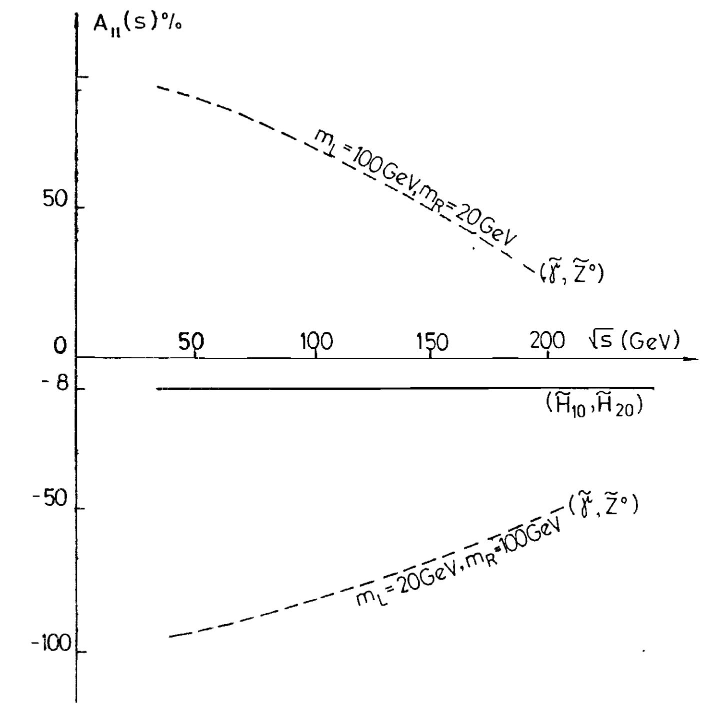


F i g. 2. Predictions for LSP and the chargino mass spectrum from $A_\parallel(s)$.

asymmetry does not depend on the values of m_L, m_R. Precise measurements of $A_\parallel$ would give information of N_{ij} and the selectron mass degeneracy.

2) If $A_\parallel$ depends on s, LSP should necessarily be of gaugino type, $m_L \neq m_R$. If $A_\parallel > 0$, then $m_L^2 \gg m_R^2$, if $A_\parallel < 0$, then $m_L^2 \ll m_R^2$. These results follow immediately from eq.(7b) determining $\sigma(\lambda_1, \lambda_2)$ in this case, if one takes into account that the lighter $\tilde e$ -exchange term is dominant in $Y_i^{\tilde e}(\theta)$. The $\tilde e_L$ and $\tilde e_R$ -exchange terms enter $Y_2^{\tilde e}(\theta)$ with opposite signs and $Y_1^{\tilde e}(\theta)$ with equal signs, so the sign of $A_\parallel$ determined by their ratio, eq.(9) is governed by the contribution of the lighter selectron.

Figure (3) illustrates the magnitude of $A_\parallel(s)$. For LSP of gaugino type, $m_L \neq m_R$, $|A_\parallel|$ decreases with $\sqrt{s}$. It amounts to about



F i g. 3. The longitudinal asymmetry for LSP of higgsino (full line) and gaugino, $m_L \neq m_R$, (dotted line) type. The constant value for $A_\parallel$ when LSP is of gaugino type, $m_L = m_R$ is determined by N_{ij}.

100% at low energies ($\sqrt{s} \approx 20$ GeV) however still remaining quite large over the energy range of interest in SLC and LEP ($A \sim 50\%$ at $\sqrt{s} \approx 150$ GeV).

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О самой легкой суперсимметричной частице
в столкновениях поляризованных e^+e^-

Рассматривается аннигиляция продольно поляризованных e^+e^- в два нейтральных фермиона в $N = 1$ СУСИ-теориях. Один из фермионов предполагается самой легкой СУСИ частицей. Показано, что измерения сечения и поляризационных асимметрий позволяет отличить следующие две возможности для самой легкой СУСИ-частицы: конда она типа хигсино или типа гейджино.

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On the Lightest Supersymmetric Particle
in Polarized e^+e^--Collisions

Annihilation of longitudinally polarized e^+e^- into two neutralinos in $N = 1$ supersymmetry is considered. One of the produced neurtalinos is assumed to be the linghtest SUSY particle (LSP). It is shown that measurement of the cross-section and asymmetry would allow one to distingush between the two cases: when LSP is of higgsino or gaugino type.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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