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CP violation in chargino production and decay into sneutrino

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Abstract

We study CP odd asymmetries in chargino production $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ and the subsequent two-body decay of one chargino into a sneutrino. We show that in the Minimal Supersymmetric Standard Model with complex parameter μ the asymmetries can reach 30%. We discuss the feasibility of measuring these asymmetries at a linear collider with $\sqrt{s} = 800$ GeV and longitudinally polarized beams.

1. Introduction

In the chargino sector of the Minimal Supersymmetric Standard Model (MSSM) [1] the higgsino mass parameter μ can be complex [2]. It has been shown that in the production of two different charginos, $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$, a CP violating phase φ_μ of μ causes a non-vanishing chargino polarization perpendicular to the production plane [3,4]. This polarization leads at tree level to triple product asymmetries [5–7], which might be large and will allow us to constrain φ_μ at a future e^+e^- linear collider [8]. Usually it is claimed that this phase has to be small for a light supersymmetric (SUSY) particle spectrum due to the experimental upper bounds of the electric dipole moments (EDMs) [9]. However, these restrictions are model dependent [10]. If cancellations among different contributions occur and, for example, if lepton flavor violating phases are present, the EDM restrictions on φ_μ may disappear [11].

We study chargino production

$$e^+ + e^- \to \tilde{\chi}_i^+ + \tilde{\chi}_j^-, \quad i, j = 1, 2, \tag{1}$$

with longitudinally polarized beams and the subsequent two-body decay of one of the charginos into a sneutrino

$$\tilde{\chi}_i^+ \to \ell^+ + \tilde{\nu}_\ell, \quad \ell = e, \mu, \tau. \tag{2}$$

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We define the triple product

$$\mathcal{T}_\ell = (\mathbf{p}_{e^-} \times \mathbf{p}_{\tilde{\chi}_i^+}) \cdot \mathbf{p}_\ell \tag{3}$$

and the T odd asymmetry

$$\mathcal{A}_\ell^{\mathrm{T}} = \frac{\sigma(\mathcal{T}_\ell > 0) - \sigma(\mathcal{T}_\ell < 0)}{\sigma(\mathcal{T}_\ell > 0) + \sigma(\mathcal{T}_\ell < 0)}, \tag{4}$$

of the cross section σ for chargino production (1) and decay (2). The asymmetry $\mathcal{A}_\ell^{\mathrm{T}}$ is not only sensitive to the phase φ_μ, but also to absorptive contributions, which could enter via s-channel resonances or final-state interactions. In order to eliminate the contributions from the absorptive parts, which do not signal CP violation, we will study the CP asymmetry

$$\mathcal{A}_\ell = \frac{1}{2}\left(\mathcal{A}_\ell^{\mathrm{T}} - \bar{\mathcal{A}}_\ell^{\mathrm{T}}\right), \tag{5}$$

where $\bar{\mathcal{A}}_\ell^{\mathrm{T}}$ is the asymmetry for the CP conjugated process $e^+e^- \to \tilde{\chi}_i^- \tilde{\chi}_j^+$; $\tilde{\chi}_i^- \to \ell^- \bar{\tilde{\nu}}_\ell$. In this context it is interesting to note that in chargino production it is not possible to construct a triple product and a corresponding asymmetry by using transversely polarized e^+ and e^- beams [3,12], therefore, one has to rely on the transverse polarization of the produced chargino.

In Section 2 we give our definitions and formalism used, and the analytical formulae for the chargino production and decay cross sections. In Section 3 we discuss some general properties of the CP asymmetries. In Section 4 we present numerical results for $\mathcal{A}_\ell$ and the cross sections. Section 5 gives a summary and conclusions.

2. Definitions and formalism

2.1. Lagrangians and couplings

The MSSM interaction Lagrangians relevant for our study are (in our notation and conventions we follow closely [1,13]):

$$\mathcal{L}_{Z^0\ell\bar{\ell}} = -\frac{g}{\cos\theta_W} Z_\mu \bar{\ell}\gamma^\mu [L_\ell P_L + R_\ell P_R]\ell, \tag{6}$$

$$\mathcal{L}_{Z^0\tilde{\chi}_j^+\tilde{\chi}_i^-} = \frac{g}{\cos\theta_W} Z_\mu \bar{\tilde{\chi}}_i^+ \gamma^\mu \times \left[O_{ij}^{\prime L} P_L + O_{ij}^{\prime R} P_R\right]\tilde{\chi}_j^+, \tag{7}$$

$$\mathcal{L}_{\ell\tilde{\nu}_\ell\tilde{\chi}_i^+} = -g V_{i1}^* \bar{\tilde{\chi}}_i^{+C} P_L \ell \tilde{\nu}_\ell^* + \text{h.c.}, \quad \ell = e, \mu, \tag{8}$$

$$\mathcal{L}_{\tau\tilde{\nu}_\tau\tilde{\chi}_i^+} = -g \bar{\tilde{\chi}}_i^{+C}\left(V_{i1}^* P_L - Y_\tau U_{i2} P_R\right)\tau\tilde{\nu}_\tau^* + \text{h.c.}, \tag{9}$$

with the couplings

$$L_\ell = T_{3\ell} - e_\ell \sin^2\theta_W, \qquad R_\ell = -e_\ell \sin^2\theta_W, \tag{10}$$

$$O_{ij}^{\prime L} = -V_{i1}V_{j1}^* - \frac{1}{2}V_{i2}V_{j2}^* + \delta_{ij}\sin^2\theta_W, \tag{11}$$

$$O_{ij}^{\prime R} = -U_{i1}^*U_{j1} - \frac{1}{2}U_{i2}^*U_{j2} + \delta_{ij}\sin^2\theta_W, \tag{12}$$

with $i, j = 1, 2$. Here $P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$, $g = e/\sin\theta_W$ is the weak coupling constant, and e_ℓ and $T_{3\ell}$ denote the charge and the third component of the weak isospin of the lepton ℓ. The τ-Yukawa coupling is given by $Y_\tau = m_\tau/(\sqrt{2}m_W\cos\beta)$ with $\tan\beta = v_2/v_1$, where $v_{1,2}$ are the vacuum expectation values of the two neutral Higgs fields. The chargino mass eigenstates $\tilde{\chi}_i^+ = \binom{\chi_i^+}{\bar{\chi}_i^-}$ are defined by $\chi_i^+ = V_{i1}w^+ + V_{i2}h^+$ and $\chi_j^- = U_{j1}w^- + U_{j2}h^-$ with $w^\pm$ and $h^\pm$ the two-component spinor fields of the Wino and the charged higgsinos, respectively. The complex unitary 2×2 matrices U_{mn} and V_{mn} diagonalize the chargino mass matrix $X_{\alpha\beta}$, $U_{m\alpha}^* X_{\alpha\beta} V_{\beta n}^{-1} = m_{\tilde{\chi}_n^+}\delta_{mn}$, with $m_{\tilde{\chi}_n^+} > 0$.

2.2. Cross section

We choose a coordinate frame such that in the laboratory system the four-momenta are

$$p_{e^-}^\mu = E_b(1, -\sin\theta, 0, \cos\theta),$$
$$p_{e^+}^\mu = E_b(1, \sin\theta, 0, -\cos\theta), \tag{13}$$

$$p_{\tilde{\chi}_i^+}^\mu = (E_{\tilde{\chi}_i^+}, 0, 0, -q),$$
$$p_{\tilde{\chi}_j^-}^\mu = (E_{\tilde{\chi}_j^-}, 0, 0, q), \tag{14}$$

with the beam energy $E_b = \sqrt{s}/2$, the scattering angle $\theta\angle(\mathbf{p}_{e^-}, \mathbf{p}_{\tilde{\chi}_j^-})$ and the azimuth ϕ is chosen zero. For the description of the polarization of chargino $\tilde{\chi}_i^+$ we choose three spin vectors in the laboratory system

$$s_{\tilde{\chi}_i^+}^{1,\mu} = (0, -1, 0, 0), \qquad s_{\tilde{\chi}_i^+}^{2,\mu} = (0, 0, 1, 0),$$
$$s_{\tilde{\chi}_i^+}^{3,\mu} = \frac{1}{m_{\tilde{\chi}_i^+}}(q, 0, 0, -E_{\tilde{\chi}_i^+}). \tag{15}$$

Together with $p_{\tilde{\chi}_i^+}^\mu / m_{\tilde{\chi}_i^+}$ they form an orthonormal set.

For the calculation of the cross section for the combined process of chargino production (1) and the subsequent two-body decay of $\tilde{\chi}_i^+$ (2), we use the spin-density matrix formalism as in [13,14]. The amplitude squared,

$$|T|^2 = \left|\Delta(\tilde{\chi}_i^+)\right|^2 \sum_{\lambda_i,\lambda_i'} \rho_P(\tilde{\chi}_i^+)^{\lambda_i\lambda_i'} \rho_D(\tilde{\chi}_i^+)_{\lambda_i'\lambda_i}, \tag{16}$$

is composed of the (unnormalized) spin-density production matrix $\rho_P(\tilde{\chi}_i^+)$, the decay matrix $\rho_D(\tilde{\chi}_i^+)$, with the helicity indices λ_i and λ_i' of the chargino and the propagator $\Delta(\tilde{\chi}_i^+) = i/[p^2_{\tilde{\chi}_i^+} - m^2_{\tilde{\chi}_i^+} + i m_{\tilde{\chi}_i^+}\Gamma_{\tilde{\chi}_i^+}]$. The production matrix $\rho_P(\tilde{\chi}_i^+)$ can be expanded in terms of the Pauli matrices σ^a, $a = 1, 2, 3$

$$\rho_P(\tilde{\chi}_i^+)^{\lambda_i\lambda_i'} = 2\left(\delta_{\lambda_i\lambda_i'} P + \sum_a \sigma^a_{\lambda_i\lambda_i'} \Sigma^a_P\right). \tag{17}$$

With our choice of the spin vectors $s^a_{\tilde{\chi}_i^+}$ (15), Σ^3_P/P is the longitudinal polarization of $\tilde{\chi}_i^+$ in the laboratory system, Σ^1_P/P is the transverse polarization in the production plane and Σ^2_P/P is the polarization perpendicular to the production plane. The analytical formulae for the expansion coefficients P and Σ^a_P are given in [13]. The coefficient Σ^2_P is non-zero only for production of an unequal pair of charginos, $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$, and obtains contributions from Z-exchange and Z–$\tilde{\nu}$ interference only [13]:

$$\Sigma^2_P = \Sigma^2_P(ZZ) + \Sigma^2_P(Z\tilde{\nu}), \tag{18}$$

with

$$\Sigma^2_P(ZZ) = 2\frac{g^4}{\cos^4\theta_W}\left|\Delta(Z)\right|^2\left(c_R^{ZZ} - c_L^{ZZ}\right) \times \mathrm{Im}\left\{O'^L_{ij} O'^{R*}_{ij}\right\} E_b^2 m_{\tilde{\chi}_j^-} q \sin\theta, \tag{19}$$

$$\Sigma^2_P(Z\tilde{\nu}) = \frac{g^4}{\cos^2\theta_W} c_L^{Z\tilde{\nu}}\, \mathrm{Im}\left\{V^*_{i1} V_{j1} O'^R_{ij} \Delta(Z)\Delta(\tilde{\nu})^*\right\} \times E_b^2 m_{\tilde{\chi}_j^-} q \sin\theta. \tag{20}$$

The propagators are defined by

$$\Delta(Z) = \frac{i}{p_Z^2 - m_Z^2 + i m_Z \Gamma_Z}, \qquad \Delta(\tilde{\nu}) = \frac{i}{p_{\tilde{\nu}}^2 - m_{\tilde{\nu}}^2}, \tag{21}$$

and the longitudinal electron and positron beam polarizations, P_{e^-} and P_{e^+}, respectively, are included in the coefficients

$$c_L^{ZZ} = L_e^2(1 - P_{e^-})(1 + P_{e^+}), \qquad c_R^{ZZ} = R_e^2(1 + P_{e^-})(1 - P_{e^+}), \tag{22}$$

$$c_L^{Z\tilde{\nu}} = L_e(1 - P_{e^-})(1 + P_{e^+}). \tag{23}$$

The contribution (19) from Z-exchange is non-zero only for $\varphi_\mu \neq 0, \pi$, whereas the Z–$\tilde{\nu}$ interference term (20), obtains also absorptive contributions due to the finite Z-width which do not signal CP violation. These, however, will be eliminated in the asymmetry $\mathcal{A}_\ell$ (5).

Analogously to the production matrix, the chargino decay matrix can be written as

$$\rho_D(\tilde{\chi}_i^+)_{\lambda_i'\lambda_i} = \delta_{\lambda_i'\lambda_i} D + \sum_a \sigma^a_{\lambda_i'\lambda_i} \Sigma^a_D. \tag{24}$$

For the chargino decay (2) into an electron or muon sneutrino the coefficients are

$$D = \frac{g^2}{2}|V_{i1}|^2\left(m^2_{\tilde{\chi}_i^+} - m^2_{\tilde{\nu}_\ell}\right), \qquad \Sigma^a_D = \underset{(+)}{-} g^2|V_{i1}|^2 m_{\tilde{\chi}_i^+}\left(s^a_{\tilde{\chi}_i^+} \cdot p_\ell\right), \quad \text{for } \ell = e, \mu, \tag{25}$$

where the sign in parenthesis holds for the conjugated process $\tilde{\chi}_i^- \to \ell^- \bar{\tilde{\nu}}_\ell$. For the decay into the tau sneutrino the coefficients are given by

$$D = \frac{g^2}{2}\left(|V_{i1}|^2 + Y_\tau^2|U_{i2}|^2\right)\left(m^2_{\tilde{\chi}_i^+} - m^2_{\tilde{\nu}_\tau}\right), \qquad \Sigma^a_D = \underset{(+)}{-} g^2\left(|V_{i1}|^2 - Y_\tau^2|U_{i2}|^2\right) m_{\tilde{\chi}_i^+}\left(s^a_{\tilde{\chi}_i^+} \cdot p_\tau\right), \tag{26}$$

where the sign in parenthesis holds for the conjugated process $\tilde{\chi}_i^- \to \tau^- \bar{\tilde{\nu}}_\tau$.

Inserting the density matrices (17) and (24) in (16) leads to

$$|T|^2 = 4\left|\Delta(\tilde{\chi}_i^+)\right|^2\left(PD + \sum_a \Sigma^a_P \Sigma^a_D\right). \tag{27}$$

The cross section and distributions in the laboratory system are then obtained by integrating $|T|^2$ over the Lorentz invariant phase space element,

$$d\sigma = \frac{1}{2s}|T|^2\, d\,\mathrm{Lips}, \tag{28}$$

where we use the narrow width approximation for the chargino propagator.

3. CP asymmetries

Inserting the cross section (28) in the definition of the asymmetry (4) we obtain:

$$\mathcal{A}_\ell^{\mathrm{T}} = \frac{\int \mathrm{Sign}[\mathcal{T}_\ell]|T|^2\, d\,\mathrm{Lips}}{\int |T|^2\, d\,\mathrm{Lips}} = \frac{\int \mathrm{Sign}[\mathcal{T}_\ell]\Sigma_P^2 \Sigma_D^2\, d\,\mathrm{Lips}}{\int P D\, d\,\mathrm{Lips}}. \qquad (29)$$

In the numerator only the CP sensitive contribution $\Sigma_P^2 \Sigma_D^2$ from chargino polarization perpendicular to the production plane remains, since only this term contains the triple product $\mathcal{T}_\ell = (\mathbf{p}_{e^-} \times \mathbf{p}_{\tilde{\chi}_i^+}) \cdot \mathbf{p}_\ell$ (3). In the denominator only the term PD remains, since all spin correlations $\sum_a \Sigma_P^a \Sigma_D^a$ vanish due to the integration over the complete phase space. For chargino decay into a tau sneutrino, $\tilde{\chi}_i^+ \to \tau^+ \tilde{\nu}_\tau$, the asymmetry $\mathcal{A}_\tau^{\mathrm{T}} \propto (|V_{i1}|^2 - Y_\tau^2 |U_{i2}|^2)/(|V_{i1}|^2 + Y_\tau^2 |U_{i2}|^2)$ is reduced, which follows from the expressions for D and Σ_D^2, given in (26).

The relative statistical error of the asymmetry $\mathcal{A}_\ell^{\mathrm{T}}$ is $\delta \mathcal{A}_\ell^{\mathrm{T}} = \Delta \mathcal{A}_\ell^{\mathrm{T}} / |\mathcal{A}_\ell^{\mathrm{T}}| = 1/(|\mathcal{A}_\ell^{\mathrm{T}}|\sqrt{N})$, where N is the number of events. For the CP asymmetry $\mathcal{A}_\ell$, defined in (5), we have $\Delta \mathcal{A}_\ell = \Delta \mathcal{A}_\ell^{\mathrm{T}}/\sqrt{2}$. The statistical significance, with which a CP asymmetry can be measured, is then given by $S_\ell = |\mathcal{A}_\ell|\sqrt{2N}$. Note that in order to measure $\mathcal{A}_\ell$ in the reaction (1) the momentum of $\tilde{\chi}_i^+$, i.e., the production plane, has to be determined. This can be done if the corresponding information from the decay of the other chargino $\tilde{\chi}_j^-$ on the opposite side is also available. This is the case if, for example, the $\tilde{\chi}_j^-$ decays like $\tilde{\chi}_j^- \to \tilde{\chi}_1^- Z^0$, $\tilde{\chi}_j^- \to \tilde{\chi}_1^0 W^-$ or $\tilde{\chi}_j^- \to \tilde{\chi}_1^- H_1^0$ and Z, W, H_1^0 decay hadronically, $Z^0 \to q\bar{q}$, $W^- \to q\bar{q}'$, $H_1^0 \to b\bar{b}$. If the masses of the charginos and $\tilde{\nu}_\ell$ as well as the masses of H_1^0 and $\tilde{\chi}_1^0$ are known, then the momentum $\mathbf{p}_{\chi_j^-}$ can be kinematically reconstructed. This is also possible if the leptonic decays $Z^0 \to \ell^+\ell^-$, $H_1^0 \to \tau^+\tau^-$ or $\tilde{\chi}_j^- \to \ell^- \bar{\tilde{\nu}}_\ell$ are used. In order to predict the expected accuracy of measuring $\mathcal{A}_\ell$, it is clear that also detailed Monte Carlo studies taking into account background and detector simulations are necessary. However, this is beyond the scope of the present work.

4. Numerical results

We present numerical results for the asymmetries $\mathcal{A}_\ell$ (5), for $\ell = e, \mu$ and the cross sections $\sigma = \sigma_P(e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_2^-) \times \mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+ \tilde{\nu}_\ell)$. We study the dependence of the asymmetries and cross sections on the MSSM parameters $\mu = |\mu| e^{i\varphi_\mu}$, M_2 and $\tan\beta$. We choose a center of mass energy of $\sqrt{s} = 800$ GeV and longitudinally polarized beams with beam polarizations $(P_{e^-}, P_{e^+}) = (-0.8, +0.6)$, which enhance $\tilde{\nu}_e$ exchange in the production process. This results in larger cross sections and asymmetries.

We study the decays of the lighter chargino $\tilde{\chi}_1^+$. For the calculation of the chargino widths $\Gamma_{\tilde{\chi}_1^+}$ and the branching ratios $\mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+ \tilde{\nu}_\ell)$ we include the following two-body decays,

$$\tilde{\chi}_1^+ \to W^+ \tilde{\chi}_n^0,\ e^+ \tilde{\nu}_e,\ \mu^+ \tilde{\nu}_\mu,\ \tau^+ \tilde{\nu}_\tau,\ \tilde{e}_L^+ \nu_e,\ \tilde{\mu}_L^+ \nu_\mu,\ \tilde{\tau}_{1,2}^+ \nu_\tau, \qquad (30)$$

and neglect three-body decays. The Higgs parameter is chosen $m_A = 1$ TeV and thus the decays into the charged Higgs bosons $\tilde{\chi}_i^\pm \to H^\pm \tilde{\chi}_n^0$ are forbidden in our scenarios. In order to reduce the number of parameters, we assume the relation $|M_1| = 5/3\, M_2 \tan^2\theta_W$. For all scenarios we fix the sneutrino and slepton masses, $m_{\tilde{\nu}_\ell} = 185$ GeV, $\ell = e, \mu, \tau$, $m_{\tilde{\ell}_L} = 200$ GeV, $\ell = e, \mu$. These values are obtained from the renormalization group equations [15], $m_{\tilde{\ell}_L}^2 = m_0^2 + 0.79 M_2^2 + m_Z^2 \cos 2\beta(-1/2 + \sin^2\theta_W)$ and $m_{\tilde{\nu}_\ell}^2 = m_0^2 + 0.79 M_2^2 + m_Z^2/2 \cos 2\beta$, for $M_2 = 200$ GeV, $m_0 = 80$ GeV and $\tan\beta = 5$. In the stau sector [16] we fix the trilinear scalar coupling parameter to $A_\tau = 250$ GeV. The stau masses are fixed to $m_{\tilde{\tau}_1} = 129$ GeV and $m_{\tilde{\tau}_2} = 202$ GeV.

In Fig. 1(a) we show the contour lines of the cross section for chargino production and decay $\sigma = \sigma_P(e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_2^-) \times \mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+ \tilde{\nu}_\ell) \times \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^- \text{ or } \tilde{\chi}_1^0 + \text{had.})$ in the M_2–φ_μ plane for $|\mu| = 400$ GeV and $\tan\beta = 5$. We calculate the $\tilde{\chi}_2^-$ branching ratio as $\mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^- \text{ or } \tilde{\chi}_1^0 + \text{had.}) = \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^- Z^0)\,\mathrm{BR}(Z^0 \to q\bar{q}) + \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-) \times \mathrm{BR}(W^- \to q\bar{q}') + \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^- H_1^0)\,\mathrm{BR}(H_1^0 \to b\bar{b})$ with $\mathrm{BR}(Z^0 \to q\bar{q}) \approx \mathrm{BR}(W^+ \to q\bar{q}') \approx 0.7$, $\mathrm{BR}(H_1^0 \to b\bar{b}) \approx 0.85$, which gives a lower bound on the total hadronic $\tilde{\chi}_2^-$ branching ratio. The production cross section $\sigma_P(e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_2^-)$ can attain values

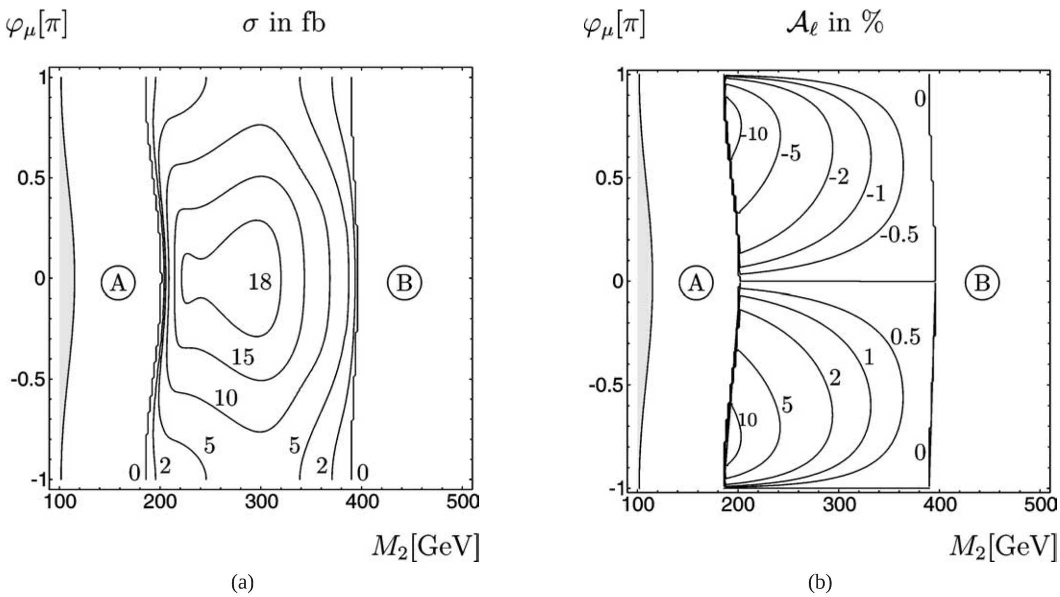

Fig. 1. Contour lines of $\sigma = \sigma_P(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) \times \mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell) \times \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 + \mathrm{had.})$, summed over $\ell = e, \mu$ (a), and the asymmetry $\mathcal{A}_\ell$ for $\ell = e$ or μ (b), in the M_2–φ_μ plane for $|\mu| = 400$ GeV, $\tan\beta = 5$, $m_{\tilde{\nu}_\ell} = 185$ GeV, $\sqrt{s} = 800$ GeV and $(P_{e^-}, P_{e^+}) = (-0.8, 0.6)$. The gray area is excluded by $m_{\tilde{\chi}_1^\pm} < 104$ GeV. The area A is kinematically forbidden by $m_{\tilde{\nu}_\ell} + m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^+}$. The area B is kinematically forbidden by $m_{\tilde{\chi}_1^+} + m_{\tilde{\chi}_2^-} > \sqrt{s}$.

from 10 fb to 150 fb and $\mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell)$, summed over $\ell = e, \mu$, can be as large as 50%. The branching ratio of $\tilde{\chi}_2^-$ decays $\mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 + \mathrm{had.})$ is of the order of 60% (25%) for $M_2 \approx 200$ GeV (350 GeV). The cross section σ plotted in Fig. 1(a) is in fact a conservative lower bound on that cross section which effectively enters in the determination of $\mathcal{A}_\ell$. It may be higher if also the leptonic decays $\tilde{\chi}_2^- \to \ell^-\tilde{\nu}_\ell$ etc. are taken into account. Note that the cross section is very sensitive to φ_μ, which has been exploited in [3,4] to constrain $\cos(\varphi_\mu)$.

The M_2–φ_μ dependence of the CP asymmetry $\mathcal{A}_\ell$ for $\ell = e$ or μ is shown in Fig. 1(b). The asymmetry can be as large as 10% and it does, however, not attain maximal values for $\varphi_\mu = 0.5\,\pi$, which one would naively expect. The reason is that $\mathcal{A}_\ell$ is proportional to a product of a CP odd (Σ_P^2) and a CP even factor (Σ_D^2), see (29). The CP odd (CP even) factor has as sine-like (cosine-like) dependence on φ_μ. Thus the maximum of $\mathcal{A}_\ell$ is shifted towards $\varphi_\mu = \pm\pi$ in Fig. 1(b). Phases close to the CP conserving points, $\varphi_\mu = 0, \pm\pi$, are favored by the experimental upper limits on the EDMs. For example, in the constrained MSSM, we have $|\varphi_\mu| \lesssim \pi/10$ [9]. However, the restrictions are very model dependent, e.g., if also lepton flavor violating terms are included [11], the restrictions may disappear. In order to show the full phase dependence of the asymmetries, we have relaxed the EDM restrictions for this purpose.

For $M_2 = 200$ GeV, we show the $\tan\beta$–φ_μ dependence of σ and $\mathcal{A}_\ell$ in Figs. 2(a), (b). The asymmetry can reach values up to 30% and shows a strong $\tan\beta$ dependence and decreases with increasing $\tan\beta$. The feasibility of measuring the asymmetry depends also on the cross section $\sigma = \sigma_P(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) \times \mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell) \times \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 +$ had.), Fig. 2(a), which attains values up to 15 fb and $\mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 + \mathrm{had.}) \approx 55$–65%.

For the phase $\varphi_\mu = 0.9\,\pi$ and $\tan\beta = 5$, we study the beam polarization dependence of $\mathcal{A}_\ell$, which can be strong as shown in Fig. 3(a). An electron beam polarization $P_{e^-} > 0$ and a positron beam polarization $P_{e^+} < 0$ enhance the channels with $\tilde{\nu}_e$ exchange in the chargino production process. For, e.g., $(P_{e^-}, P_{e^+}) = (-0.8, 0.6)$ the asymmetry can attain -7%, Fig. 3(a), with $\sigma_P(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) \approx 10$ fb and $\mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell) \approx 50$%, summed over $\ell = e, \mu$. The cross section $\sigma = \sigma_P(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) \times \mathrm{BR}(\tilde{\chi}_1^+ \to$

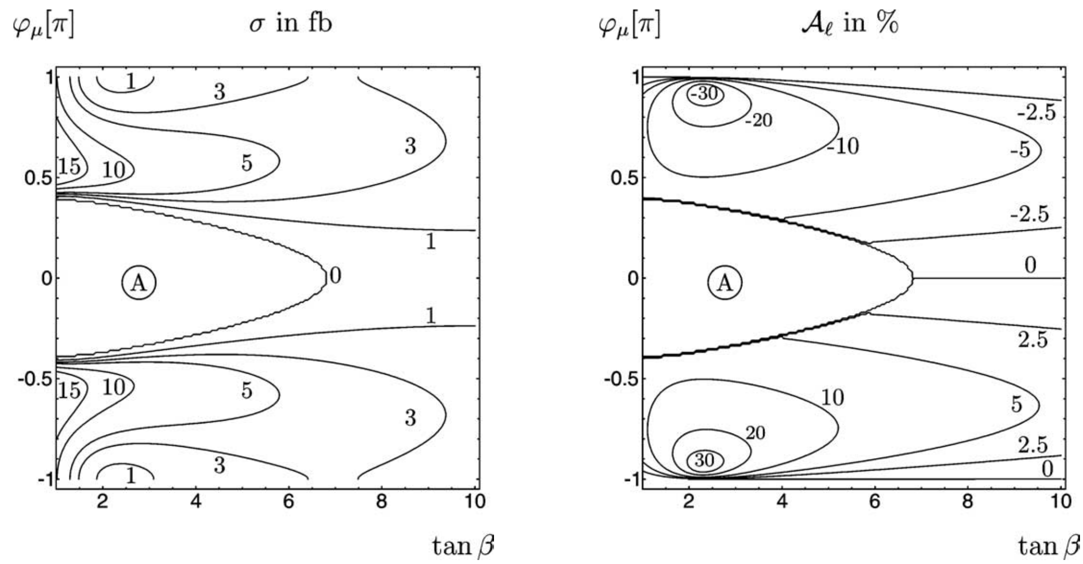

Fig. 2. Contour lines of $\sigma = \sigma_P(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) \times \mathrm{BR}(\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell) \times \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 + \text{had.})$, summed over $\ell = e, \mu$, (a), and the asymmetry $\mathcal{A}_\ell$ for $\ell = e$ or μ (b), in the $\tan\beta$–φ_μ plane for $M_2 = 200$ GeV, $|\mu| = 400$ GeV, $m_{\tilde{\nu}_\ell} = 185$ GeV, $\sqrt{s} = 800$ GeV and $(P_{e^-}, P_{e^+}) = (-0.8, 0.6)$. The area A is kinematically forbidden by $m_{\tilde{\nu}_\ell} + m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^+}$.

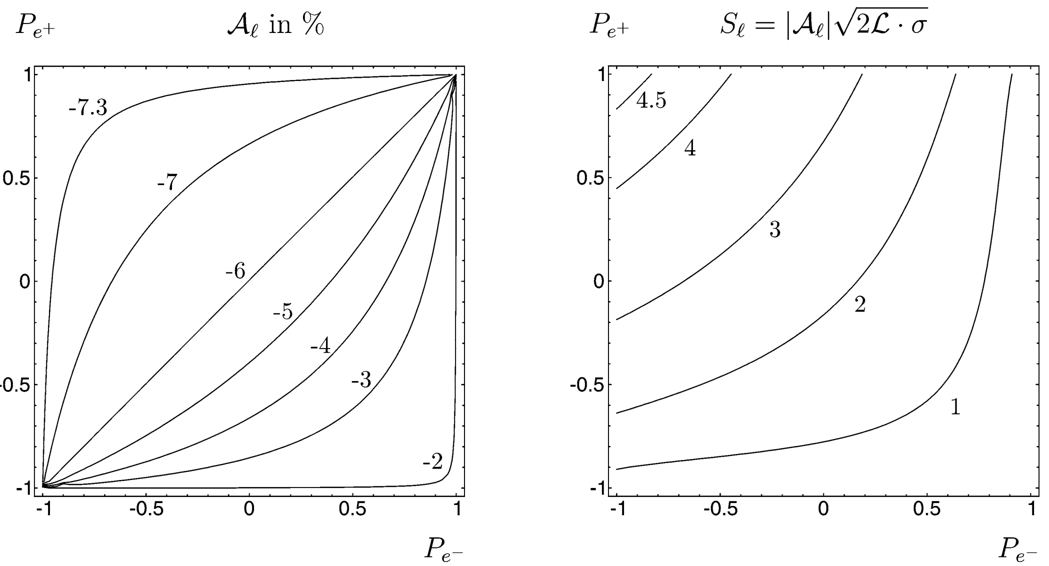

Fig. 3. Contour lines of the asymmetry $\mathcal{A}_\ell$ for $\ell = e$ or μ (a), and the significance S_ℓ (b), for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-$; $\tilde{\chi}_1^+ \to \ell^+\tilde{\nu}_\ell$; $\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0$ + had., in the $(P_{e^-}$–$P_{e^+})$-plane for $\varphi_\mu = 0.9\,\pi$, taking $|\mu| = 400$ GeV, $M_2 = 200$ GeV, $\tan\beta = 5$, $m_{\tilde{\nu}_\ell} = 185$ GeV, $\sqrt{s} = 800$ GeV and $\mathcal{L} = 500\ \mathrm{fb}^{-1}$.

$\ell^+\tilde{\nu}_\ell) \times \mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 + \mathrm{had.})$ with $\mathrm{BR}(\tilde{\chi}_2^- \to \tilde{\chi}_1^-$ or $\tilde{\chi}_1^0 + \mathrm{had.}) = 60\%$ ranges between 1.4 fb for $(P_{e^-}, P_{e^+}) = (0,0)$ and 4.1 fb for $(P_{e^-}, P_{e^+}) = (-1, 1)$. The statistical significance $S_\ell = |\mathcal{A}_\ell|\sqrt{2\mathcal{L}\cdot\sigma}$ is shown in Fig. 3(b) for $\mathcal{L} = 500\ \mathrm{fb}^{-1}$. We have $S_\ell \approx 4$ for $(P_{e^-}, P_{e^+}) = (-0.8, 0.6)$, and thus $\mathcal{A}_\ell$ could be accessible at a linear collider, even for $\varphi_\mu = 0.9\,\pi$, by using polarized beams.

5. Summary and conclusions

We have studied CP violation in chargino production with longitudinally polarized beams, $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$, and subsequent two-body decay of one chargino into the sneutrino $\tilde{\chi}_i^+ \to \ell^+\tilde{\nu}_\ell$. We have defined the T odd asymmetries $\mathcal{A}_\ell^{\mathrm{T}}$ of the triple product $(\mathbf{p}_{e^-} \times \mathbf{p}_{\tilde{\chi}_i^+})\cdot\mathbf{p}_\ell$. The CP odd asymmetries $\mathcal{A}_\ell = \frac{1}{2}(\mathcal{A}_\ell^{\mathrm{T}} - \bar{\mathcal{A}}_\ell^{\mathrm{T}})$, where $\bar{\mathcal{A}}_\ell^{\mathrm{T}}$ denote the CP conjugated of $\mathcal{A}_\ell^{\mathrm{T}}$, are sensitive to the phase φ_μ of the higgsino mass parameter μ. At tree level, the asymmetries have large CP sensitive contributions from spin correlation effects in the production of an unequal pair of charginos. In a numerical discussion for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-$ production, we have found that $\mathcal{A}_\ell$ for $\ell = e$ or μ can attain values up to 30%. By analyzing the statistical errors, we have shown that, even for, e.g., $\varphi_\mu \approx 0.9\,\pi$, the asymmetries could be accessible in future e^+e^- collider experiments in the 800 GeV range with high luminosity and longitudinally polarized beams.

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