CP violation in chargino production at the one-loop level

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Outline

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Motivation

- radiative corrections in MSSM could be of order 10%
- so far only CP-conserving case at one loop thoroughly examined
- MSSM with CP violating phases:
  $M_1 = |M_1| e^{i\Phi_1}$, $\mu = |\mu| e^{i\Phi_\mu}$, $A_f = |A_f| e^{i\Phi_f}$
  - $\longrightarrow$ strong bounds on these phases from EDMs exist, however
  - $\longrightarrow$ large phases possible if accidental cancelations occur
  - $\longrightarrow$ or 1st and 2nd generation of squarks are heavy
  - $\longrightarrow$ Φ_1 poorly constrained
- calculation of radiative corrections to CP violating observables, e.g. asymmetries in sparticles production, asymmetries of triple products of momenta and/or spins, asymmetries in decay widths
  - $\longrightarrow$ such observables provide unambiguous way of detecting CP violating phases
- here we analyze gaugino/higgsino sector of complex MSSM at one loop level

Chargino sector of MSSM

- chargino mass matrix in gauge eigenstate basis $(\tilde{W}^-, \tilde{H}^-)$

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2} m_W \cos\beta \\ \sqrt{2} m_W \sin\beta & \mu \end{pmatrix}$$

- diagonalization using unitary matrices U and V

$$V^* M_{\tilde{\chi}^\pm} U^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

- mass eigenstates in Weyl representation

$$U \begin{pmatrix} \tilde{W}_L^- \\ \tilde{H}_d^- \end{pmatrix} = \begin{pmatrix} \chi_{1L}^- \\ \chi_{2L}^- \end{pmatrix} \quad V \begin{pmatrix} \tilde{W}_R^+ \\ \tilde{H}_u^+ \end{pmatrix} = \begin{pmatrix} \chi_{1R}^+ \\ \chi_{2R}^+ \end{pmatrix}$$

- Dirac spinors

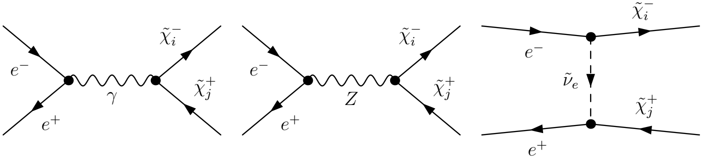
$$\tilde{\chi}_1^- = \begin{pmatrix} \chi_{1L}^- \\ \overline{\chi}_{1R}^- \end{pmatrix}, \quad \tilde{\chi}_2^- = \begin{pmatrix} \chi_{2L}^- \\ \overline{\chi}_{2R}^- \end{pmatrix}$$

Outline

1. Introduction
2. Chargino production at tree-level
3. Loop corrections to chargino production
4. Numerical results
5. Summary

Production mechanism

- chargino production at the tree-level in e^+e^- collisions



- for non-diagonal pair $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ no contribution from photon exchange
- production amplitude after Fierz transformation

$$\mathcal{A}[e^+e^- \to \tilde{\chi}_i^- \tilde{\chi}_j^+] = \frac{e^2}{s} Q^{ij}_{\alpha\beta} \Big(\bar{v}(e^+)\gamma_\mu P_\alpha u(e^-)\Big) \Big(\bar{u}(\tilde{\chi}_i^-)\gamma^\mu P_\beta v(\tilde{\chi}_j^+)\Big)$$

- four bilinear couplings Q_{LL}, Q_{RL}, Q_{LR}, Q_{RR} depend on mixing angles of matrices U, V

Amplitude structure

- unpolarized differential cross-section

$$\frac{d\sigma^{\{ij\}}}{d\cos\theta\, d\phi} = \frac{\alpha^2}{4s}\lambda^{1/2}\Big((1-(\mu_i^2-\mu_j^2)^2+\lambda\cos^2\theta)Q_1+4\mu_i\mu_j Q_2+2\lambda^{1/2}Q_3\cos\theta\Big)$$

P	CP	Quartic charges
even	even	$Q_1 = \frac{1}{4}\left(\lvert Q_{RR}\rvert^2+\lvert Q_{LL}\rvert^2+\lvert Q_{RL}\rvert^2+\lvert Q_{LR}\rvert^2\right)$ $Q_2 = \frac{1}{2}\mathrm{Re}\left(Q_{RR}Q_{RL}^*+Q_{LL}Q_{LR}^*\right)$ $Q_3 = \frac{1}{4}\left(\lvert Q_{RR}\rvert^2+\lvert Q_{LL}\rvert^2-\lvert Q_{RL}\rvert^2-\lvert Q_{LR}\rvert^2\right)$
	odd	$Q_4 = \frac{1}{2}\mathrm{Im}\left(Q_{RR}Q_{RL}^*+Q_{LL}Q_{LR}^*\right)$

- Q_4 can be probed by observables sensitive to chargino polarization component normal to the production plane

CP transformation in chargino production

- S matrix element for chargino production

$$\langle\tilde{\chi}_i^+(\mathbf{k}_1),\tilde{\chi}_j^-(\mathbf{k}_2)|S|e^+(\mathbf{p}_1),e^-(\mathbf{p}_2)\rangle$$

- P transformation: $\mathbf{p}_{1,2}\leftrightarrow-\mathbf{p}_{1,2}$, $\mathbf{k}_{1,2}\leftrightarrow-\mathbf{k}_{1,2}$

$$\langle\tilde{\chi}_i^+(-\mathbf{k}_1),\tilde{\chi}_j^-(-\mathbf{k}_2)|S|e^+(-\mathbf{p}_1),e^-(-\mathbf{p}_2)\rangle$$

- C transformation

$$\langle\tilde{\chi}_i^-(\mathbf{k}_1),\tilde{\chi}_j^+(\mathbf{k}_2)|S|e^-(\mathbf{p}_1),e^+(\mathbf{p}_2)\rangle$$

- CP transformation

$$\langle\tilde{\chi}_j^+(-\mathbf{k}_2),\tilde{\chi}_i^-(-\mathbf{k}_1)|S|e^+(-\mathbf{p}_2),e^-(-\mathbf{p}_1)\rangle$$

- in center of mass frame: $\mathbf{p}_1=-\mathbf{p}_2$ and $\mathbf{k}_1=-\mathbf{k}_2$

$$\langle\tilde{\chi}_j^+(\mathbf{k}_1),\tilde{\chi}_i^-(\mathbf{k}_2)|S|e^+(\mathbf{p}_1),e^-(\mathbf{p}_2)\rangle$$

- no CP violation in diagonal chargino final states $\tilde{\chi}_1^-\tilde{\chi}_1^+$, $\tilde{\chi}_2^-\tilde{\chi}_2^+$
- at tree level for non-diagonal chargino pair production

$$\sigma(\tilde{\chi}_1^-\tilde{\chi}_2^+)-\sigma(\tilde{\chi}_1^+\tilde{\chi}_2^-)=0$$

CP-odd observables

- CP violating effects can be probed by observables sensitive to the chargino polarization component normal to the production plane

  [Choi ea.]

- decay widths difference of charginos $\tilde{\chi}_i^- \to W^- \tilde{\chi}_1^0$ and $\tilde{\chi}_i^+ \to W^+ \tilde{\chi}_1^0$ is sensitive to the phase of μ parameter

  [Eberl ea., Yang, Du]

- CP effects appear also for polarized initial beams when one takes into account also chargino decays $\Rightarrow$ triple products of momenta of initial and final state particles: $\mathbf{p}_{e^-} \cdot (\mathbf{p}_{\tilde{\chi}_i^+} \times \mathbf{p}_W)$

  [Bartl ea., Kittel ea.]

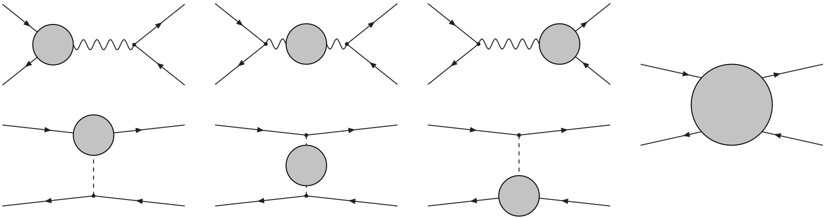
- beyond tree level no reason to expect $\sigma(\tilde{\chi}_1^- \tilde{\chi}_2^+) - \sigma(\tilde{\chi}_1^+ \tilde{\chi}_2^-) = 0$

  $\Rightarrow$ possibility to construct CP sensitive observable without polarization of electron/positron beams at one-loop

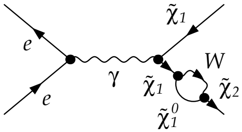
  [Osland, Vereshagin, Kalinowski, KR]

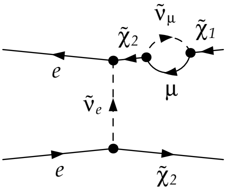
Outline

Structure of corrections



- three types of one-loop contributions: vertex diagrams, self-energy diagrams and box diagrams ⇒ use *FeynArts/FormCalc/LoopTools*
- inclusion of corrections on external chargino lines necessary



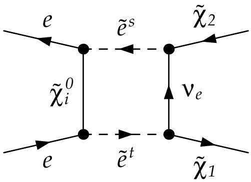


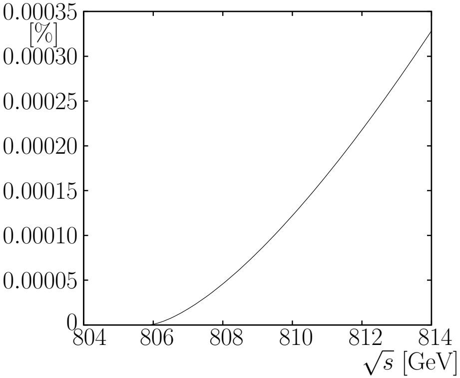
Source of CP asymmetries

- CP violating effects appear due to interference between complex couplings and absorptive parts of loop integrals

$\longrightarrow$ example: box diagram with selectron exchange

$\longrightarrow$ asymmetry appears above selectron production threshold





CP asymmetry in $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$

- matrix element squared at one loop

$$|\mathcal{M}_{\rm loop}|^2 = |\mathcal{M}_{\rm tree}|^2 + 2\,{\rm Re}(\mathcal{M}_{\rm tree}^* \mathcal{M}_{\rm loop})$$

- asymmetry in production cross section of non-diagonal chargino pairs induced by radiative corrections

$$A_{12} = \frac{\sigma^{\rm loop}(e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_2^-) - \sigma^{\rm loop}(e^+e^- \to \tilde{\chi}_2^+ \tilde{\chi}_1^-)}{\sigma^{\rm tree}(e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_2^-) + \sigma^{\rm tree}(e^+e^- \to \tilde{\chi}_2^+ \tilde{\chi}_1^-)}$$

- asymmetry vanishes at the tree level $\Rightarrow$ it is finite at one loop
- soft and hard QED corrections cancel in the numerator
- A_{12} can be sensitive to the phases of μ, A_t, M_1, A_b, A_τ

Outline

Chosen parameters

- gaugino mass parameters

$$|M_1| = 100\text{ GeV},\ M_2 = 200\text{ GeV},\ |\mu| = 400\text{ GeV},\ \tan\beta = 10$$

- sfermion parameters

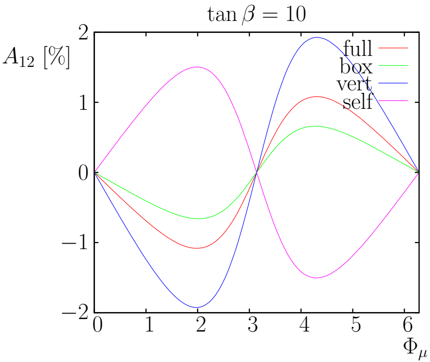
$$m_{\tilde{q}} \equiv M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = 450\text{ GeV}$$
$$M_{\tilde{Q}} \equiv M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 300\text{ GeV}$$
$$m_{\tilde{l}} \equiv M_{\tilde{L}_{1,2,3}} = M_{\tilde{E}_{1,2,3}} = 150\text{ GeV}$$
$$A \equiv |A_t| = -A_b = -A_\tau = 400\text{ GeV}$$

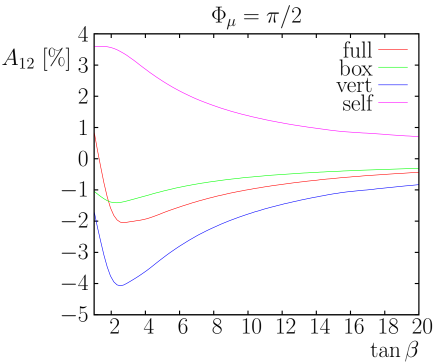
- resulting masses:

$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$
186.7	421.8	97.5	187.0	405.8	421.2	204.9	438.6

Asymmetry for $\Phi_\mu \neq 0$

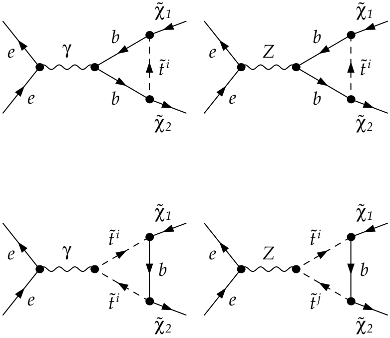
- dependence of asymmetry on the phase of μ parameter
- large cancelations between different contributions
- for low and high $\tan\beta$, asymmetry small due to small value of imaginary parts of couplings

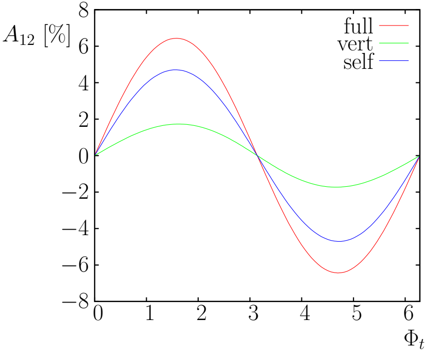




Asymmetry for $A_t \neq 0$

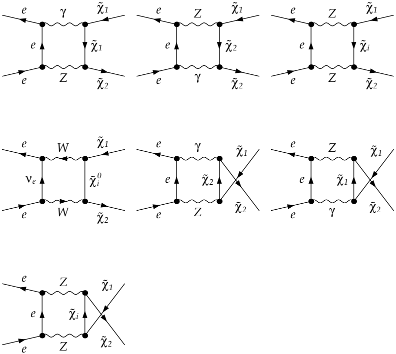
- only contributions from diagrams with stop exchange enter
- asymmetry can reach 6%
- gives access to CP violation in stop sector

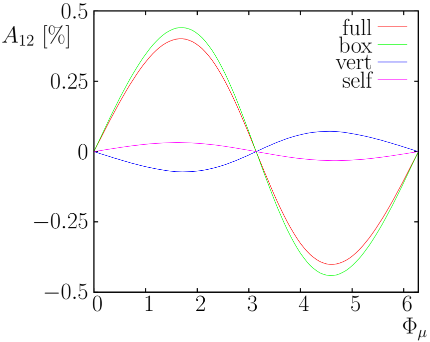




Case of heavy sfermions

- take heavy sfermions with masses 10 TeV - sfermion contributions can be neglected
- only gauge boson exchange contributes to asymmetry
- dominant contribution from box diagrams





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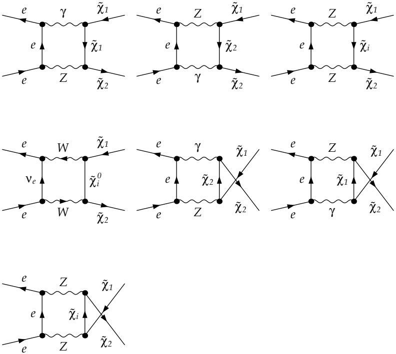

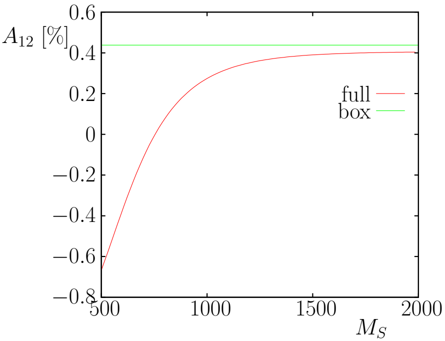

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Summary

- non-zero CP-violating asymmetry in chargino production for unpolarized initial e^+e^- beams
- asymmetry induced by loop effects
- could be of the order of few % for phases of μ and A_t
  $\Rightarrow$ access to CP properties of chargino and stop sectors

- Outlook:
  Full analysis of production+decay required at one-loop for precision physics at the ILC