Measurement of CP Violation in the MSSM Neutralino Sector with the ILD

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Supersymmetric models provide many new complex phases which lead to CP violating effects in collider experiments. As an example, CP-sensitive triple product asymmetries in neutralino production $e^+ e^- \to \tilde{\chi}_i^0 \tilde{\chi}_1^0$ and subsequent leptonic two-body decays $\tilde{\chi}_i^0 \to \tilde{\ell}_R \ell$, $\tilde{\ell}_R \to \tilde{\chi}_1^0 \ell$, for $\ell = e, \mu$, are studied within the Minimal Supersymmetric Standard Model. A full ILD detector simulation has been performed at a center of mass energy of $\sqrt{s} = 500$ GeV, including the relevant Standard Model background processes, a realistic beam energy spectrum, beam backgrounds and a beam polarization of 80% and -60% for the electron and positron beams, respectively. Assuming an integrated luminosity of 500 fb^{-1} collected by the experiment and the performance of the current ILD detector, a relative measurement accuracy of 10% for the CP-sensitive asymmetry can be achieved in the chosen scenario.

1 Introduction

Supersymmetry (SUSY) [1] is among the most favoured and most studied extensions of the Standard Model (SM) and is capable of solving many of its problems. One of its features is that the Minimal Supersymmetric Standard Model (MSSM) provides a number of complex parameters which can serve as sources of CP violation. They are conventionally chosen to be the Higgsino mass parameter, $\mu = |\mu| e^{i\phi_\mu}$, the U(1) and SU(3) gaugino mass parameters, $M_1 = |M_1| e^{i\phi_1}$ and $M_3 = |M_3| e^{i\phi_3}$, respectively, and the trilinear scalar coupling parameters, $A_f = |A_f| e^{i\phi_{A_f}}$, of the third generation sfermions ($f = b, t, \tau$). CP phases can give rise to CP-violating signals in collider experiments [2], which have to be measured to determine or constrain the phases independently of measurements of electric dipole moments (EDM). Although also CP-even observables, such as masses or branching ratios, are sensitive to the CP phases, CP-odd observables are needed for direct evidence of CP violation.

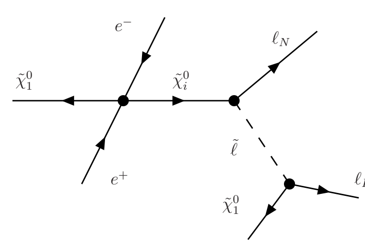

Figure 1: Schematic picture of neutralino production and decay.

In this report neutralino pair production $e^+ e^- \to \tilde{\chi}_i^0 \tilde{\chi}_1^0$, for $i = 2, 3$, and the subsequent leptonic two-body decay of one of the neutralinos $\tilde{\chi}_i^0 \to \tilde{\ell}_R \ell$ followed by $\tilde{\ell}_R \to \tilde{\chi}_1^0 \ell$, for $\ell = e, \mu$, at the ILC is studied [3]. Figure 1 shows a schematic picture of the process. The CP-sensitive spin correlations of the neutralino in its production process allow to probe the phase of the Higgsino mass parameter μ and the gaugino parameter M_1 [4].

A full ILD [5] detector simulation is performed in order to investigate in detail the prospects to measure CP-sensitive observables at the ILC. All relevant SM background is taken into account, simulated with a realistic beam energy spectrum and beam backgrounds [6].

2 CP-odd observables and benchmark scenario

In neutralino production, effects from CP-violating phases can only occur if two different neutralinos are produced. CP asymmetries can then be defined with triple products of particle momenta. Due to the spin correlation the asymmetries show hints for CP phases already at tree level. For the process shown in Fig. 1, a T-odd triple product of the beam and the final lepton momenta can be defined as [3]

$$\mathcal{T} \quad = \quad (\mathbf{p}_{e^-} \times \mathbf{p}_{\ell^+}) \cdot \mathbf{p}_{\ell^-}. \tag{1}$$

The corresponding asymmetry is

$$\mathcal{A}(\mathcal{T}) \quad = \quad \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}, \tag{2}$$

where σ is the cross section for neutralino production and decay. Its sign depends on the charge of the leptons, which has to be tagged in the experimental analysis.

For the full simulation study a benchmark scenario has been chosen such that the gaugino phase $\phi_1 = 0.2\pi$ corresponds to a maximal CP asymmetry and the Higgsino phase is zero, since it is strongly constrained by EDM bounds. The other parameters in the neutralino sector are $M_2 = 300\,\text{GeV}$, $|M_1| = 150\,\text{GeV}$, $|\mu| = 165\,\text{GeV}$ and $\tan\beta = 10$. This leads to the neutralino masses $m_{\tilde{\chi}^0_1} = 117$ GeV, $m_{\tilde{\chi}^0_2} = 169$ GeV, $m_{\tilde{\chi}^0_3} = 181$ GeV and $m_{\tilde{\chi}^0_4} = 330$ GeV, while the slepton masses are $m_{\tilde{\ell}_R} = 166$ GeV and $m_{\tilde{\ell}_L} = 280$ GeV. The neutralino pair production cross sections are calculated to be $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2) = 244$ fb and $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_3) = 243$ fb, while the slepton pair production cross sections are $\sigma(e^+e^- \to \tilde{e}^+_R\tilde{e}^-_R) = 304$ fb and $\sigma(e^+e^- \to \tilde{\mu}^+_R\tilde{\mu}^-_R) = 97$ fb. The slepton pair production is the main background, since there are two lightest neutralinos and two opposite-sign electrons or muons in the final state as in the case of the neutralino $\tilde{\chi}^0_1\tilde{\chi}^0_i$ production. Furthermore, beam polarizations of $(P_{e^-}, P_{e^+}) = (0.8, -0.6)$ have been chosen, which enhance slightly the SUSY cross section and the asymmetries, while the background from WW- and chargino-pair production is suppressed. In this scenario the CP asymmetries are $\mathcal{A}(\mathcal{T})_{\tilde{\chi}^0_1\tilde{\chi}^0_2} = -9.2\%$ and $\mathcal{A}(\mathcal{T})_{\tilde{\chi}^0_1\tilde{\chi}^0_3} = 7.7\%$.

3 Detector simulation study and parameter fit

The ILD is a concept under study for a multipurpose particle detector for the ILC. It is designed for an excellent precision in momentum and energy measurement over a large solid angle. A detailed description can be found in [5]. In the simulation all active elements and also cables, cooling systems, support structures and dead regions are taken into account [6]. The radiation hard beam calorimeter is used to suppress background from $\gamma\gamma$ events at low angles. All relevant SM backgrounds and SUSY processes are generated using `Whizard` [7].

initial selection	no significant activity in BCAL	
	number of all tracks $N_{\text{tracks}} \leq 7$	
lepton selection	$\ell^+\ell^-$ pair with $\ell = e, \mu$	
	$|\cos\theta| < 0.99$, min. energy $E > 3$ GeV	
	lower energetic ℓ with $E < 18$ GeV, or	
	higher energetic ℓ with $E > 38$ GeV	
	higher energetic ℓ with $E \in [15, 150]$ GeV	
	$\theta_{\text{acop}} > 0.2\pi$, $\theta_{\text{acol}} > 0.2\pi$	
final preselection	$\mathbf{p}_{\text{T}}^{\text{miss}} > 20$ GeV	
	$E_{\text{vis}} < 150$ GeV	
	$m_{\ell\ell} < 55$ GeV	

Table 1: Preselection cuts, see Ref. [3] for details.

3.1 Event selection and measured asymmetry

A clean sample of signal events is needed in order to clearly measure the CP-violating effects in neutralino production. Otherwise the asymmetry will be reduced by the CP-even background events. Therefore, preselection cuts as listed in Tab. 1 are applied to reject as much background as possible, while preserving good signal efficiency. Electrons and muons are identified using the *Particle Flow* approach [3]. The cuts exploit the energy and angular distributions of the final state leptons, as well as the high missing transverse momentum $\mathbf{p}_{\text{T}}^{\text{miss}}$ due to the escaping neutralinos. Additional cuts on the total visible energy E_{vis} as well as on the invariant mass $m_{\ell\ell}$ distributions further reduce the background contamination.

Figure 2(a) shows the $\mathbf{p}_{\text{T}}^{\text{miss}}$ distribution of the SM and SUSY background as well as of the signal after the lepton selection. It can be seen that most of the background is removed with the cut $\mathbf{p}_{\text{T}}^{\text{miss}} > 20$ GeV. Figure 2(b) shows the distribution of the invariant di-lepton mass after all cuts except the one on $m_{\ell\ell}$. The signal lepton pair from $\tilde{\chi}_3^0$ ($\tilde{\chi}_2^0$) decays has a sharp endpoint at 51 GeV (22 GeV), which can also be exploited for mass measurements. The invariant mass cut also removes SM backgrounds from ZZ and WW production. The remaining event sample consists of 28039 $\tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ ($\ell \neq \tau$) events, 45966 $\tilde{\chi}_1^0\tilde{\chi}_3^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ ($\ell \neq \tau$) events and 34223 $\tilde{\ell}\tilde{\ell} \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ ($\ell \neq \tau$) events. All other SM and SUSY background processes sum up to about 6000 events.

In order to distinguish the $\tilde{\chi}_1^0\tilde{\chi}_2^0$ events from the $\tilde{\chi}_1^0\tilde{\chi}_3^0$ events, and to further clean the event sample, a kinematic selection procedure is applied, as described in [3]. A number of kinematic constraints derived from the final state momenta are used to classify events as signal or background. An event is selected only if it is classified exclusively as signal-like. Four event classes are considered: $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_1^0\tilde{\chi}_3^0$, $\tilde{\ell}_R^+\tilde{\ell}_R^-$ and W^+W^-. Table 2 shows the number of events that are classified exclusively as one of the four event classes. It can be observed that the large contamination of the event sample by $\tilde{\ell}_R^+\tilde{\ell}_R^-$ events can be drastically reduced.

The CP asymmetry can now be calculated from Eq. (2) to be $\mathcal{A}(\mathcal{T})_{\tilde{\chi}_1^0\tilde{\chi}_2^0} = -11.3\% \pm 0.7\%$ and $\mathcal{A}(\mathcal{T})_{\tilde{\chi}_1^0\tilde{\chi}_3^0} = +10.9\% \pm 0.7\%$. The absolute values are slightly higher than the ones

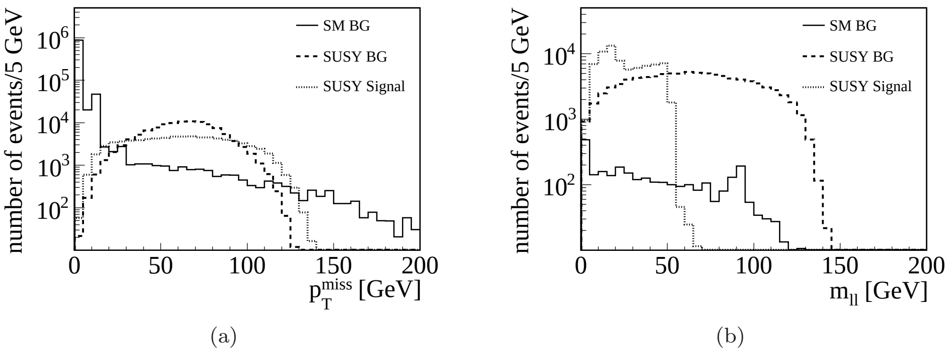

Figure 2: (a) Missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ distribution of SM background, SUSY background and SUSY signal after the lepton selection. (b) Invariant mass $m_{\ell\ell}$ distribution of the lepton pair after all preselection cuts except the cut on $m_{\ell\ell}$. The events are simulated for $\mathcal{L} = 500$ fb^{-1}, beam polarization $(P_{e^-}, P_{e^+}) = (0.8, -0.6)$ at $\sqrt{s} = 500$ GeV, and MSSM parameters as in the benchmark scenario discussed in Sec. 2.

class	only $\tilde\chi_1^0\tilde\chi_2^0$	only $\tilde\chi_1^0\tilde\chi_3^0$	only $\tilde\ell_R^+\tilde\ell_R^-$	only W^+W^-
$\tilde\chi_1^0\tilde\chi_2^0 \to \tilde\chi_1^0\tilde\chi_1^0\ell\ell$ $(\ell \neq \tau)$	18343	615	51	855
$\tilde\chi_1^0\tilde\chi_3^0 \to \tilde\chi_1^0\tilde\chi_1^0\ell\ell$ $(\ell \neq \tau)$	290	20132	372	635
all SUSY background	1153	3055	5626	951
all SM background	87	256	44	81

Table 2: Number of preselected events, that fulfill the requirements of the kinematic selection procedure, for $\mathcal{L} = 500$ fb^{-1}.

calculated in the benchmark scenario, since the asymmetry depends non-trivially on the cut values. This has been studied in [3] and can be taken into account in a parameter fit.

3.2 Fit of the parameters in the neutralino sector

In the final step of the analysis, the accuracy to determine the parameters in the neutralino sector of the MSSM is estimated. These are the six free parameters of the neutralino mass matrix $|M_1|$, M_2, $|\mu|$, $\tan\beta$, ϕ_1 and ϕ_μ. As input for the fit a number of CP-even observables is used together with the measured asymmetries (see Ref. [3] for details): $m_{\tilde\chi_1^0} = 117.3 \pm 0.2$ GeV, $m_{\tilde\chi_2^0} = 168.5 \pm 0.5$ GeV, $m_{\tilde\chi_3^0} = 180.8 \pm 0.5$ GeV, $\sigma(\tilde\chi_1^0\tilde\chi_2^0) \times \text{BR}(\tilde\chi_2^0 \to \tilde\ell_R\ell) = 130.9 \pm 1.4$ fb, $\sigma(\tilde\chi_1^0\tilde\chi_3^0) \times \text{BR}(\tilde\chi_3^0 \to \tilde\ell_R\ell) = 155.7 \pm 1.6$ fb, $\sigma(\tilde\chi_2^0\tilde\chi_2^0) \times \text{BR}(\tilde\chi_2^0 \to \tilde\ell_R\ell)^2 = 4.8 \pm 0.3$ fb, $\sigma(\tilde\chi_3^0\tilde\chi_3^0) \times \text{BR}(\tilde\chi_3^0 \to \tilde\ell_R\ell)^2 = 26.3 \pm 0.7$ fb and $\sigma(\tilde\chi_2^0\tilde\chi_3^0) \times \text{BR}(\tilde\chi_2^0 \to \tilde\ell_R\ell) \times \text{BR}(\tilde\chi_3^0 \to \tilde\ell_R\ell) = 28.9 \pm 0.7$ fb. The fitted values of the parameters of the neutralino mass matrix are listed in Tab. 3. It is remarkable that the moduli of the phases ϕ_1, ϕ_μ can also be determined with high precision, using the CP-even observables alone. However, only an inclusion of CP-odd asymmetries in the fit allows to resolve the sign ambiguities of the

$\lvert M_1 \rvert$	M_2	$\lvert\mu\rvert$	$\tan\beta$	ϕ_1	ϕ_μ
150.0 ± 0.7 GeV	300 ± 5 GeV	165.0 ± 0.3 GeV	10.0 ± 1.6	0.63 ± 0.05	0.0 ± 0.2

Table 3: Results of the parameter fit.

phases. Without the CP-odd asymmetries in the fit there is a twofold ambiguity, $\phi_1 = \pm 0.6$, and even fourfold if $\phi_\mu \neq 0$. Thus, the triple product asymmetries are not only a direct test of CP violation, but are also essential to determine the correct values of the phases.

4 Summary and conclusions

The first full detector simulation study to measure SUSY CP phases at the ILC has been presented. Triple products of the final state lepton momenta in neutralino decays have been used as CP-odd observables. Realistic collider conditions have been simulated and all relevant SM backgrounds have been taken into account. A detailed cut flow analysis has been performed, including the development of a kinematic selection procedure that was used to obtain a very clean signal sample and to distinguish events from different neutralino decays. In the chosen benchmark scenario the asymmetry could be measured with a relative precision of 10% with $500\,\mathrm{fb}^{-1}$ of data. Finally, the parameters of the neutralino mixing matrix have been fitted to CP-even and CP-odd observables and the complex phases could be determined with a precision of about 10%.

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