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SPIN EFFECTS IN NEUTRALINO PRODUCTION IN e^+e^- ANNIHILATION WITH POLARIZED BEAMS* **

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We study the process $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ and the subsequent decay $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\ell^+\ell^-$ with polarized beams, including the complete spin correlations of $\tilde{\chi}^0_2$. We present numerical results for the lepton energy and angular distributions, and for the distribution of the opening angle between the leptons for $\sqrt{s} = 500$ GeV. The effects of spin correlations are important in the lepton angular distribution, especially for gaugino–like neutralinos. The opening angle distribution is particularly suitable for distinguishing between higgsino- and gaugino-like neutralinos. The polarized cross sections and lepton angular distributions are very sensitive to the mixing of the neutralinos.

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1. Introduction

Most studies of neutralino production $e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0$ and decay of neutralinos have been performed in the Minimal Supersymmetric Standard Model (MSSM). (See, for example [1–3], and references therein.) Usually, in these studies the spin correlations between the production and decay process have been neglected. It is expected that these spin correlations are important in the angular distributions.

Angular distributions and angular correlations of the decay products of neutralinos can give valuable information on their mixing character. Their measurement is very suitable for constraining the parameter space of the MSSM. In this contribution we study $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$ with the subsequent decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$, including the complete spin correlations of $\tilde{\chi}_2^0$. We also take into account beam polarization. We give numerical results for polarized cross sections, forward–backward asymmetries, lepton angular distributions, lepton opening angular distributions and lepton energy distributions at $\sqrt{s} = 500$ GeV.

2. General formalism

Both the production process, $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$, and the decay process, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$ contain contributions from Z^0 exchange and from $\tilde{\ell}_L$ and $\tilde{\ell}_R$ exchange. A treatment of these processes properly taking into account the polarization of $\tilde{\chi}_2^0$ has been given in [5] following the method of [4].

The amplitude $T = \Delta_2 P^{\lambda_2} D_{\lambda_2}$ of the combined process is a product of the helicity amplitude P^{λ_2} for the production process times the helicity amplitude D_{λ_2} for the decay process and the propagator $\Delta_2 = 1/[s_2 - m_2^2 + im_2\Gamma_2]^{-1}$ of $\tilde{\chi}_2^0$ with helicity λ_2, summed over λ_2. s_2, m_2, Γ_2 denote the four–momentum squared, mass and width of $\tilde{\chi}_2^0$. The amplitude squared $|T|^2 = |\Delta_2|^2 \rho_P^{\lambda_2\lambda_2'} \rho^D_{\lambda_2'\lambda_2}$ is thus composed of the unnormalized spin density production matrix $\rho_P^{\lambda_2\lambda_2'} = P^{\lambda_2}P^{\lambda_2'*}$ of $\tilde{\chi}_2^0$ and the decay matrix $\rho^D_{\lambda_2'\lambda_2} = D_{\lambda_2}D^*_{\lambda_2'}$.

Interference terms between various helicity amplitudes preclude factorization in a production factor $\sum_{\lambda_2}|P^{\lambda_2}|^2$ times a decay factor $\overline{\sum}_{\lambda_2}|D_{\lambda_2}|^2$. The analytical formulae are given in [5].

3. Numerical results and discussion

Neutralinos are linear superpositions of the photino $\tilde{\gamma}$ and the zino $\tilde{Z}$ and the two higgsinos $\tilde{H}_a^0$ and $\tilde{H}_b^0$. The composition of the neutralino states depend on the three SUSY mass parameters M, M' (with the GUT relation

$M' = \frac{5}{3} M \tan^2\theta_W$) and μ, and on the ratio $\tan\beta = v_2/v_1$ of the vacuum expectation values of the Higgs fields [6]. The masses of the sleptons are determined by the common scalar mass parameter m_0, and M and $\tan\beta$ [7]. We shall consider two representative scenarios which differ significantly in the nature of the two lowest mass eigenstates $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$: (A) M=380 GeV, $\mu = -180$ GeV, $\tan\beta = 2$, $m_0 = 80$ GeV; (B) M=185 GeV, $\mu = 550$ GeV, $\tan\beta = 1.6$, $m_0 = 260$ GeV. Using the short–hand notation $\tilde{\chi}^0_i = (\tilde{\gamma}|\tilde{Z}|\tilde{H}^0_a|\tilde{H}^0_b)$, in (A) both neutralinos $\tilde{\chi}^0_1 = (-.37|+.29|-.21|-.86), m_{\tilde{\chi}^0_1} = 170$ GeV and $\tilde{\chi}^0_2 = (-.03|+.17|-.94|-.30), m_{\tilde{\chi}^0_2} = 195$ GeV have strong higgsino components. In (B) $\tilde{\chi}^0_1 = (+.83|-.55|+.09|+.04), m_{\tilde{\chi}^0_1} = 88$ GeV and $\tilde{\chi}^0_2 = (-.56|-.81|+.18|+.06), m_{\tilde{\chi}^0_2} = 170$ GeV have dominating gaugino components, $\tilde{\chi}^0_1$ being almost a pure bino and $\tilde{\chi}^0_2$ nearly a pure wino.

3.1. Unpolarized beams

The total cross section for the combined process is independent of spin correlations [8]. For unpolarized beams it is 4.7 fb in scenario (A) and 4.1 fb in scenario (B).

3.1.1. Lepton angular distributions

In Figs. 1 and 2 we present numerical results for the distribution $d\sigma/d\cos\Theta_-$ with Θ_- being the angle between the outgoing leptons ℓ^- and the electron beam in the laboratory system. We compare our results with those assuming factorization of the differential cross section into production and decay (Figs. 1–2).

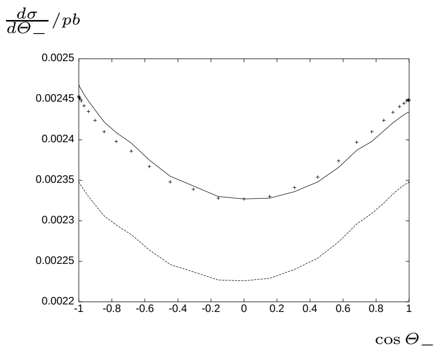

Fig. 1: Lepton angular distribution in (A) for $m_0 = 80$ GeV with spin correlations (upper solid), for assumed factorization (dotted) and for pure Z^0-exchange (lower solid).

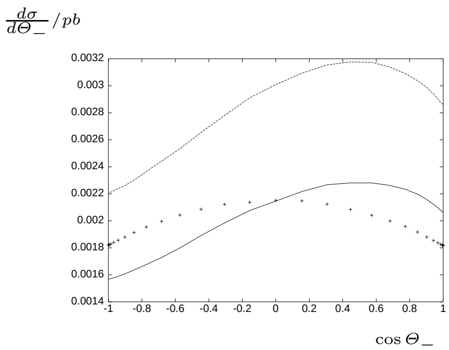

Fig. 2: Lepton angular distribution in (B) for $m_0 = 260$ GeV with spin correlations (lower solid), for assumed factorization (dotted) and for pure slepton-exchange (upper solid).

The spin effect is largest in the forward and backward direction. For gaugino-like neutralinos it amounts to about 15%, for higgsino–like neutralinos it is smaller. The resulting forward-backward asymmetry A_{FB} depends sensitively on the mixing character of the neutralinos. For higgsino-like neutralinos (scen. (A)) the angular distribution is nearly forward–backward symmetric with a minimum at $\Theta_- = 90^o$ For gaugino-like neutralinos (scen. (B)), however, the forward hemisphere is favoured (Table I).

3.1.2. The lepton opening angle distributions

Owing to the Majorana character of the neutralinos the distribution $d\sigma/d\cos\Theta_{+-}$ of the opening angle between both outgoing leptons factorizes.

The distributions are completely different for scenario (A) (Fig. 6) and (B) (Fig. 7). For gaugino-like neutralinos it is rather flat with a maximum near $\Theta_{+-} = 40^0$, whereas for higgsino–like neutralinos it is much steeper with a peak at $\Theta_{+-} = 0^0$ (notice the different scales in Figs. 6 and 7). For gaugino-like neutralinos the position of the maximum depends strongly on the kinetic energy of the decaying neutralino. With increasing kinetic energy it moves from $\pi/2$ to 0^0. For higgsino-like neutralinos the maximum is always at 0^0, but the distribution becomes much steeper with increasing energy. In both scenarios most of the leptons are emitted with an opening angle between 0 and $\pi/2$ (approximately 76% for scen. (A) and 69% for scen. (B)). The opening angle distribution depends only slightly on the value of m_0. Therefore, this distribution is more suitable for the discrimination between gaugino- and higgsino-like neutralinos than the lepton angular distribution which has a stronger m_0 dependence (compare with [9]).

3.2. Polarized beams

We have computed the angular and energy distributions for longitudinal polarization $P_- = \pm 0.9$ of the electron beam and $P_+ = \pm 0.4$ of the positron beam ($P_\pm > 0$ ($P_\pm < 0$) for right-handed (left-handed) polarized beams).

In the following the different polarization states are denoted by the sign of P_- and P_+, (0 0) denotes the case of unpolarized beams.

In Table I the total cross sections for the different beam polarizations are given in increasing order of magnitude. For higgsino-like neutralinos the cross section is highest for right-handed electrons and left-handed positrons. For the gaugino case it is highest for left-handed electrons and right-handed positrons due to the wino-like character of $\tilde{\chi}^0_2$. For gaugino-like neutralinos the dependence on the beam polarization is also more pronounced than for the higgsino case.

TABLE I

Total cross sections and Asymmetries for different combinations (signP_-,signP_+) of electron polarization $P_- = \pm.9$ and positron polarization $P_+ = \pm.4$.

A	$(--)$	$(++)$	(-0)	(00)	$(+0)$	$(-+)$	$(+-)$
σ /fb	2.9	3.2	4.5	4.7	5.0	6.1	6.8
A_{FB} / %	.48	-.75	.58	-.16	-.83	.63	-.87
B	$(++)$	$(+0)$	$(+-)$	(00)	$(--)$	(-0)	$(-+)$
σ /fb	.87	.94	1.0	4.1	4.4	7.2	10.1
A_{FB} / %	2.6	-1.8	-5.6	9.2	11	11	11

3.2.1. Lepton angular distribution for polarized beams

For higgsino-like neutralinos the distribution is nearly independent of the beam polarization and almost the same as for unpolarized beams (Fig. 3). Similarly, for the gaugino-like scenario (B) and left-handed electrons only the magnitude of the distribution changes for different positron polarization (Fig. 4). The consequence of non-factorization of the angular distribution in production and decay is most pronounced for gaugino-like neutralinos and right-handed electrons (Fig. 5).

For unpolarized beams the differential cross section $d\sigma/\cos\Theta_-$ is larger in the forward hemisphere. For e^-e^+-polarization $(+0)$ the distribution is nearly symmetric. For beam polarization $(+-)$ the backward hemisphere is favoured.

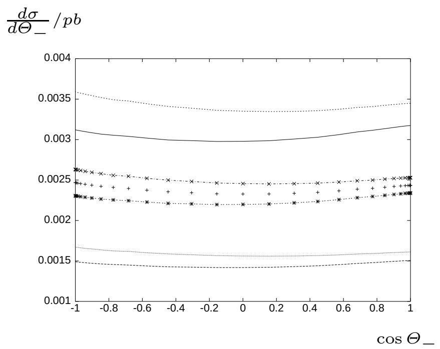

Fig. 3: Lepton angular distribution in (A) with beam polarization. Order of lines according to the order of total cross sections in Table I.

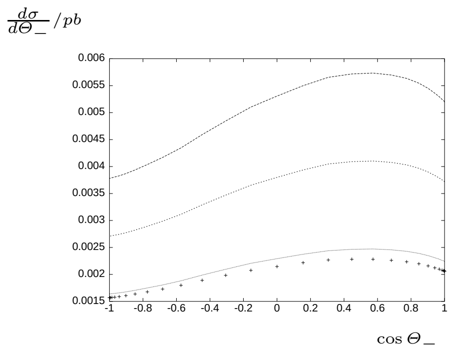

Fig. 4: Lepton angular distribution in (B) for left-handed polarized electrons, $(-+)$,(-0),$(--)$ (solid) and for unpolarized beams (dotted). Order of lines according to the order of total cross sections in Table I.

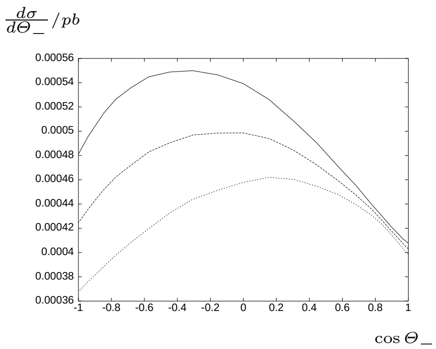

Fig. 5: Lepton angular distribution in (B) for right-handed polarized electrons, $(+-)$,$(+0)$,$(++)$ (solid). Order of lines according to the order of total cross sections in Table 1.

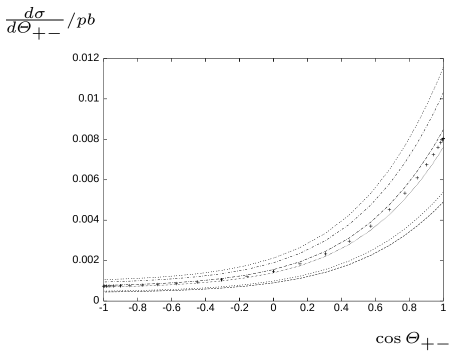

Fig. 6: Opening angle distribution in (A) with beam polarization. Order of lines according to the order of total cross sections in Table 1 (solid) and for unpolarized case (dotted).

3.2.2. The lepton opening angle distribution for polarized beams

Also in the case of polarized beams the opening angle distribution factorizes into the contributions from production and decay due to the Majorana nature of the neutralino. In both scenarios the only effect of beam polarization is to increase or to reduce the cross sections without changing the shape. The dependence on beam polarization is the same as that for the total cross section, Table 1. It is different for gaugino- and higgsino-like neutralinos. Figs. (6$-$7) shows the opening angle distribution for different beam polarization for higgsino-like neutralinos, scen. (A) and for gaugino-like neutralinos, scen. (B).

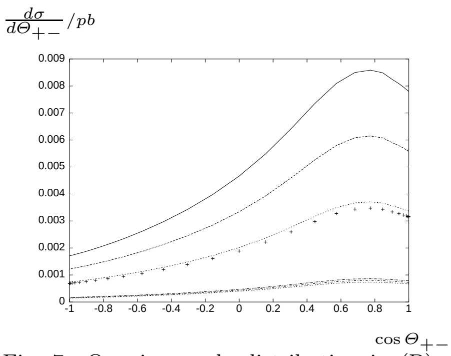

Fig. 7: Opening angle distribution in (B) with beam polarization. Order of lines according to the order of total cross sections in Table 1 (solid) and for unpolarized beams (dotted).

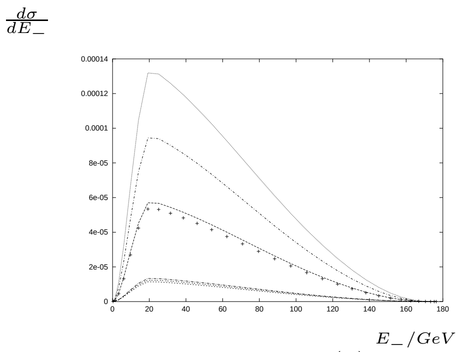

Fig. 8: Energy distribution in (B) with beam polarization. Order of lines according to the order of total cross sections in Table 1 (solid) and for unpolarized beams (dotted).

3.2.3. Energy distributions for polarized beams

The energy distributions of the outgoing leptons in the laboratory frame again factorize due to the Majorana character of the decaying $\tilde{\chi}_2^0$. Since in both scenarios the shape is very similar, we only show the energy spectra of ℓ^- for scen. (B) and different combinations of beam polarization (Fig. 8). As a consequence of factorization the shape is independent of beam polarization. Because of CP invariance and the Majorana character the energy spectra of ℓ^- and ℓ^+ are identical [10].

4. Summary and conclusions

We have studied the production of neutralinos, $e^+ + e^- \to \tilde{\chi}_1^0 + \tilde{\chi}_2^0$ with polarized beams and the subsequent leptonic decay, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \ell^+ + \ell^-$. We have fully taken into account the spin correlations between production and decay. The lepton angular and energy distributions, and the distribution of the opening angle between the outgoing leptons at $\sqrt{s} = 500$ GeV have been computed for two representative scenarios.

The quantum mechanical interference effects modify appreciably the decay lepton angular distributions. Especially for gaugino-like neutralinos we find contributions up to 15% from spin correlations between production and decay. The shape of the angular distributions depends on the beam polarization. The effect of spin correlations is strong for right-handed electrons and gaugino–like neutralinos. It is smaller for left-handed electrons in both scenarios considered. The mixing character of the neutralinos influences the beam polarization dependence of the total cross section. Therefore, the polarization of both beams is very useful for constraining the parameters of the MSSM.

Owing to the Majorana character of the neutralinos the quantum mechanical interference effects between various polarization states of the decaying neutralino $\tilde{\chi}_2^0$ cancel in the energy spectrum and in the distribution of the $\ell^-\ell^+$-opening angle. Consequently, these distributions factorize into production and decay similarly to the case of spinless particles. Accordingly, the shape of these distributions is independent of the beam polarization.

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