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CP asymmetries in $e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$

A. Bartl[a*] H. Fraas[b†], O. Kittel[a,b‡], W. Majerotto[c§]

[a] *Institut für Theoretische Physik, Universität Wien, Boltzmanngasse 5, A-1090 Wien, Austria*

[b] *Institut für Theoretische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*

[c] *Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften, Nikolsdorfergasse 18, A-1050 Wien, Austria*

Abstract

We study two CP sensitive triple-product asymmetries for neutralino production $e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ and the subsequent leptonic two-body decays $\tilde{\chi}_i^0 \to \tilde{\ell}\,\ell$ of one of the neutralinos and of the slepton $\tilde{\ell} \to \tilde{\chi}_1^0\,\ell$ at an e^+e^--linear collider with $\sqrt{s} =$ 500 GeV. We calculate the asymmetries in the Minimal Supersymmetric Standard Model with complex parameters μ and M_1. We show that the largest asymmetries are 10% or 25% and estimate the event rates which are necessary to measure the asymmetries. Polarized electron and positron beams can significantly enhance the asymmetries and cross sections. In addition, we show how the two decay leptons can be distinguished by making use of their energy distributions.

*e-mail: bartl@ap.univie.ac.at
†e-mail: fraas@physik.uni-wuerzburg.de
‡e-mail: kittel@physik.uni-wuerzburg.de
§e-mail: majer@qhepu3.oeaw.ac.at

1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) [1] contains new sources of CP violation if the parameters of the model are complex. In the neutralino sector of the MSSM these are the $U(1)$ and $SU(2)$ gaugino mass parameters M_1 and M_2, respectively, and the higgsino mass parameter μ. One of these parameters, usually M_2, can be made real by redefining the fields. The non-vanishing phases of M_1 and μ cause CP-violating effects already at tree level, which could be large and thus observable in high energy collider experiments [2].

In this note we study neutralino production (for recent studies with complex parameters and polarized beams see [3, 4, 5])

$$e^- + e^+ \ \rightarrow \ \tilde{\chi}^0_i + \tilde{\chi}^0_j \tag{1}$$

and the subsequent leptonic two-body decay of one neutralino

$$\tilde{\chi}^0_i \ \rightarrow \ \tilde{\ell} + \ell_1, \tag{2}$$

and of the decay slepton

$$\tilde{\ell} \ \rightarrow \ \tilde{\chi}^0_1 + \ell_2; \quad \ell = e, \mu. \tag{3}$$

The decay of the other neutralino $\tilde{\chi}^0_j$ is not considered. For a schematic picture of the production and decay process see Fig. 1.

T-odd observables [3, 6, 7, 8, 9] are a useful tool to study the CP-violating effects of the parameters M_1 and μ. They involve triple-products of particle momenta or spin vectors. For neutralino production (1) and the two-body decay chain of the neutralino (2)-(3) we introduce the triple-product

$$\mathcal{T}_I \ = \ (\vec{p}_{e^-} \times \vec{p}_{\chi_i}) \cdot \vec{p}_{\ell_1}, \tag{4}$$

which changes sign under time reversal. We define the T-odd asymmetry

$$\mathcal{A}_I = \frac{\sigma(\mathcal{T}_I > 0) - \sigma(\mathcal{T}_I < 0)}{\sigma(\mathcal{T}_I > 0) + \sigma(\mathcal{T}_I < 0)} = \frac{N_+ - N_-}{N_+ + N_-}, \tag{5}$$

where σ is the cross section $\sigma(e^-e^+ \to \tilde{\chi}^0_i\tilde{\chi}^0_j) \times \mathrm{BR}(\tilde{\chi}^0_i \to \tilde{\ell}\ell_1) \times \mathrm{BR}(\tilde{\ell} \to \tilde{\chi}^0_1\ell_2)$ defined below. The asymmetry $\mathcal{A}_I$ is thus the difference between the number of events with the lepton ℓ_1 above (N_+) and below (N_-) the production plane.

One can show that $\mathcal{A}_I$ is due to the polarization of the neutralino perpendicular to the production plane, which is non-vanishing only if there are CP-violating phases in the neutralino sector and if different neutralinos are produced [3, 4, 5]. In order to measure the asymmetry $\mathcal{A}_I$, the momentum $\vec{p}_{\chi_i}$ of neutralino $\tilde{\chi}^0_i$ and thus the production plane has to be reconstructed.

Considering also the leptonic two-body decay of the slepton (3), we can construct another T-odd observable replacing the neutralino momentum $\vec{p}_{\chi_i}$ in Eq. (4) by the lepton momentum $\vec{p}_{\ell_2}$ from the slepton decay. We define the second triple-product and the corresponding T-odd asymmetry as

$$\mathcal{T}_{II} = (\vec{p}_{e^-} \times \vec{p}_{\ell_2}) \cdot \vec{p}_{\ell_1}, \qquad \mathcal{A}_{II} = \frac{\sigma(\mathcal{T}_{II} > 0) - \sigma(\mathcal{T}_{II} < 0)}{\sigma(\mathcal{T}_{II} > 0) + \sigma(\mathcal{T}_{II} < 0)}. \tag{6}$$

Measuring $\mathcal{A}_{II}$ does not require the reconstruction of the neutralino momentum. Like in $\mathcal{A}_I$, the contributions to $\mathcal{A}_{II}$ also stem from the CP-violating neutralino polarization. However, $\mathcal{A}_{II}$ is smaller than $\mathcal{A}_I$ because the CP-violating contribution from the production is washed out by the kinematics of the slepton decay (3). Due to CPT invariance, the T-odd asymmetries (5) and (6) are CP-odd if the widths of the exchanged particles and final state interactions are neglected, which is done in this work.

The cross section in the laboratory system is obtained by integrating the amplitude squared $|T|^2$ over the Lorentz invariant phase space element $d\mathrm{Lips}(s, p_{\chi_j}, p_{\ell_1}, p_{\chi_1}, p_{\ell_2})$:

$$d\sigma = \frac{1}{2s}|T|^2 d\mathrm{Lips}; \qquad |T|^2 = 4\ |\Delta(\tilde{\chi}^0_i)|^2\ |\Delta(\tilde{\ell})|^2 (PD_1 + \vec{\Sigma}_P \vec{\Sigma}_{D_1})\ D_2. \tag{7}$$

To the total cross section, only the terms PD_1 contribute and the spin correlation terms $\vec{\Sigma}_P \vec{\Sigma}_{D1}$ vanish. However, the spin correlation terms contribute to the asymmetries $\mathcal{A}_I$ and $\mathcal{A}_{II}$. The analytical formulae for P and Σ^a_P are given in [5]. The expressions for D_1, D_2 and $\Sigma^a_{D_1}$ will be given in [10], where also more details of the calculation and additional numerical results can be found. We use the narrow width approximation for the propagators $\Delta(k) = 1/[s_k - m_k^2 + i m_k \Gamma_k]$, $k = \tilde{\chi}^0_i, \tilde{\ell}$.

In order to measure the asymmetries $\mathcal{A}_I$ and $\mathcal{A}_{II}$, the two leptons ℓ_1 and ℓ_2 from the neutralino (2) and selectron decay (3), respectively, have to be distinguished. This can be achieved by measuring the energies of the two leptons and making use of their different energy distributions. Owing to the Majorana property of the neutralinos, the contributions of the spin correlations to the energy distributions vanish if CP is conserved [11]. In the case of CP violation, they vanish only to leading order perturbation theory [11]. In our case, the contributions are proportional to the widths of the exchanged particles in the production process (1) and thus can be neglected.

2 Numerical results

We now present numerical results for $e^-e^+ \to \tilde{\chi}^0_1 \tilde{\chi}^0_2$ with the subsequent decay of $\tilde{\chi}^0_2$ into the right selectron and right smuon, $\chi^0_2 \to \tilde{\ell}_R \ell_1$. We study the dependence of the asymmetries and the production cross section on the parameters $\mu = |\mu|\, e^{i\,\varphi_\mu}$, $M_1 = |M_1|\, e^{i\,\varphi_{M_1}}$ and M_2 for $\sqrt{s} = 500$ and longitudinally polarized beams with $P_- = 0.8$ and $P_+ = -0.6$. We fix $\tan\beta = 10$ and assume $|M_1| = 5/3 \tan^2\theta_W M_2$. We use the renormalization group equations [13] for the selectron and smuon masses, $m^2_{\tilde{\ell}_R} = m_0^2 + 0.23 M_2^2 - m_Z^2 \cos 2\beta \sin^2\theta_W$, taking $m_0 = 100$ GeV.

Fig. 2a shows the $|\mu|$–M_2 dependence of the asymmetry $\mathcal{A}_{II}$ for $\varphi_{M_1} = 0.5\ \pi$ and $\varphi_\mu = 0$. The gray shaded area is excluded for chargino masses $m_{\tilde{\chi}^\pm_1} < 104$ GeV. In the

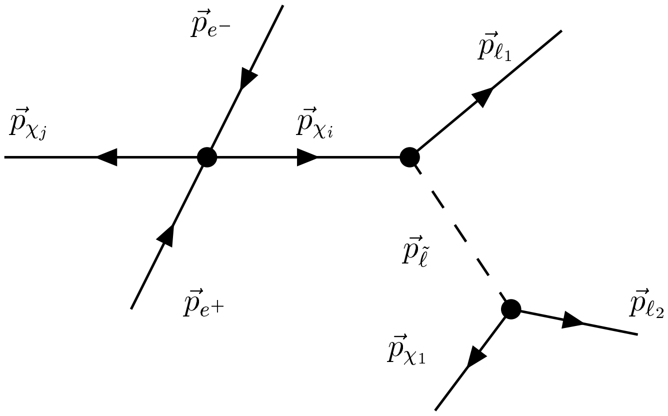


Figure 1: Schematic picture of the neutralino production and decay process.

blank areas either the sum of the neutralino masses is larger than $\sqrt{s} = 500$ GeV or the two body decay (2) of the neutralino into the right selectron and smuon is not open.

In the region $|\mu| \lesssim 250$ GeV, where the right selectron exchange dominates in the neutralino production process, the asymmetry reaches large values up to 9.5% for our choice of beam polarization. This enhances the asymmetry up to a factor of 2 compared to the case of unpolarized beams. With increasing $|\mu|$ the asymmetry decreases and finally changes sign. This is due to the increasing contributions of the left selectron exchange which contributes to the asymmetry with opposite sign and dominates for $|\mu| \gtrsim 300$ GeV because of the larger $\tilde{\chi}^0_2 - \tilde{e}_L$ coupling. In this region the asymmetry can be enhanced up to a factor 2 by reversing the signs of both beam polarizations.

The contour lines of the cross section $\sigma(e^-e^+ \to \tilde{\chi}^0_1\tilde{\chi}^0_2) \times \mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\ell}_R\ell_1) \times \mathrm{BR}(\tilde{\ell}_R \to \tilde{\chi}^0_1\ell_2)$ with $\mathrm{BR}(\tilde{\ell}_R \to \tilde{\chi}^0_1\ell_2) = 1$ is shown in Fig. 2b in the $|\mu|$–M_2 plane for $\varphi_\mu = 0$ and $\varphi_{M_1} = 0.5\,\pi$. For $|\mu| \lesssim 250$ GeV the right selectron exchange dominates in the production process $e^-e^+ \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ and is enhanced by our choice of beam polarization $P_- = 0.8$ and $P_+ = -0.6$. No beam polarization would reduce the values of the cross section in that region by a factor as small as 0.4. For $|\mu| \gtrsim 300$ GeV, a sign reversal of both polarizations would enhance the cross section by a factor between 1 and 20.

The branching ratio $\mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\ell}_R\ell)$ (summed over both signs of charge) is more than 40% in those regions where the cross section is larger than 20 fb. The branching ratio decreases with increasing $|\mu| \gtrsim 300$ GeV if the two-body decays into the lightest neutral Higgs boson h^0 and/or the Z boson are kinematically allowed. The decay into left selectrons and smuons can be neglected because these channels are either not open or the branching fraction is smaller than 1%. For $M_2 \lesssim 200$ GeV the decay into the lightest stau $\tilde{\tau}_1$ is larger than 80% if, for example, $A_\tau = -250$ GeV.

The sensitivity of the asymmetry $\mathcal{A}_I$ on the CP phases can be seen from the contour plot in the φ_μ–φ_{M_1} plane, Fig. 3, for $|\mu| = 240$ GeV and $M_2 = 400$. The asymmetry $\mathcal{A}_I$ varies between -27% and 27%. For unpolarized beams this asymmetry would be reduced roughly by a factor 0.33. It is remarkable that these maximal values are not necessarily

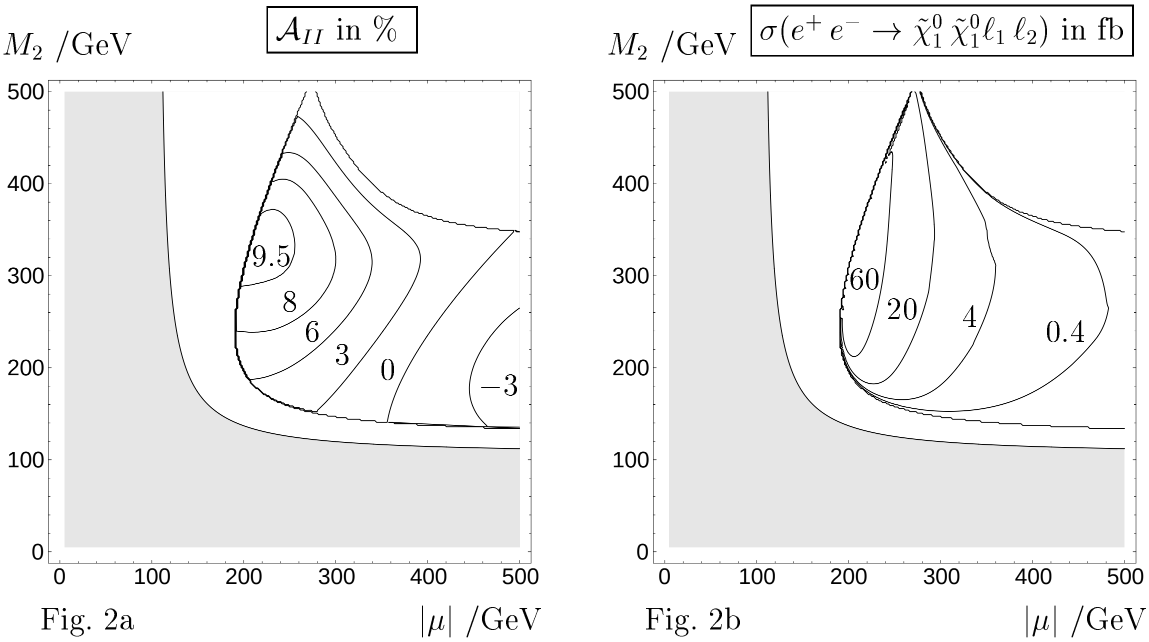


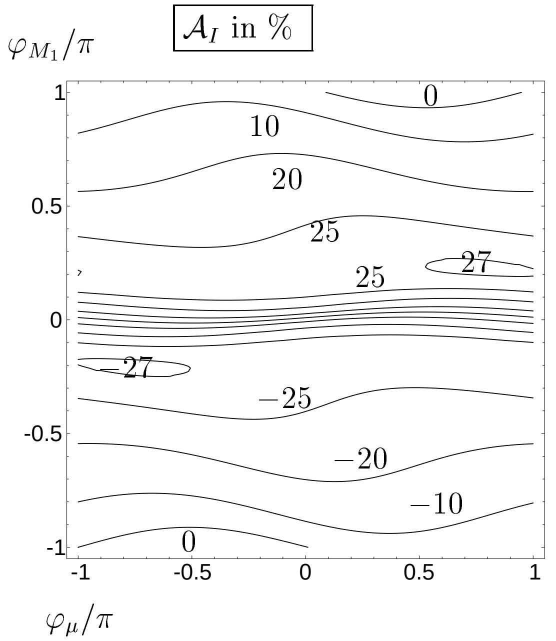
Figure 2: Contour plots for $e^+ e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$; $\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell_1$; $\tilde{\ell}_R \to \tilde{\chi}_1^0 \ell_2$ for $\ell = e, \mu$ in the $|\mu|$–M_2 plane with $\varphi_{M_1} = 0.5\pi$, $\varphi_\mu = 0$, $\tan\beta = 10$, $P_- = 0.8$ and $P_+ = -0.6$.

obtained for maximal CP phases. In our scenario the asymmetry is much more sensitive to variations of the phase φ_{M_1} around 0. On the other hand, the asymmetry is rather insensitive to φ_μ.

The asymmetry $\mathcal{A}_{II}$, which does not require the momentum identification of the $\tilde{\chi}_2^0$, has a similar dependence on the phases as $\mathcal{A}_I$, because both are due to the non-vanishing neutralino polarization. However, $\mathcal{A}_{II}$ is reduced almost by a factor 3, because there the CP-violating effect from the production is washed out by the kinematics of the slepton decay.

The relative statistical error of each asymmetry $\mathcal{A}$ can be calculated to $\delta\mathcal{A} = \Delta\mathcal{A}/\mathcal{A} = S/(\mathcal{A}\sqrt{N})$, with S standard deviations, assuming a Gaussian distribution of the asymmetry $\mathcal{A}$. Here, $N = \mathcal{L}\sigma$ is the number of events with $\mathcal{L}$ the total integrated luminosity and σ the total cross section. Assuming $\delta\mathcal{A} \approx 1$, it follows $S \approx \mathcal{A}\sqrt{N}$. For example, in order to measure an asymmetry of 5% with S=2 (confidence level of 95%), one would need at least 1.5×10^3 events. This corresponds to a total cross section for reactions (1)-(3) of 3.1 fb with $\mathcal{L} = 500$ fb^{-1}.

The two leptons ℓ_1 and ℓ_2 from the decays (2) and (3) have to be distinguished in order to measure the asymmetries $\mathcal{A}_I$ (4) and $\mathcal{A}_{II}$ (6). We show in Fig. 4 an example of the energy distributions of lepton ℓ_1 (dashed line) and lepton ℓ_2 (solid line) with $\tan\beta = 10$, $|\mu| = 240$ GeV, $M_2 = 400$ GeV for $\varphi_\mu = 0$ and $\varphi_{M_1} = 0.5\pi$. The selectron mass is $m_{\tilde{\ell}_R} = 220$ GeV, the LSP mass is $m_{\tilde{\chi}_1^0} = 180$ GeV and the second neutralino mass is



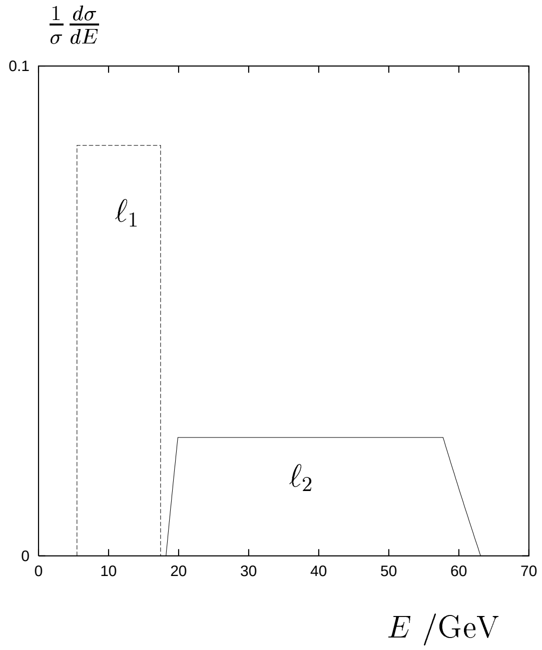


Figure 3: Contour plot for $\mathcal{A}_I$ in the φ_{M_1}–φ_μ plane for $M_2 = 400$ GeV, $|\mu| = 240$ GeV, $\tan\beta = 10$, $m_{\tilde{\ell}_R} = 221$ GeV.

Figure 4: Energy distributions for ℓ_1 (dashed line) and ℓ_2 (solid line) for $M_2 = 400$ GeV, $|\mu| = 240$ GeV, $\tan\beta = 10$, $m_{\tilde{\ell}_R} = 220$ GeV.

$m_{\tilde{\chi}^0_2} = 230$ GeV. Due to the larger mass difference of 40 GeV between $\tilde{\ell}_R$ and $\tilde{\chi}^0_1$ compared to the $\tilde{\chi}^0_2$–$\tilde{\ell}_R$ mass difference of 10 GeV, ℓ_2 is more energetic than ℓ_1 as the endpoints of the energy distributions depend on these mass differences. The two distributions shown in Fig. 4 do not overlap and one can distinguish between the two leptons event by event.

However, depending on the values of the masses involved, there are different types of energy distributions possible. The energy distributions also may overlap if the mass differences between $\chi^0_1, \tilde{\ell}_R$ and $\tilde{\chi}^0_2$ are similar. In this case only those leptons can be distinguished, whose energies are not both in the overlapping region. One has to apply cuts which reduce the number of events.

3 Summary and conclusion

We have considered two CP sensitive triple-product asymmetries in neutralino production $e^+e^- \to \tilde{\chi}^0_i \tilde{\chi}^0_j$ and the subsequent leptonic two-body decay chain of one neutralino $\tilde{\chi}^0_i \to \tilde{\ell}\,\ell$, $\tilde{\ell} \to \tilde{\chi}^0_1\,\ell$ for $\ell = e, \mu$. The CP sensitive contributions to the asymmetries are due to tree level spin effects in the production process of an unequal pair of neutralinos. The asymmetries are induced only if CP-violating phases of the gaugino and higgsino mass parameters M_1 and/or μ are present in the neutralino sector of the MSSM.

In a numerical study for $e^+ e^- \to \tilde{\chi}^0_1 \tilde{\chi}^0_2$ and for the neutralino decay into a right slepton, we have shown that the asymmetry $\mathcal{A}_{II}$ can go up to 10% and the asymmetry $\mathcal{A}_I$ can be as large as 25%. Depending on the MSSM scenario, the asymmetries should be accessible in future electron-positron linear collider experiments in the 500 GeV range. Longitudinally polarized electron and positron beams can enhance both asymmetries considerably.

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