Probing CP Violation with Kinematic Reconstruction at the LHC

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We discuss the potential of observing effects of CP-violation phases in squark decay chains at the LHC [1]. As the CP-odd observable, we use the asymmetry composed by triple products of final state momenta. There are good prospects of observing these effects using the method of kinematic reconstruction for the final and intermediate state particles. We also discuss the main experimental factors and the expected sensitivity.

1 Introduction

The search for Supersymmetry (SUSY) is one of the main goals of present and future colliders since it is one of the best motivated extensions of the Standard Model (SM). An important feature of SUSY models is the possibility of introducing many new sources of CP violation as required to explain baryon asymmetry in the universe. A careful analysis of how to observe new CP-violating effects in future experiments will be required and in the following we discuss the example in the Minimal Supersymmetric Standard Model.

CP-odd observables are the unambiguous way of discovering hints of complex parameters in the underlying theory. One of the examples of such an observable is via exploiting triple product correlations of momenta and/or spins of the final state particles, see [2] for a recent review. They follow from totally antisymmetric expressions

\[ \epsilon_{\mu\nu\rho\sigma} a^\mu b^\nu c^\rho d^\sigma, \]

where \( a, b, c \), and \( d \) are 4-momenta or spins of the particles involved. Such a covariant product can be expanded in terms of the momenta as follows

\[ \epsilon_{\mu\nu\rho\sigma} p_\mu a \cdot (p_\rho c \times p_\sigma d) + E_a \cdot (p_c \times p_d) - E_b \cdot (p_a \times p_d) - E_c \cdot (p_a \times p_b). \]  

As we evaluate only one triple product, we miss the contributions of the other combinations and the asymmetry is diluted. However, if we are in the rest frame of the decaying particle, the momentum components of the four vector vanish and we are now only left with the single triple product that we are interested in:

\[ \epsilon_{\mu\nu\rho\sigma} p_\mu a \cdot (p_c \times p_d) \rightarrow m_a \cdot (p_c \times p_d). \]  

Production of strongly interacting particles will have the largest cross sections at the Large Hadron Collider (LHC). Therefore, in Ref. [1], we studied possible CP-violating effects in squark decay chains

\[ \tilde{q} \rightarrow \chi_2^0 + q \rightarrow \chi_1^0 \ell^+ \ell^- + q. \]  

In the last step of the above decay chain we have the genuine three-body leptonic decay of the neutralino \( \chi_2^0 \). In this decay chain one can construct the \( T_N \)-odd triple product [3] of momenta of the final state particles

\[ T = p_{\ell^+} \cdot (p_{\ell^+} \times p_{\ell^-}). \]  

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Using this triple product one can construct a CP-odd asymmetry

\[ A_T = \frac{N_{T_+} - N_{T_-}}{N_{T_+} + N_{T_-}}, \]  

(5)

where \( N_{T_+} \) (\( N_{T_-} \)) are the numbers of events for which \( T \), Eq. (4), is positive (negative), see also [4]. At the parton level, the asymmetry due to the phase of the bino mass parameter \( M_1 = |M_1|e^{i\phi_1} \) can reach 15% in the neutralino \( \tilde{\chi}^0_2 \) rest frame, cf. Fig. 1. However, due to the internal proton structure, particles produced at the LHC get large, undetermined boosts. As a consequence, the asymmetry is strongly diluted as can be seen in Fig. 2 with the maximum value of \( \sim 2\% \). This makes the observation of CP-violating effects very challenging [5].

We show that the discovery potential can be greatly increased if one can reconstruct momenta of all the particles involved including those escaping detection [1]. We apply this technique to the squark decay chain, Eq. (3), and analyze the possible enhancement of the signal.

## 2 CP asymmetry in the laboratory frame

We start with studying the impact of parton density functions (PDFs) on the asymmetry. We observe a reduction by an order of magnitude in the asymmetry, Eq. (5), compared with the asymmetry in the

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neutralino rest frame, see Fig. 3. This is because in a boosted squark frame the momentum vector of the squark may now flip to the opposite side of the plane formed by $\ell^+$ and $\ell^-$. This changes the sign of the triple product, Eq. (4), causing a significant dilution. The other dilution factor that has to be taken into account are anti-squarks $\tilde{q}^*$. They will be produced along with squarks, however at a much lower rate, what is a consequence of the valence quarks present in the colliding protons \[1\]. As the asymmetries due to $\tilde{q}_L$ and $\tilde{q}^*_L$ have the opposite sign, the asymmetry would vanish if we had equal numbers of both species.

Including the above effects, we end up with a maximum value of $|A_T| = 1.7\%$ for our scenario. Using the total production cross section and the branching ratios for the decay chain, Eq. (3), one can get the expected number of events. Fig. 3 shows the integrated luminosity needed to observe the asymmetry at the $3\sigma$-level. For $L = 100\, fb^{-1}$ a wide range of values for $\phi_1$ can be probed.

### 3 CP asymmetry with momentum reconstruction

As mentioned before the asymmetry has the maximum value in the neutralino rest frame. Therefore, the full reconstruction of kinematics of the underlying process would in principle restore the original value of the asymmetry, cf. \[1\]. However, the squark decay chain itself offers too little kinematical constraints. Hence we consider associated production of squark and gluino in order to perform the reconstruction,

$$pp \rightarrow \tilde{q}_L \tilde{g},$$

where the following gluino decay chain is dominant

$$\tilde{g} \rightarrow \tilde{t}_1 \tilde{t} \rightarrow \tilde{\chi}_1^0 b \ell \rightarrow \tilde{\chi}_1^0 \ell^+ \nu_\ell b \ell.$$  

Again, in the last step we have the three-body leptonic chargino decay, see Fig. 4.

For this process one can formulate 6 on-shell \[5\] conditions for the intermediate particles and the final state LSP from the squark decay chain:

$$m_{\tilde{X}_1}^2 = (P_{\tilde{X}_1})^2,$$
$$m_{\tilde{X}_2}^2 = (P_{\tilde{X}_2} + P_{\ell^+} + P_{\nu_\ell})^2,$$
$$m_{\tilde{q}}^2 = (P_{\tilde{q}})^2,$$
$$m_{\tilde{\chi}_1^0}^2 = (P_{\tilde{\chi}_1^0} + P_{\ell^+} + P_{\nu_\ell})^2,$$
$$m_{\tilde{t}^+_L}^2 = (P_{\tilde{t}^+_L} + P_{\ell^+} + P_{\nu_\ell})^2,$$
$$m_{\tilde{g}}^2 = (P_{\tilde{t}^+} + P_t)^2.$$
Together with two equations involving missing transverse momentum

$$-\vec{p}_{\text{miss}}^T = -\vec{p}_{\tilde{\chi}_0^1}^T + \vec{p}_{\tilde{\chi}_0^1}^T + \vec{p}_{\nu_{\ell}}^T,$$

(9)

this gives 8 equations (6 linear and 2 quadratic). The components of the four-momenta of the invisible final state particles are the 8 unknowns and the system can therefore be solved [1]. In principle one gets up to four real solutions, but there are no additional kinematic constraints to pick the correct solution. Hence, only the events that give the same sign for the triple product, Eq. (4), in all cases, are taken into account. This guarantees that we take the correct sign for the triple product for the calculation of the asymmetry but reduces the number of available events.

The procedure allows one to reconstruct the momenta of the intermediate particles, in particular $\tilde{q}_L$ and $\tilde{\chi}_2^0$. It is now possible to calculate the triple product in the rest frame of the decaying particle, neutralino $\tilde{\chi}_2^0$, and in principle to restore its maximal asymmetry, as shown in Fig. 3b. There is a significant improvement compared to the situation before the reconstruction, cf. Fig. 3, but we still observe dilution due to the anti-squark admixture in the sample.

Finally, we include some of the experimental effects in our analysis. We impose basic selection cuts and momentum smearing due to the finite detector resolution, see Ref. [1] for details. With momentum smearing included, there is a significant number of events where do not obtain the correct rest frame of the neutralino $\tilde{\chi}_2^0$. This results in an increased dilution and a further reduction in the number of usable events. Nevertheless, the asymmetry can be restored to a reasonable value in the observable range, see Fig. 5.

## 4 Conclusions

In [1] we have studied the possibility of observing CP-violating effects in the squark cascade decay chain at the LHC. It was shown that CP-odd observables may be successfully probed by kinematic reconstruction of momenta of the particles involved in the process. Such an measurement at the LHC can directly influence future searches at a linear collider and provide hints of the origin of the matter-antimatter asymmetry of the universe.

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