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CP VIOLATION IN SUPERSYMMETRY*

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Abstract

A review about some recent studies on the determination of the CP-violating complex parameters in supersymmetry at an e^+e^- linear collider is presented. CP-even observables, like masses, cross sections and branching ratios, can have a strong dependence on the supersymmetric phases. However, CP-odd observables, like asymmetries based on triple product correlations, are necessary to unambiguously establish CP violation. In the chargino and neutralino sector these asymmetries can be as large as 30 % and will therefore be an important tool for the search for CP-violating effects in supersymmetry.

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CP VIOLATION IN SUPERSYMMETRY[a]

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A review about some recent studies on the determination of the CP-violating complex parameters in supersymmetry at an e^+e^- linear collider is presented. CP-even observables, like masses, cross sections and branching ratios, can have a strong dependence on the supersymmetric phases. However, CP-odd observables, like asymmetries based on triple product correlations, are necessary to unambiguously establish CP violation. In the chargino and neutralino sector these asymmetries can be as large as 30 % and will therefore be an important tool for the search for CP-violating effects in supersymmetry.

1 Introduction

The small amount of CP violation in the Standard Model (SM), which is caused by the phase in the Cabibbo-Kobayashi-Maskawa matrix, is not sufficient to explain the baryon-antibaryon asymmetry of the universe [1]. The Lagrangian of the Minimal Supersymmetric Standard Model (MSSM) contains several complex parameters, which can give rise to new CP-violating phenomena [2]. After eliminating unphysical phases two complex parameters remain in the neutralino and chargino sector, the U(1) gaugino mass parameter M_1 and the higgsino mass parameter μ. Furthermore the SU(3) gaugino mass parameter M_3 and the trilinear scalar couplings A_f in the sfermion sector can be complex.

The phases of the complex parameters are constrained or correlated by the experimental upper limits on the electric dipole moments of electron, neutron and the atoms ^{199}Hg and ^{205}Tl [3]. For example, the phase of μ is restricted to $|\phi_\mu| \lesssim 0.1\pi$ in mSUGRA-type models. However, there may be cancellations between the contributions of different complex parameters, which allow larger values for the phases [4,5]. Moreover, the restrictions are very model dependent. For example, when also lepton flavor violating terms are included, then the restriction on ϕ_μ may disappear [6].

In this contribution I will summarize several projects how to determine the supersymmetric (SUSY) phases with help of CP-even and CP-odd observables at a future e^+e^- linear collider.

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2 CP-even Observables

The study of production and decay of charginos ($\tilde{\chi}_i^{\pm}$) and neutralinos ($\tilde{\chi}_i^0$) and a precise determination of the underlying SUSY parameters M_1, M_2, μ and $\tan\beta$ including the phases ϕ_{M_1} and ϕ_μ will play an important role at future linear colliders [7]. In [8] methods to determine these parameters based on neutralino and chargino mass and cross section measurements have been presented. In [5] the impact of the SUSY phases on chargino, neutralino and selectron production has been analyzed and significances for the existence of non-vanishing phases have been defined. In [9] chargino production $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$ at a linear collider with transversely polarized beams has been analyzed. It is shown that CP-odd triple product correlations involving the transverse beam polarizations vanish, if at least one subsequent chargino decay is not observed. However, for subsequent chargino decays $\tilde{\chi}_j^- \to \ell^-\tilde{\nu}_\ell$ or $\tilde{\chi}_j^- \to W^-\tilde{\chi}_1^0$ it is possible to define CP-even azimuthal asymmetries, which have a strong dependence on ϕ_μ and ϕ_{M_1} (Fig. 1 (a)). Further methods to probe the CP properties of neutralinos are described in [10].

In contrast to the parameters of the chargino and neutralino sector it is more difficult to measure the trilinear couplings A_f in the sfermion sector. Cross section measurements of sfermion production processes allow the determination of the sfermion masses and mixing angles which in turn allow the determination of the parameters A_f in the real case [11]. In [12,13,14] the impact of the CP phases of A_τ, A_t, A_b, μ and M_1 on production and decay of $\tilde{\tau}_{1,2}$, $\tilde{\nu}_\tau$, $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$ have been studied. The branching ratios of fermionic decays of $\tilde{\tau}_1$ and $\tilde{\nu}_\tau$ show a significant phase dependence for $\tan\beta \lesssim 10$ whereas it becomes less pronounced for $\tan\beta > 10$. The branching ratios of $\tilde{\tau}_2$ into Higgs bosons depend very sensitively on the phases for $\tan\beta \gtrsim 10$. The branching ratios of $\tilde{t}_{1,2}$ show a pronounced phase dependence in a large region of the MSSM parameter space (Fig. 1 (b)). In the case of $\tilde{b}_{1,2}$ decays there can be an appreciable φ_{A_b} dependence, if $\tan\beta$ is large and the decays into Higgs bosons are allowed. Further the expected accuracy in determining the SUSY parameters has been estimated by a global fit of measured masses, branching ratios and production cross sections. A_τ, A_t and A_b can be expected to be measured with 10 %, 2 − 3 % and 50 % accuracy, respectively, $\tan\beta$ with 1 % (2 %) accuracy in case of small (large) $\tan\beta$ and the other parameters with approximately 1 % accuracy.

3 CP-odd Observables

In order to unambiguously establish CP violation in SUSY, including the signs of the phases, the use of CP-odd observables is inevitable. In SUSY T-odd

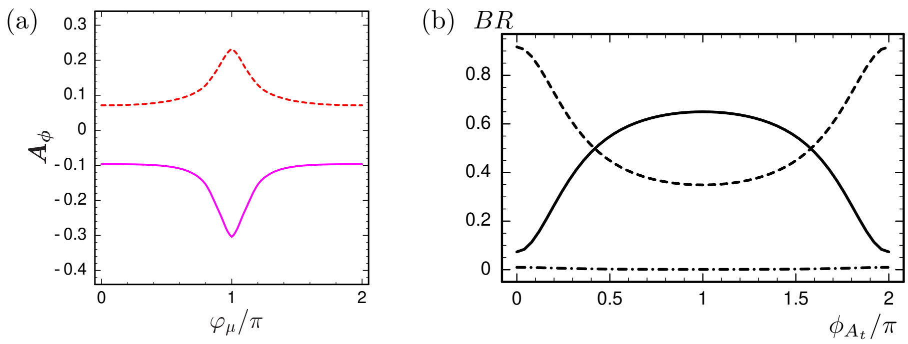

Figure 1: (a) Azimuthal asymmetry A_ϕ for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-$ with the subsequent decays $\tilde{\chi}_j^- \to \ell^-\tilde{\nu}_\ell$ (solid) and $\tilde{\chi}_j^- \to W^-\tilde{\chi}_1^0$ (dashed) for $\sqrt{s} = 800$ GeV, transverse beam polarizations $P_{e^-}^\perp = 0.8$, $P_{e^+}^\perp = 0.6$ and $|\mu| = 400$ GeV, $M_2 = 200$ GeV, $|M_1|/M_2 = 5/3 \tan^2\theta_W$, $\phi_{M_1} = 0$, $\tan\beta = 3$, $m_{\tilde{\nu}} = 150$ GeV. From[9]. (b) Branching ratios BR of the decays $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ (solid), $\tilde{t}_1 \to \tilde{\chi}_1^0 t$ (dashed) and $\tilde{t}_1 \to W^+\tilde{b}_1$ (dashdotted) for $\tan\beta = 6$, $M_2 = 300$ GeV, $|\mu| = 350$ GeV, $|A_b| = |A_t| = 800$ GeV, $\varphi_\mu = \pi$, $\varphi_{M_1} = \varphi_{A_b} = 0$, $m_{\tilde{t}_1} = 350$ GeV, $m_{\tilde{t}_2} = 700$ GeV, $m_{\tilde{b}_1} = 170$ GeV, $M_{\tilde{Q}} > M_{\tilde{U}}$ and $m_{H^\pm} = 900$ GeV. From [13].

triple product correlations between momenta and spins of the involved particles allow the definition of CP-odd asymmetries already at tree level [15]. Such asymmetries have been analyzed for neutralino and chargino production with subsequent three-body[16] and two-body decays[17,18], where full spin correlations between production and decay have to be included [19].

A Monte Carlo study of T-odd asymmetries in selectron and neutralino production and decay including initial state radiation, beamstrahlung, SM backgrounds and detector effects has been given in [20]. It has been found that asymmetries $A_T \sim 10\,\%$ are detectable after few years of running of a linear collider.

In [16] a T-odd asymmetry

$$A_T = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)} = \frac{\int \mathrm{sign}(\mathcal{T})|T|^2 d\mathrm{Lips}}{\int |T|^2 d\mathrm{Lips}}$$

is defined with help of the triple product $\mathcal{T} = \vec{p}_{\ell^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{e^-})$ of the initial electron momentum $\vec{p}_{e^-}$ and the two final lepton momenta $\vec{p}_{\ell^+}$ and $\vec{p}_{\ell^-}$, where T denotes the amplitude and $\int |T|^2 d\mathrm{Lips}$ is proportional to the cross section σ of the process $e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0 \to \tilde{\chi}_i^0\tilde{\chi}_1^0\ell^+\ell^-$. A_T can be directly measured without reconstruction of the momentum of the decaying neutralino or further final-state analyses. In representative scenarios of the SUSY parameters it has

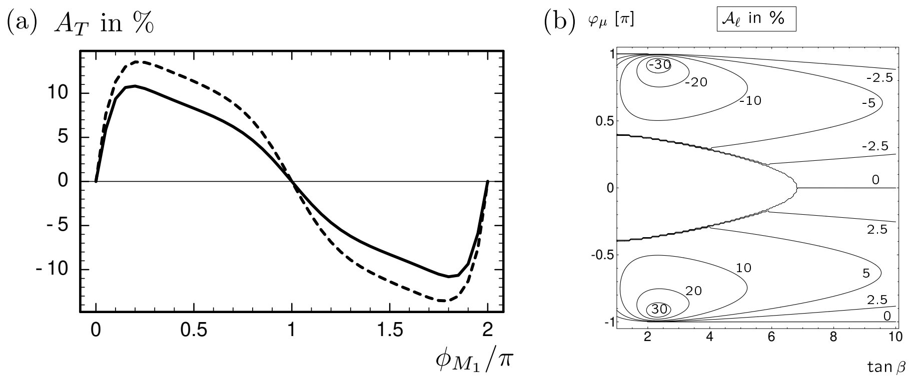

Figure 2: (a) T-odd asymmetry A_T for $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell^+\ell^-$, $\ell = e, \mu$, for $\sqrt{s} = 500$ GeV (solid), $\sqrt{s} = 350$ GeV (dashed) and $P_{e^-} = -0.8$, $P_{e^+} = +0.6$ for $|M_1| = 150$ GeV, $M_2 = 300$ GeV, $|\mu| = 200$ GeV, $\phi_\mu = 0$, $\tan\beta = 10$, $m_{\tilde{\ell}_L} = 267.6$ GeV, $m_{\tilde{\ell}_R} = 224.4$ GeV. From [16]. (b) Contours of the CP-odd asymmetry $\mathcal{A}_\ell$ for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-$, $\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell$, $\ell = e, \mu$, for $\sqrt{s} = 800$ GeV, $P_{e^-} = -0.8$, $P_{e^+} = +0.6$ and $|\mu| = 400$ GeV, $M_2 = 200$ GeV, $m_{\tilde{\nu}} = 185$ GeV. From [18].

been shown that the asymmetry can reach values $A_T = \mathcal{O}(10\,\%)$ (Fig. 2 (a)).

In [18] a CP-odd asymmetry $A = \frac{1}{2}(A_T - \bar{A}_T)$, where $\bar{A}_T$ denotes the CP conjugate of A_T, in chargino production $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$ with subsequent two-body decay $\tilde{\chi}_i^+ \to \ell^+\tilde{\nu}_\ell$, $\ell = e, \mu, \tau$, is studied with help of the triple product $\mathcal{T} = \vec{p}_{\ell^+} \cdot (\vec{p}_{e^-} \times \vec{p}_{\tilde{\chi}_i^+})$. To measure this asymmetry the momentum $\vec{p}_{\tilde{\chi}_i^+}$ of the decaying chargino has to be reconstructed. A is sensitive to ϕ_μ and reaches values up to 30 % in some regions of the parameter space (Fig. 2 (b)).

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