EFFECTS OF CP PHASES ON THE PHENOMENOLOGY OF SUSY PARTICLES

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We review our recent studies on the effects of CP-violating supersymmetric (SUSY) parameters on the phenomenology of neutralinos, charginos and third generation squarks. The CP-even branching ratios of the squarks show a pronounced dependence on the phases of $A_t$, $A_b$, $\mu$ and $M_1$ in a large region of the supersymmetric parameter space, which can be used to get information on these phases. In addition we have studied CP-odd observables, like asymmetries based on triple product correlations. In neutralino and chargino production with subsequent three-body decays these asymmetries can be as large as 20%.

1. Introduction

The Lagrangian of the Minimal Supersymmetric Standard Model (MSSM) contains several complex parameters, which are new sources of CP-violation. In the sfermion sector of the MSSM the trilinear scalar couplings $A_f$ and the higgsino mass parameter $\mu$ can be complex. In the chargino and neutralino sector the parameter $\mu$ and the U(1) gaugino mass parameter $M_1$ can be complex, taking $M_2$ real.

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 $^{199}\text{Hg}$ and $^{205}\text{Tl}$. In a constrained MSSM the restrictions on the phases can be rather severe. However, there may be cancellations between the contributions of different complex parameters, which allow larger values for the phases.

The study of production and decay of charginos ($\tilde{\chi}_1^\pm$) and neutralinos ($\tilde{\chi}_1^0$) and a precise determination of the underlying supersymmetric (SUSY) parameters $M_1$, $M_2$, $\mu$ and $\tan\beta$ including the phases $\varphi_{M_1}$ and $\varphi_{\mu}$ will play

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an important role at the International Linear Collider (ILC)\(^2\). In\(^3\) methods to determine these parameters based on neutralino and chargino mass and cross section measurements have been presented. In\(^4\) 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\(^5\) CP-even azimuthal asymmetries in chargino production at the ILC with transversely polarized beams have been analyzed.

Concerning the determination of the trilinear couplings \(A_f\), detailed studies in the real MSSM have been performed in\(^6\). In the complex MSSM the polarization of final top quarks and tau leptons from the decays of third generation sfermions can be a sensitive probe of the CP-violating phases\(^7\). In\(^8\) the effects of the CP phases of \(A_\tau\), \(\mu\) and \(M_1\) on production and decay of tau sleptons (\(\tilde{\tau}_{1,2}\)) and tau sneutrinos (\(\tilde{\nu}_\tau\)) have been studied. The branching ratios of \(\tilde{\tau}_{1,2}\) and \(\tilde{\nu}_\tau\) can show a strong phase dependence. The expected accuracy in the determination of \(A_\tau\) has been estimated to be of the order of 10\(^\%\) by a global fit of measured masses, branching ratios and production cross sections. The impact of the SUSY phases on the decays of the third generation squarks has been discussed in\(^9,10,11\) and will be reviewed in Sec. 2.

In order to unambiguously establish CP violation in supersymmetry, including the signs of the phases, a measurement of CP-odd observables is inevitable. T-odd triple product correlations between momenta and spins of the involved particles allow the construction of CP-odd asymmetries already at tree level\(^12,13\). Asymmetries of this kind in scalar fermion decays have been discussed in\(^14\). T-odd asymmetries in neutralino and chargino production with subsequent two-body decays have been analyzed in\(^15\). For leptonic two-body decays asymmetries up to 30\(^\%\) can occur. CP-odd observables involving the polarization of final \(\tau\) leptons from two-body decays of neutralinos have been studied in\(^16\). T-odd asymmetries in neutralino and chargino production with subsequent three-body decays\(^17,18\) will be discussed in Sec. 3.

2. Decays of Third Generation Squarks

In\(^9,10,11\) we have studied the effects of the phases of the parameters \(A_t\), \(A_b\), \(\mu\) and \(M_1\) on the phenomenology of the third generation squarks, the top squarks \(\tilde{t}_{1,2}\) and the bottom squarks \(\tilde{b}_{1,2}\). We have focused especially on the effects of \(\varphi_{A_t}\) and \(\varphi_{A_b}\) in order to find methods to determine these parameters. The third generation squark sector is particularly interesting
because of the effects of the large Yukawa couplings. The phases of $A_f$ and $\mu$ enter directly the squark mass matrices and the squark-Higgs couplings, which can cause a strong phase dependence of suitable observables. In the case of top squarks the $\mu$ term in the off-diagonal element of the mass matrix is suppressed by $1/\tan\beta$, hence the phase dependence of the decay matrix elements is essentially determined by $\varphi_{A_t}$ in a large part of the SUSY parameter space with $|A_t| \gg |\mu|/\tan\beta$. This can lead to a strong phase dependence of many partial decay widths and branching ratios.

In the case of bottom squarks the mixing is smaller because of the smaller bottom quark mass. It is only important for large $\tan\beta$, when the $\mu$ term in the off-diagonal element of the mass matrix is large. However, in the squark-Higgs couplings the phase $\varphi_{A_b}$ appears independent of the bottom squark mixing. This can lead to a strong $\varphi_{A_b}$ dependence of bottom squark and top squark partial decay widths into Higgs bosons.

We first discuss the $\varphi_{A_t}$ and $\varphi_{A_b}$ dependence of top squark and bottom squark partial decay widths and branching ratios. We have analyzed fermionic decays $\tilde{q}_i \to \tilde{\chi}^\pm_j q'$, $\tilde{q}_i \to \tilde{\chi}^0_j q$ and bosonic decays $\tilde{q}_i \to \tilde{q}_j^* H^\pm$, $\tilde{q}_i \to \tilde{q}_j^* W^\pm$, $\tilde{q}_2 \to \tilde{q}_1 H_1$, $\tilde{q}_2 \to \tilde{q}_1 Z$ of $\tilde{t}_{1,2}$ and $\tilde{b}_{1,2}$. In the complex MSSM the CP-even and CP-odd neutral Higgs bosons mix and form three mass eigenstates $H_{1,2,3}$. This can also cause a phase dependence of the widths of the decays into Higgs bosons.

In Fig. 1 we show the partial decay widths $\Gamma$ and branching ratios $B$ of the $\tilde{t}_1$. All partial decay widths, especially $\Gamma(\tilde{t}_1 \to \tilde{\chi}^+_1 b)$, have a pronounced $\varphi_{A_t}$ dependence, which leads to a strong $\varphi_{A_t}$ dependence of the branching ratios. This $\varphi_{A_t}$ dependence of the partial decay widths is caused by that of the top squark mixing matrix which enters the respective couplings. In the case of the heavy $\tilde{t}_2$ many decay channels can be open and can show a strong $\varphi_{A_t}$ dependence.

In Fig. 2 we show $\tilde{b}_1$ decay widths and branching ratios. Only $\Gamma(\tilde{b}_1 \to H^- \tilde{t}_1)$ shows a pronounced $\varphi_{A_b}$ dependence, which leads to a strong $\varphi_{A_b}$ dependence of the branching ratios. This is caused by the $\varphi_{A_b}$ dependence of the $H^\pm \tilde{t}_L \tilde{b}_R$ coupling. The other partial decay widths depend only very weakly on $\varphi_{A_b}$. This is typical for the $\varphi_{A_b}$ dependence of the $\tilde{b}_{1,2}$ decays. Only the partial decay widths into Higgs bosons, $\Gamma(\tilde{b}_1 \to H^- \tilde{t}_1)$ for $\tilde{b}_1$ and $\Gamma(\tilde{b}_2 \to H^- \tilde{t}_{1,2})$, $\Gamma(\tilde{b}_2 \to H_{1,2,3} \tilde{b}_1)$ for $\tilde{b}_2$, can show a strong phase dependence for large $\tan\beta$.

In order to estimate the precision which can be expected in the determination of the underlying SUSY parameters we have made a global fit of the top squark and bottom squark decay branching ratios as well as masses
Figure 1. (a) Partial decay widths $\Gamma$ and (b) branching ratios $B$ of the decays $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ (solid), $\tilde{t}_1 \to \tilde{\chi}_1^0 b$ (dashed), $\tilde{t}_1 \to \tilde{\chi}_2^0 \tilde{t}$ (dashdotted) and $\tilde{t}_1 \to \tilde{\chi}_1^0 \tilde{t}$ (dotted) for $\tan \beta = 50$, $M_2 = 233.2$ GeV, $|M_1/M_2| = 5/3 \tan^2 \theta_W$, $|\mu| = 377.0$ GeV, $|A_t| = 498.9$ GeV, $\varphi_\mu = \varphi_M_1 = \varphi_A_t = 0$, $m_{\tilde{t}_1} = 530.6$ GeV, $m_{\tilde{t}_2} = 695.9$ GeV, $M_\tilde{Q} > M_\tilde{U}$ and $m_{H^\pm} = 416.3$ GeV. From $^9$.

Figure 2. (a) Partial decay widths $\Gamma$ and (b) branching ratios $B$ of the decays $\tilde{b}_1 \to \tilde{\chi}_1^0 b$ (solid), $\tilde{b}_1 \to \tilde{\chi}_2^0 b$ (dashed), $\tilde{b}_1 \to H^- \tilde{t}_1$ (dotted) and $\tilde{b}_1 \to W^- \tilde{t}_1$ (dashdotted) for $\tan \beta = 30$, $M_2 = 200$ GeV, $|M_1/M_2| = 5/3 \tan^2 \theta_W$, $|\mu| = 300$ GeV, $|A_t| = |A_b| = 600$ GeV, $\varphi_\mu = \pi$, $\varphi_A_t = \pi/4$, $\varphi_M_1 = 0$, $m_{\tilde{t}_1} = 170$ GeV, $M_\tilde{Q} > M_\tilde{D}$ and $m_{H^\pm} = 150$ GeV. From $^9$.

and production cross sections in $^{11}$. In order to achieve this the following assumptions have been made: (i) At the ILC the masses of the charginos, neutralinos and the lightest Higgs boson can be measured with high precision. If the masses of the squarks and heavier Higgs bosons are below 500 GeV, they can be measured with an error of 1% and 1.5 GeV, respectively. (ii) The masses of the squarks and heavier Higgs bosons, which are heavier than 500 GeV, can be measured at a 2 TeV $e^+e^-$ collider like CLIC with an error of 3% and 1%, respectively. (iii) The gluino mass can be measured at the LHC with an error of 3%. (iv) For the production cross
sections \( \sigma(e^+e^- \rightarrow \tilde{t}_i\tilde{t}_j) \) and \( \sigma(e^+e^- \rightarrow \tilde{b}_i\tilde{b}_j) \) and the branching ratios of the \( \tilde{t}_i \) and \( \tilde{b}_i \) decays we have taken the statistical errors, which we have doubled to be on the conservative side. We have analyzed two scenarios, one with small \( \tan \beta = 6 \) and one with large \( \tan \beta = 30 \). In both scenarios we have found that \( \text{Re}(A_t) \) and \( |\text{Im}(A_t)| \) can be determined with relative errors of 2 – 3%. For \( A_b \) the situation is considerably worse because of the weaker dependence of the observables on this parameter. The corresponding errors are of the order of 50%. For the squark mass parameters \( M_{\tilde{Q}}, M_{\tilde{U}}, M_{\tilde{D}} \) the relative errors are of order of 1%, for \( \tan \beta \) of order of 3% and for the other fundamental SUSY parameters of order of 1 – 2%. In this analysis we have used the tree-level formulae for the top squark and bottom squark decay widths. One-loop corrections are discussed in and the references therein.

3. T-odd Asymmetries in Neutralino and Chargino Production and Decay

We have studied T-odd asymmetries in neutralino and chargino production with subsequent three-body decays

\[ e^+e^- \rightarrow \tilde{\chi}_i + \tilde{\chi}_j \rightarrow \tilde{\chi}_i + \tilde{\chi}_0^f \tilde{f}^{(\prime)}, \]  

where the full spin correlations between production and decay have to be included. Then in the amplitude squared \(|T|^2\) of the combined process products like

\[ i \epsilon_{\mu\nu\rho\sigma} p_\mu p_\nu j p_\rho k p_\sigma \]  

appear in those terms which depend on the spin of the decaying neutralino or chargino. Together with the complex couplings these terms can give real contributions to suitable observables at tree-level. Examples are the triple products \( T_1 = \vec{p}_{e^-} \cdot (\vec{p}_f \times \vec{p}_{f^{(\prime)}}) \) of the initial electron momentum \( \vec{p}_{e^-} \) and the two final fermion momenta \( \vec{p}_f \) and \( \vec{p}_{f^{(\prime)}} \) or \( T_2 = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_f) \) of the initial electron momentum \( \vec{p}_{e^-} \), the momentum of the decaying neutralino or chargino \( \vec{p}_{\tilde{\chi}_j} \) and one final fermion momentum \( \vec{p}_f \). With these triple products we define the T-odd asymmetries

\[ A_T = \frac{\sigma(T_1 > 0) - \sigma(T_1 < 0)}{\sigma(T_1 > 0) + \sigma(T_1 < 0)} = \frac{\int \text{sign}(T_1)|T|^2d\text{Lips}}{\int |T|^2d\text{Lips}}, \]  

where \( \int |T|^2d\text{Lips} \) is proportional to the cross section \( \sigma \) of the process (1). \( A_T \) is odd under naive time-reversal operation and hence CP-odd, if higher order final-state interactions and finite-widths effects can be neglected.

We first consider neutralino production and subsequent leptonic three-body decay \( e^+e^- \rightarrow \tilde{\chi}_i^0 + \tilde{\chi}_j^0 \rightarrow \tilde{\chi}_i^0 + \tilde{\chi}_1^0 \ell^+\ell^- \) and define the triple product
the analyzed three-body decay is strongly suppressed because \( m_{\tilde{\chi}_1} \) parameter space with \( \sigma \) values \( \propto m_{\tilde{\chi}_1} \). Figure 3. Contours (a) of the T-odd asymmetry \( A_T \) in \% and (b) of the cross section \( \sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0\ell^+\ell^-) \), summed over \( \ell = e, \mu \), in fb, respectively, for \( \tan \beta = 10 \), \( m_{\tilde{\chi}_1} = 267.6 \) GeV, \( m_{\tilde{\chi}_1} = 224.4 \) GeV, \( |M_1|/M_2 = 5/3 \tan^2 \theta_W \), \( \varphi_{M_1} = 0.5 \pi \) and \( \varphi_\mu = 0 \) with \( \sqrt{s} = 500 \) GeV and \( P_{e^-} = -0.8 \), \( P_{e^+} = +0.6 \). The dark shaded area marks the parameter space with \( m_{\tilde{\chi}_1} < 103.5 \) GeV excluded by LEP. In the light shaded area the analyzed three-body decay is strongly suppressed because \( m_{\tilde{\chi}_1} > m_Z + m_{\tilde{\chi}_1} \) or \( m_{\tilde{\chi}_2} > m_{\tilde{\chi}_1} \). From 17.

\[ T_1 = \vec{p}_{\ell^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) \] and the corresponding asymmetry \( A_T \). Then \( A_T \) can be directly measured without reconstruction of the momentum of the decaying neutralino. We show in Fig. 3 the asymmetry \( A_T \) and the corresponding cross section \( \sigma \) for \( \tilde{\chi}_1^0\tilde{\chi}_2^0 \) production and subsequent decay of \( \tilde{\chi}_2^0 \), \( e^+e^- \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \tilde{\chi}_2^0\ell^+\ell^- \). As can be seen, asymmetries \( A_T \) of the order of 10 \% can be reached in the parameter region where the cross section is of the order of 10 fb. Also for the associated production and decay of \( \tilde{\chi}_2^0 \) and \( \tilde{\chi}_3^0 \), \( e^+e^- \rightarrow \tilde{\chi}_3^0 + \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_3^0 + \tilde{\chi}_2^0\ell^+\ell^- \), the asymmetry \( A_T \) has values \( O(10 \%) \) in large parameter regions, where the corresponding cross sections \( \sigma \) are of the order of 10 fb. For \( e^+e^- \rightarrow \tilde{\chi}_4^0 + \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_4^0 + \tilde{\chi}_2^0\ell^+\ell^- \) we have obtained asymmetries \( A_T \approx 6 \% \), however the cross section is only \( \sigma \lesssim 1 \) fb.

We have also studied chargino production and subsequent hadronic three-body decay \( e^+e^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_2^0\ell^- \). As an example we consider the triple product \( T_1 = \vec{p}_{\ell^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) \) and the corresponding asymmetry \( A_T \). In this case it is important to tag the \( c \) jet to discriminate between the two jets and to measure the sign of \( T_1 \). For the associated
production and decay of $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^-$, $e^+e^- \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^0\bar{sc}$, asymmetries $A_T$ of the order of 10% are reached for almost real parameter $\mu$ around $\varphi_\mu = \pi$. In the chargino sector even for the pair production and decay process $e^+e^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0\bar{sc}$ asymmetries $A_T \approx 5\%$ can appear, which can only originate from the decay process, because all couplings in the production process are real. This means that the contributions from the decay to $A_T$ play an important role in chargino production with subsequent hadronic decays. This can also be seen in Fig. 4 (a), where $A_T$ can be large for $\varphi_\mu = 0$ and $\varphi_{M_1} \neq 0$. It is furthermore remarkable that $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0\bar{sc})$ can be rather large, for example 117 fb in the scenario $M_2 = 350$ GeV, $|\mu| = 260$ GeV and the other parameters as in Fig. 4 (a), where $A_T \approx 4\%$.

If the momentum of the decaying chargino $\tilde{\chi}_1^+$ can be reconstructed, for example with help of information from the decay of the $\tilde{\chi}_i^-$, the process $e^+e^- \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_i^- + \tilde{\chi}_1^0\bar{sc} + \ell^+\nu$ can be analyzed, where the chargino decays leptonically. Then the triple product $T_2 = \vec{p}_{\tilde{\chi}_1^-} \cdot (\vec{p}_{\tilde{\chi}_1^+} \times \vec{p}_{\ell^+})$ can be used to define $A_T$. For the associated production and decay of $\tilde{\chi}_1^+$ and $\tilde{\chi}_2^-$, $e^+e^- \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_2^- + \tilde{\chi}_1^0\ell^+\nu$, asymmetries $A_T \gtrsim 20\%$ can occur. But in the region with largest asymmetries around $|\mu| = 320$ GeV and $M_2 = 120$ GeV the cross section is very small ($\sigma \approx 0.1$ fb). However, for decreasing $|\mu|$ the cross section increases and reaches $\sigma \approx 2$ fb for $|\mu| = 220$ GeV and $M_2 = 120$ GeV.
4. Conclusions

Using the CP-violating MSSM as our framework we have studied the impact of the complex parameters $A_t$, $A_b$, $\mu$ and $M_1$ on the decays of top squarks and bottom squarks. In the case of top squark decays all partial decay widths and branching ratios can have a strong $\varphi_{A_t}$ dependence because of the large mixing in the top squark sector. If $\tan \beta$ is large and decay channels into Higgs bosons are open, top squark and bottom squark branching ratios can show also a strong $\varphi_{A_t}$ dependence. This strong phase dependence of CP-even observables like branching ratios has to be taken into account in SUSY particle searches at future colliders. It will affect the determination of the underlying MSSM parameters. In order to estimate the expected accuracy in the determination of the MSSM parameters we have made a global fit of masses, branching ratios and production cross sections in two scenarios with small and large $\tan \beta$. We have found that $A_t$ can be determined with an error of $2 - 3\%$, whereas the error of $A_b$ is likely to be of the order of $50\%$. Furthermore $\tan \beta$ can be determined with an error of $3\%$ and the other fundamental MSSM parameters with errors of $1 - 2\%$.

The measurement of CP-odd observables is inevitable to unambiguously establish CP violation in supersymmetry. This will allow to determine the phases including their signs. We have studied T-odd asymmetries in neutralino and chargino production with subsequent three-body decays. These asymmetries are based on triple product correlations between incoming and outgoing particles. They appear already at tree-level because of spin correlations between production and decay. The T-odd asymmetries can be as large as $20\%$ and will therefore be an important tool for the search for CP violation in supersymmetry and the unambiguous determination of the phases of the SUSY parameters.

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