CP VIOLATION IN THE CHARGINO/NEUTRALINO SECTOR OF THE MSSM* **

Jan Kalinowski, Krzysztof Rolbiecki

Institute of Theoretical Physics, University of Warsaw
Hoża 69, 00-681 Warsaw, Poland

The CP-violating effects in the neutralino sector of the MSSM can be observed in event-counting type experiments, *i.e.* without the need of exploiting variables sensitive to beam or neutralino polarization. On the other hand, such CP-odd effects in the chargino sector can be generated only at the loop level. We contrast the two sectors and present results of full one-loop analysis of the CP-odd asymmetry in the non-diagonal chargino pair production in e^+e^- collisions.

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1. Introduction

Supersymmetry (SUSY) [1], one of the most promising extensions of the Standard Model (SM), introduces many new sources of CP violation that may be needed to explain baryon asymmetry of the universe. Experimental bounds on lepton, neutron and mercury electric dipole moments (EDM) [2] restrict some of the CP phases to be vanishing or require internal cancelations among various contributions [3]. In the absence of any reliable theory of CP violation, however, scenarios with some of the phases large and arranged consistent with experimental EDM data have to be investigated. In such CP-violating scenarios charginos and neutralinos (denoted generically by $\tilde{\chi}$) might be light enough to be copiously produced at hadron and lepton colliders, and thus provide information on CP phases.

Many phenomena will be affected by non-vanishing CP phases: sparticle masses, their decay rates and production cross sections, SUSY contributions to SM processes *etc.* However, most unambiguous way to detect the presence of CP-violating phases would be to study CP-odd observables measurable at future accelerators — the LHC and the ILC. To build a CP-odd observable in a four-fermion process (*e.g.* $e^+e^- \to \tilde{\chi}_i\tilde{\chi}_j$ or $\tilde{\chi}_i \to f\bar{f}'\tilde{\chi}_j$) one typically uses spin information of one of the particles involved. For example, a measurement of the fermion polarization s transverse to the production plane [4] allows one to build a CP-odd observable $s \cdot (p_e \times p_{\tilde{\chi}})$. This requires either transverse beam polarization and/or spin-analyzer of produced $\tilde{\chi}$'s via angular distributions of their decay products [5]. Another possibility is to look into triple products involving momenta of the decay products of charginos/neutralinos [6,7].

However, direct CP sensitive observables can also be constructed from simple event-counting type experiments if several processes are measured. In the neutralino sector, due to their Majorana nature, such a direct CP sensitive observable can be constructed already at tree level [8–11], while in the chargino sector it can be build at one-loop [12,13].

In this contribution we contrast these two sectors and present a CP-odd observable constructed beyond tree level from chargino production cross section without polarized e^+e^- beams or measurement of chargino polarization. The CP asymmetry can be induced by the complex higgsino mass parameter μ or complex trilinear coupling in top squark sector A_t. Since the asymmetry can reach a few percent, it can be detected in simple event-counting experiments at future colliders.

2. CP-violating effects in chargino and neutralino production at tree level

In e^+e^- collisions charginos are produced at tree-level via the s-channel γ, Z exchange and t-channel $\tilde{\nu}_e$ exchange, while the neutralino production receives contributions from the s-channel Z exchange and from both t- and u-channel selectron exchanges.

Due to Poincaré invariance the unpolarized differential cross section may depend only on masses m_i, m_j and on two independent scalar variables s and t. As a result, the unpolarized differential cross-sections for equal-mass fermions $m_i = m_j$ in the final state are always CP-even. However, if the fermion species in the final state are different, beyond tree level the CP-odd asymmetry can be built from the unpolarized cross sections for non-diagonal chargino pair production $\sim \sigma(\tilde{\chi}_1^+\tilde{\chi}_2^-) - \sigma(\tilde{\chi}_2^+\tilde{\chi}_1^-)$ [12], as we will discuss it in the next section. Although the Majorana nature prevents to construct a corresponding CP-asymmetry for neutralinos, this same Majorana nature

opens up a possibility of investigating the CP-violation already at tree level by studying the energy behavior of the cross sections for non-diagonal neutralino pair production near thresholds [8, 9, 11].

In CP-invariant theories, the CP parity of a pair of Majorana fermions $\tilde{\chi}_i^0 \tilde{\chi}_j^0$ produced through a vector or axial vector current with positive intrinsic CP parity is given by

$$1 = \eta^i \eta^j (-1)^L \tag{1}$$

in the non-relativistic limit, where η^i is the CP parity of $\tilde{\chi}_i^0$ and L is the angular momentum [14]. Therefore, in e^+e^- collisions neutralinos with the same CP parities (for example for $i = j$) can be excited only in the P-wave. The S-wave excitation, with the characteristic steep rise $\sim \beta$ (where β is the neutralino c.m. velocity) of the cross section near threshold, can occur only for non-diagonal pairs with opposite CP parities of the produced neutralinos [15].

If, however, CP is violated the angular momentum of the produced neutralino pair is no longer restricted by Eq. (1) and all non-diagonal pairs are excited in the S-wave [8, 9]. This is illustrated in Fig. 1, where the threshold behavior of the neutralino pairs {12}, {13} and {23} for the CP-conserving (left panel) case is contrasted to the CP-violating case (right panel). Even for relatively small CP phase $\Phi_1 = \pi/5$, implying small impact on CP-even quantities, the change in the energy dependence near threshold can be quite dramatic. Thus, observing the $\{ij\}$, $\{ik\}$ and $\{jk\}$ pairs to be excited *all* in S-wave would therefore signal CP violation.
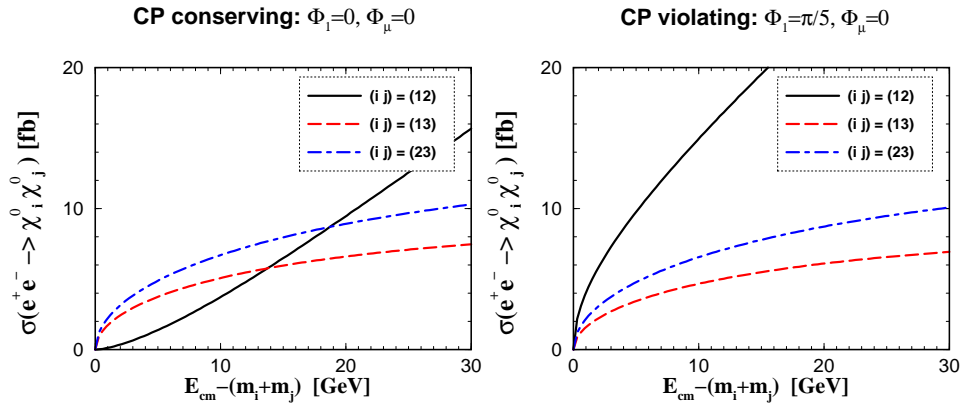

Fig. 1. The threshold behavior of the neutralino production cross-sections $\sigma^{\{ij\}}$ in the CP-conserving (left panel) and the CP-violating (right panel) cases; $\{ij\}$ as indicated in the figure (from [9]).

Similarly the CP violation can be studied by investigating the threshold behavior of the invariant mass distribution of two fermions in the neutralino decay $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 f^+ f^-$ [8]. In the CP-conserving case the decay amplitude satisfies the relation

$$1 = -\eta^i \eta^j (-1)^L \,, \tag{2}$$

in the non-relativistic limit of two neutralinos, where L is the orbital angular momentum of the final state of $\tilde{\chi}_j^0$ and fermion current. The relative minus sign is a consequence of two u-spinors for neutralino current in the decay amplitude as compared to the u- and v-spinors in the production. The immediate consequence of the selection rules (1) and (2) is that, in CP-invariant theories, if the production of a pair of neutralinos with the same (opposite) CP parity is excited slowly in P-wave (steeply in S-wave) in $e^+ e^-$ collisions, then the neutralino to neutralino decay is excited sharply in S-wave (slowly in P-wave). Therefore, the CP violation can clearly be signalled by the simultaneous S-wave excitations of the production of any non-diagonal $\{ij\}$ neutralino pair in $e^+ e^-$ annihilation near threshold and of the fermion invariant mass distribution of the corresponding neutralino 3-body decay near the end point. This is an interesting observation particularly if only the light neutralinos $\tilde{\chi}_{1,2}^0$ among the four neutralino states happen to be kinematically accessible in the initial phase of $e^+ e^-$ linear colliders. The combined analysis of the threshold excitation of the production process, $e^+ e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$, and the fermion invariant mass distribution of the decay, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 f \bar{f}$, near the end point, as seen in Fig. 2, can serve as one of the most powerful probes of CP violation in the neutralino system even in the initial phase of $e^+ e^-$ linear colliders. The lepton invariant mass distribution near the end point in the neutralino decay alone can also be measured at the LHC providing information on the relative CP parities of the two lightest neutralinos.

3. CP-odd asymmetry in chargino production at one loop

As shown in [16], no CP-violation effects can be observed at the tree-level for the non-diagonal $\tilde{\chi}_i^+ \tilde{\chi}_j^-$ chargino pairs without the polarization measurement of final charginos. However the situation is different if we go beyond tree-level approximation.

Radiative corrections to the chargino pair production include the following generic one-loop Feynman diagrams: the virtual vertex corrections, the self-energy corrections to the $\tilde{\nu}$, Z and γ propagators, and the box diagrams contributions. We also have to include corrections on external chargino legs.
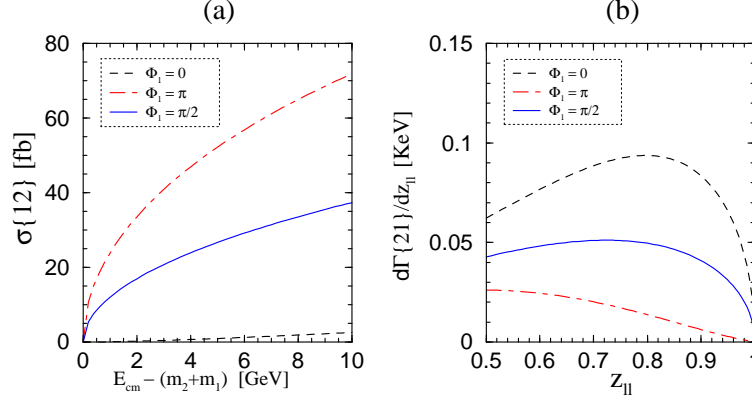
Fig. 2. (a) The threshold behavior of the neutralino production cross sections $\sigma\{12\}$ near the threshold and (b) the lepton invariant mass distribution of the decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \, l^+ l^-$ near the end point (from [10]).

The one-loop CP asymmetry for the non-diagonal chargino pair is defined as

$$A_{12} = \frac{\sigma_{\text{loop}}^{12} - \sigma_{\text{loop}}^{21}}{\sigma_{\text{tree}}^{12} + \sigma_{\text{tree}}^{21}}, \tag{3}$$

where σ^{12}, σ^{21} denote cross sections for production of $\tilde{\chi}_1^+ \tilde{\chi}_2^-$ and $\tilde{\chi}_2^+ \tilde{\chi}_1^-$, respectively. The one-loop corrected matrix element squared is given by

$$|\mathcal{M}_{\text{loop}}|^2 = |\mathcal{M}_{\text{tree}}|^2 + 2\text{Re}(\mathcal{M}_{\text{tree}}^* \mathcal{M}_{\text{loop}}). \tag{4}$$

Since the asymmetry A_{12} vanishes at tree-level it has to be UV finite. Because the structure of counter terms is the same as the tree level graphs, using the same arguments as for the tree-level amplitude it can be shown that renormalization procedure does not give rise to the asymmetry. Nevertheless self-energy and vertex corrections are UV-divergent, and proper treatment of divergences is needed.

Loop diagrams with internal photon line also introduce infrared singularities. They can be removed by adding emission of soft photons from external charged particles. The sum of both contributions is then IR finite, however it depends on the soft photon cut. On the other hand soft photon emission part has the form of tree-level amplitude multiplied by soft photon factor. Therefore, the terms arising due to soft photon bremsstrahlung do not affect the asymmetry A_{12}. Similar arguments apply for hard photon emission from external fermions.

The CP asymmetry Eq. (3) arises due to the interference between complex couplings, which in our case appear in complex mixing matrices of charginos or stops, and non-trivial imaginary part from Feynman diagrams — the absorptive part. Such contributions appear when some of the intermediate state particles in loop diagrams go on-shell. Therefore we take the following scenario: gaugino/higgsino mass parameters $|M_1| = 100$ GeV, $M_2 = 200$ GeV, $|\mu| = 400$ GeV with $\tan\beta = 10$. This gives the following chargino masses: $m_{\tilde{\chi}_1^-} = 186.7$ GeV, $m_{\tilde{\chi}_2^-} = 421.8$ GeV. For the sfermion sector we assume universal slepton mass $M_{\tilde{L}_{1,2,3}} = M_{\tilde{E}_{1,2,3}} = 150$ GeV, while for squarks $m_{\tilde{q}} \equiv M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = 450$ GeV and $M_{\tilde{Q}} \equiv M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 300$ GeV and for the sfermion trilinear coupling: $|A_t| = -A_b = -A_\tau = A = 400$ GeV.

In our numerical analysis we consider the dependence of the asymmetry (3) on the phase of the higgsino mass parameter $\mu = |\mu|e^{i\Phi_\mu}$ and soft trilinear top squark coupling $A_t = |A_t|e^{i\Phi_t}$. In Fig. 3 we show the CP asymmetry as a function of the phase of μ and A_t, left and middle panel, respectively. Contributions due to box corrections, vertex corrections and self energy corrections have been plotted in addition to the full result. In this scenario the asymmetry can reach $\sim 1\%$ for the μ parameter and $\sim 6\%$ for A_t, respectively. We note that for the asymmetry due to the non-zero phase of the higgsino mass parameter there are significant cancelations among various contributions. In addition, we also show in the right panel of Fig. 3 the dependence of the asymmetry due to A_t as a function of $\tan\beta$.
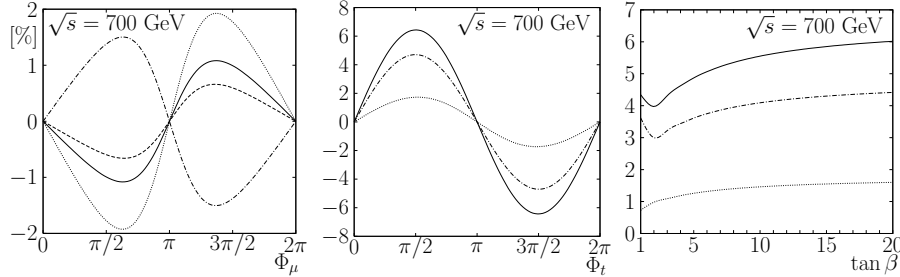

Fig. 3. Asymmetry A_{12} as a function of the phase of μ parameter (left), the phase of A_t (middle), and as a function of $\tan\beta$ with $\Phi_t = \pi/3$ (right). Different lines denote full asymmetry (full line) and contributions from box (dashed), vertex (dotted) and self energy (dash-dotted) diagrams (from [13]).

For the asymmetry generated by the μ parameter all possible one-loop diagrams containing absorptive part contribute. The situation is different for the phase of the trilinear coupling A_t — when chargino mixing matrices remain real. In this case only vertex and self-energy diagrams containing stop lines contribute to the asymmetry [13].

4. Summary

It has been shown that the CP-odd observable can be constructed from unpolarized chargino and neutralino production cross sections alone without polarized beams nor the need of measuring chargino/neutralino polarizations in the final state. While the Majorana nature of neutralinos allows to probe the CP violation via the threshold behavior of the production/decay rate, in the chargino sector the CP-odd asymmetry arises at one-loop and is generated by the interference between complex couplings and absorptive parts of one-loop integrals. The effect is significant for the phases of the higgsino mass parameter μ and the trilinear coupling in the stop sector A_t. At future colliders it may give information about CP violation in chargino and stop sectors.

REFERENCES

[1] H.P. Nilles, *Phys. Rep.* **110**, 1 (1984); H.E. Haber, G.L. Kane, *Phys. Rep.* **117**, 75 (1985).

[2] V. Barger, T. Falk, T. Han, J. Jiang, T. Li, T. Plehn, *Phys. Rev.* **D64**, 056007 (2001) [arXiv:hep-ph/0101106].

[3] T. Ibrahim, P. Nath, arXiv:0705.2008[hep-ph] and references therein.

[4] Y. Kizukuri, N. Oshimo, arXiv:hep-ph/9310224.

[5] G. Moortgat-Pick, H. Fraas, *Phys. Rev.* **D59**, 015016 (1999) [hep-ph/9708481]; G. Moortgat-Pick, H. Fraas, A. Bartl, W. Majerotto, *Eur. Phys. J.* **C9**, 521 (1999); Erratum *Eur. Phys. J.* **C9**, 549 (1999) [hep-ph/9903220]; G. Moortgat-Pick, A. Bartl, H. Fraas, W. Majerotto, *Eur. Phys. J.* **C18**, 379 (2000) [hep-ph/0007222]; S.Y. Choi, H.S. Song, W.Y. Song, *Phys. Rev.* **D61**, 075004 (2000) [hep-ph/9907474].

[6] O. Kittel, A. Bartl, H. Fraas, W. Majerotto, *Phys. Rev.* **D70**, 115005 (2004) [arXiv:hep-ph/0410054].

[7] A. Bartl, K. Hohenwarter-Sodek, T. Kernreiter, O. Kittel, M. Terwort, arXiv:0802.3592[hep-ph].

[8] S.Y. Choi, J. Kalinowski, G.A. Moortgat-Pick, P.M. Zerwas, *Eur. Phys. J.* **C22**, 563 (2001) [arXiv:hep-ph/0108117]; Addendum *Eur. Phys. J.* **C23**, 769 (2002) [arXiv:hep-ph/0202039].

[9] J. Kalinowski, *Acta Phys. Pol. B* **34**, 3441 (2003) [arXiv:hep-ph/0306272].

[10] S.Y. Choi, *Phys. Rev.* **D69**, 096003 (2004) [arXiv:hep-ph/0308060].

[11] S.Y. Choi, B.C. Chung, J. Kalinowski, Y.G. Kim, K. Rolbiecki, *Eur. Phys. J.* **C46**, 511 (2006) [arXiv:hep-ph/0504122].

[12] P. Osland, A. Vereshagin, *Phys. Rev.* **D76**, 036001 (2007) [arXiv:0704.2165[hep-ph]]; P. Osland, J. Kalinowski, K. Rolbiecki, A. Vereshagin, arXiv:0709.3358[hep-ph].

[13] K. Rolbiecki, J. Kalinowski, *Phys. Rev.* **D76**, 115006 (2007) [arXiv:0709.2994[hep-ph]]; *Acta Phys. Pol. B* **38**, 3557 (2007) [arXiv:0710.3318[hep-ph]].

[14] G. Moortgat-Pick, H. Fraas, *Eur. Phys. J.* **C25**, 189 (2002) [arXiv:hep-ph/0204333].

[15] J. Ellis, J.M. Frère, J.S. Hagelin, G.L. Kane, S.T. Petcov, *Phys. Lett.* **B132**, 436 (1983).

[16] S.Y. Choi, A. Djouadi, H.S. Song, P.M. Zerwas, *Eur. Phys. J.* **C8**, 669 (1999) [arXiv:hep-ph/9812236].