CP Violating Effects in Stop Decay

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We study the discovery potential of new CP violating phases in a $\tilde{t}_1$ cascade decay via $\tilde{\chi}_2^0$ at a future linear electron-positron collider of 1 TeV center-of-mass energy. As observables we discuss triple product asymmetries. We find that assuming successful momentum reconstruction a maximal asymmetry can be observed with at least 1000 fb^{-1} collected data.

1 Introduction

Although the Standard Model very successfully describes the elementary particles and their interactions apart from gravity, the model not only fails to give a description of all matter in the universe, but furthermore cannot illuminate thoroughly why matter exists at all. To answer this question we know that a proper understanding of CP-violation is crucial [1]. Unfortunately, the single CP violating phase in the CKM matrix of the Standard Model that has been determined by B-meson experiments [2] is not sufficient [1]. Thus, we need additional sources of CP-violation to describe the observed baryon asymmetry in the universe.

Such new CP violating phases are introduced in the MSSM. Given that they can change masses [3], total cross sections [4] and branching ratios [5], there are in principle various ways to detect them at colliders. However, these all are CP-even observables. This means that one cannot be sure about their definite CP violating nature, because particle and antiparticle both exhibit the same dependence. This is especially problematic in a model that has as many free parameters as the MSSM. A potential way to fake a CP violating effect on the stop mass, for example, is to arrange the soft breaking scalar quark masses with non-universal values. Additionally, potentially large loop corrections can complicate CP-violation studies by also changing these observables. Therefore one would like to work with CP-odd observables, which cannot be mimicked by other parameters of the theory and thus are a definite signature of CP-violation. However, the problem with many of these observables, like rate asymmetries of branching ratios [6], rate asymmetries of cross sections [7] or angular distributions [8], is that they are actually loop effects. Thus, obvious problems arise concerning the measurability, since one does not expect large signals from loop effects. Fortunately the CPT-theorem connects CP- and T-violation. Combined with additional assumptions one can then construct so-called $\mathrm{T_N}$-odd observables that are useful to examine tree-level CP-violation at colliders [9, 10]. If re-scattering effects are absent, a non-vanishing expectation value of a $\mathrm{T_N}$-odd observable indicates CP-violation. Therefore we must also probe the charge conjugated process to exclude the possibility of re-scattering. For further information we recommend [11] which review CP-violation in the context of supersymmetry.

2 Studying CP-Violation in Stop Decay

2.1 Formalism and Chosen Scenario

We study the discovery potential of new CP violating phases in the following two-body cascade decay of the stop at a future linear electron-positron collider of 1 TeV center-of-mass energy,

$$\tilde{t}_1 \to \tilde{\chi}_2^0 + t\,, \qquad t \to W^+ + b\,, \qquad \tilde{\chi}_2^0 \to \tilde{l}_{\mathrm{R}}^{\pm} + l_1^{\mp}\,, \qquad \tilde{l}_{\mathrm{R}}^{\pm} \to \tilde{\chi}_1^0 + l_2^{\pm}\,.$$

The stop and neutralino sector contain three phases, namely a phase of the trilinear top quark coupling, ϕ_{A_t}, a phase of the higgsino mass parameter, ϕ_μ, and conventionally a phase of the first gaugino mass, ϕ_{M_1}. However, the latter two (especially ϕ_μ) are heavily constrained by experiment [12]. Therefore we do not consider them and focus on ϕ_{A_t} in this study.

Since we want to test the capability of a future linear collider, we use a "light" scenario without strict unification of gaugino and scalar masses. The relevant masses and branching ratios are presented in Tab. 1.

As CP-odd observables we use asymmetries of triple products of final state or reconstructed momenta,

$$\mathcal{A}_T = \frac{N_{\mathcal{T}+} - N_{\mathcal{T}-}}{N_{\mathcal{T}+} + N_{\mathcal{T}-}} = \frac{\int \mathrm{sign}\{\mathcal{T}\}\,|T|^2 \mathrm{dlips}}{\int |T|^2 \mathrm{dlips}} ,$$

$m_{\tilde{t}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{l}_R^\pm}$	$\mathrm{BR}_{\tilde{t}_1}$	$\mathrm{BR}\tilde{\chi}_2^0$
344	84.5	124.5	96	11.99 %	11.53 %

Table 1: Masses in GeV and branching ratios for the chosen scenario with all CP violating phases set to zero.

where $N_{\mathcal{T}\pm}$ denote the numbers of events with positive or negative triple product, respectively, T the amplitude of the process of interest and dlips the Lorentz invariant phase space. In our case the above decay chain provides two triple products originating from the covariant product in the spin-spin-dependent part of the amplitude, namely

$$\mathcal{T}_{l_1}^{\mp} = \left(\vec{p}_{l_1^\mp} \cdot [\vec{p}_W \times \vec{p}_t]\right) , \qquad \mathcal{T}_{ll} = (\vec{p}_b \cdot [\vec{p}_{l^+} \times \vec{p}_{l^-}]) .$$

To reveal CP-violation we then measure the corresponding triple product asymmetries, $\mathcal{A}_{l_1}$ and $\mathcal{A}_{ll}$. However, in order to make a definite statement on CP-violation, we need to combine the measurements of both charge-conjugated processes. Since the asymmetry changes sign under charge conjugation, this forces us to claim knowledge of the stop charge for both triple products. Not knowing the charge of the stop would result in a cancellation of the asymmetry. Fortunately, the $\tilde{t}_1$-charge can be established by requiring that the antiparticle decays via a single lepton. Thus, overall we observe a tri-lepton final state [10]. But in demanding this we loose statistical significance, since we reduce the total number of events due to requiring specific decays. To optimise the situation and gain a factor of two one therefore should not fix the charge determination to the antiparticle decay, but allow charge determination from the particle as well. Here we would use the antiparticle decay to form the triple product.

Furthermore, we need to identify the leptons from the neutralino and slepton decay for the triple product, $\mathcal{T}_{l_1}^{\mp}$. This is due to the fact that the correlation for the far lepton is much weaker than for the near lepton. Hence, the use of the far lepton results in a smaller triple product, which dilutes the asymmetry. The identification of the leptons can be done by the momentum reconstruction technique presented in [10]. Note, however, that we have to know the masses of all particles of the decay chain for this.

Nevertheless, momentum reconstruction is very important apart from lepton identification, because unlike the covariant product the mentioned triple products are not Lorentz invariant. The asymmetry, $\mathcal{A}_{l_1}$, for example, is maximal in the neutralino or stop rest frame and is diluted for any boost.

In contrast to $\mathcal{T}_{l_1}^{\mp}$, we do not need to identify the leptons for $\mathcal{T}_{ll}$, but only to measure the lepton charges. Thus, if a distinction between near and far lepton is not possible for some reason, this triple product provides an alternative. However, an inertial frame in which $\mathcal{T}_{ll}$ is completely equivalent to the covariant product does not exist. This is the case, because the covariant product contains a $\tilde{\chi}_1^0$-dependent contribution. Consequently, although $\mathcal{T}_{ll}$ is valuable when momentum reconstruction is not possible, it will lead to a smaller asymmetry than $\mathcal{T}_{l_1}^{\mp}$ (assuming full momentum reconstruction). This can also be understood physically, since the second lepton is not directly correlated to the spin of the intermediate neutralino. Hence, the triple products are smaller.

2.2 Numerical Results

To obtain a maximal asymmetry, we evaluate $\mathcal{A}_{l_1}$ in the reconstructed $\tilde{\chi}_2^0$ rest frame and $\mathcal{A}_{ll}$ in the reconstructed W rest frame (see Fig. 1). The shape of the curves immediately illustrates that $\mathcal{A}_{l_1}$ and $\mathcal{A}_{ll}$ are CP-odd. The triple product, $\mathcal{T}_{l_1}$, evokes the larger asymmetry, because $\mathcal{T}_{ll}$ does not represent the complete covariant product in any inertial frame. Both asymmetries are maximal for $\phi_{A_t} \approx 1.2\pi$, with $\mathcal{A}_{ll} \approx 9.3$ % and $\mathcal{A}_{l_1} \approx 15.5$ %.

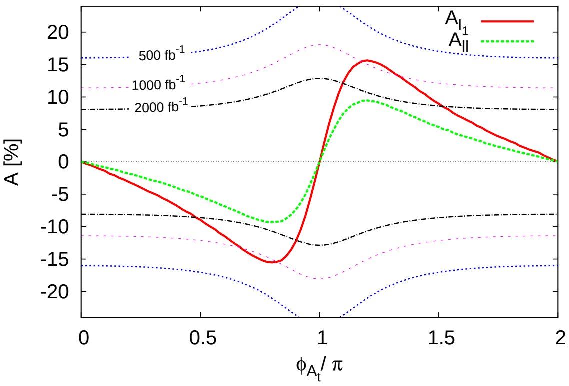

Figure 1: The asymmetries, $\mathcal{A}_{l_1}$ and $\mathcal{A}_{ll}$, along with the lines showing the asymmetry required for a 3σ observation at a given integrated luminosity of 500 fb^{-1}, 1000 fb^{-1} and 2000 fb^{-1} at $\sqrt{s} = 1$ TeV in the case of momentum reconstruction. $\mathcal{A}_{l_1}$ is evaluated in the $\tilde{\chi}_2^0$ and $\mathcal{A}_{ll}$ in the W rest frame.

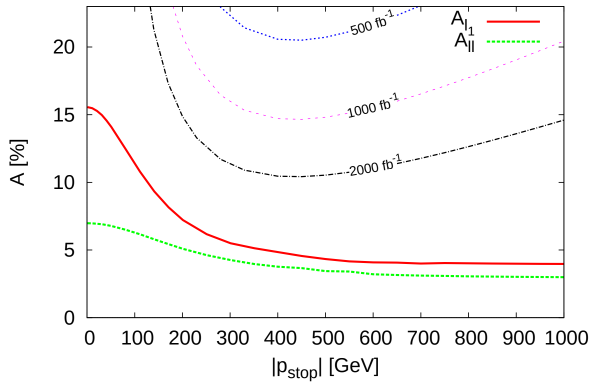

Figure 2: Both triple product asymmetries, $\mathcal{A}_{l_1}$ and $\mathcal{A}_{ll}$, for $\phi_{A_t} = 1.2\pi$ in the laboratory frame as functions of the absolute value of stop three-momentum and 3σ-limits for integrated luminosities of 500 fb^{-1}, 1000 fb^{-1} and 2000 fb^{-1}.

Furthermore, Fig. 1 contains the 3σ-limits for integrated luminosities of 500 fb^{-1}, 1000 fb^{-1} and 2000 fb^{-1}. Assuming successful momentum reconstruction we see that for 2000 fb^{-1} collected data one would be able to observe a triple product asymmetry in the region of a maximal CP violating angle, $1.1\pi < \phi_{A_t} < 1.5\pi$. With 1000 fb^{-1} the asymmetry can still be exposed close to the maximum ($1.18\pi < \phi_{A_t} < 1.33\pi$), whereas 500 fb^{-1} is not sufficient to reveal CP-violation via triple product asymmetries here. In particular $\mathcal{A}_{ll}$ needs more data.

If we are not able to reconstruct the $\tilde{\chi}_1^0$-momentum and are forced to use the diluted asymmetries in the laboratory frame directly, both asymmetries attain too small magnitudes to be detected at a 3σ-level with the expected luminosity. At the maximum of $\phi_{A_t} \approx 1.2\pi$ the asymmetries are determined to be $\mathcal{A}_{ll} \approx 3.9$ % and $\mathcal{A}_{l_1} \approx 5.0$ %. Note that the dilution due to energy dependence of $\mathcal{A}_{ll}$ is less significant than for $\mathcal{A}_{l_1}$, which is diluted by approximately 70 %. Notice further that we have not included the dilution from misidentified leptons in $\mathcal{A}_{l_1}$ yet. We will come back to both points in a moment.

Looking at Fig. 1 again, we notice that the bands which indicate the limit of measurability for a certain luminosity are not constant, but vary with ϕ_{A_t}. The reason for this is that the stop mass - and hence the production cross section - as well as the branching ratio, BR$(\tilde{t}_1 \to \tilde{\chi}_2^0 t)$, depend on the trilinear coupling phase, ϕ_{A_t}. As the stop mass increases as $\phi_{A_t} \to \pi$ from 344 GeV to 354 GeV, the production cross section, $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1^*)$, decreases from 12.3 fb to 11.2 fb. At the same time, the stop branching ratio, BR$(\tilde{t}_1 \to \tilde{\chi}_2^0 t)$, drops from 11.99 % to 5.16 %, since due to the increasing stop mass and changing mixing angle another decay channel, namely $\tilde{t}_1 \to \tilde{\chi}_2^+ b$, becomes prominent. This affects the total cross section which in turn influences the significance of our observable. The total number of events one can expect for a certain luminosity is calculated using our result for the production cross section and the `Herwig++`-results for the branching ratios at tree-level [13]. We draw attention to the fact that the depletion of the branching ratio is much more severe.

We already mentioned that the reconstruction of all momenta in the decay chain is important for a measurement of the triple product asymmetries, because these quantities are not Lorentz invariant. To demonstrate this we compute both asymmetries at their maximum, $\phi_{A_t} = 1.2\pi$, as functions of the stop three-momentum in the laboratory frame, as is presented in Fig. 2.

We read off that both asymmetries are maximal in the stop rest frame and are depleted for increasing stop three-momentum. This can be understood recalling the geometrical picture of triple products. Concerning the relative orientation of $\vec{p}_{l_1}$ to the three-momenta, $\vec{p}_W$ and $\vec{p}_t$, that establish the plane in our triple product, we note that the triple product and therefore the angle between $\vec{p}_{l_1}$ and the plane is maximal in the rest frame of the neutralino. Performing a boost on the system results in a smaller angle as all momenta are boosted forward in the same direction. Thus, as all vectors lie close together, it is more likely that the lepton can accidentially flip orientation with respect to the reference plane and hence change the sign of the triple product. Since this inversion is a random function of the boost and not connected to CP-violation, the asymmetry is depleted.

Although both asymmetries exhibit a manifest energy dependence, the triple product asymmetry, $\mathcal{A}_{l_1}$, is significantly more diluted than the asymmetry, $\mathcal{A}_{ll}$. This can be explained by the fact that the far lepton included in this triple product originates from the slepton which always experiences a boost, even if the stop is at rest. Therefore a boost of the stop will result in a proportionally less boosted slepton and far lepton, because the stop momentum is shared over the whole decay chain.

From the additionally plotted 3σ-limits we can extract a strong energy dependence of the level of measurability. This traces back to the severe energy dependence of the production process. Note that for an absolute value for the stop three-momentum of around 400 GeV we obtain the best measurability. This corresponds to a center-of-mass energy of roughly 1 TeV for our 344 GeV stop.

Recall that $\mathcal{A}_{l_1}$ requires lepton identification via momentum reconstruction. Thus, another dilution can be caused by the wrong assignment of near and far leptons for the triple product, $\mathcal{T}_{l_1}^{\mp}$. Although the second lepton is correlated via the slepton decay to the neutralino, which determines the momentum of the near lepton, the correlation is much weaker. Consequently the triple product is smaller. The corresponding depletion of our observable can be quantified to around 60 %. However, if we are not able to reconstruct momenta, we are forced to evaluate the triple product in the laboratory frame. As specified above, this already accounts for a dilution by approximately 70 %. Thus without momentum reconstruction, the asymmetry, $\mathcal{A}_{l_1}$, is reduced to roughly 2 % at the maximum and therefore not feasible for our study.

3 Conclusions

We observed that for the chosen scenario the CP violating phase, ϕ_{A_t}, of the trilinear top coupling accounted for a maximal triple product asymmetry of approximately 15.5 %. Under the assumption of successful momentum reconstruction this asymmetry could be measured for 2000 fb^{-1} collected data in the region of a maximal CP violating angle, $1.10\pi < \phi_{A_t} < 1.5\pi$. With an integrated luminosity of 1000 fb^{-1} the asymmetry could still be exposed close to the maximum ($1.18\pi < \phi_{A_t} < 1.33\pi$).

As a conclusion we emphasise that a future linear collider is essential for a precise measurement of the parameters of supersymmetry. However, for the particular scenario studied, it turned out to be challenging to reveal CP-violation with a reasonable amount of data. Nevertheless, other decay chains, *e. g.* via charginos, may result in a higher cross section and hence a better statistical significance.

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