CP-sensitive observables in MSSM at one loop

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IPPP Durham

Outline

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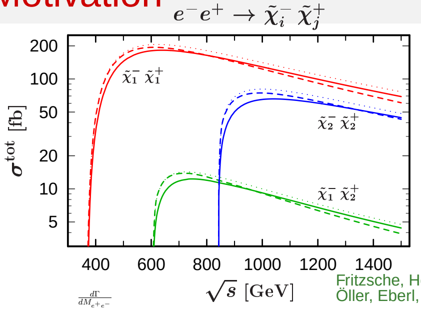
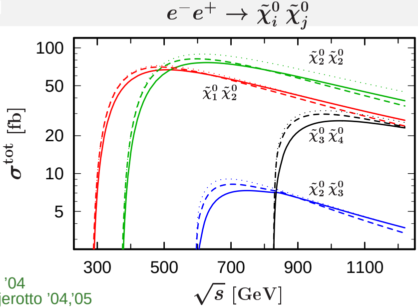
Motivation

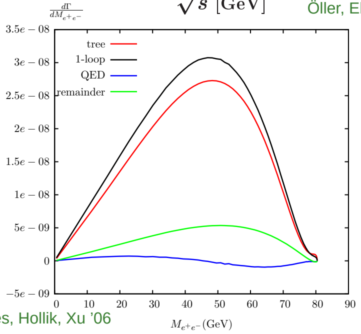
- radiative corrections in MSSM could be of order 10%
- so far only CP-conserving case at one loop thoroughly examined
- MSSM with CP violating phases:
  $M_1 = |M_1|e^{i\Phi_1}$, $\mu = |\mu|e^{i\Phi_\mu}$, $A_f = |A_f|e^{i\Phi_f}$
  - → strong bounds on these phases from EDMs exist, however
  - → large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

Motivation

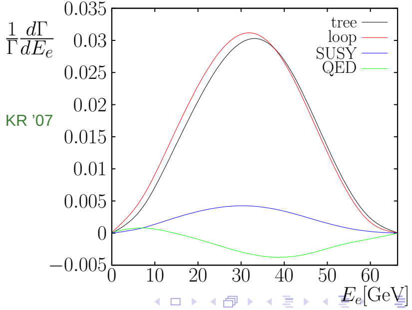




Fritzsche, Hollik '04
Öller, Eberl, Majerotto '04,'05



Drees, Hollik, Xu '06



KR '07

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Minimal Supersymmetric Standard Model

particles		spin 0	spin 1/2	$SU(3)_c, SU(2)_L, U(1)_Y$
squarks and quarks	Q	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(3 flavors)	U	$\tilde{u}^*_R$	$u^\dagger_R$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	D	$\tilde{d}^*_R$	$d^\dagger_R$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons and leptons	L	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e}_L \end{pmatrix}$	$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(3 flavors)	E	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs bosons and	H_u	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$
higgsinos	H_d	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

particles	spin $\frac{1}{2}$	spin 1	$SU(3)_c, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm\ \tilde{W}^0$	$W^\pm\ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Chargino sector of the 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

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

Neutralino sector of MSSM

- neutralino mass matrix in gauge eigenstate basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

- diagonalization of mass matrix

$$\mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) = N^* M_{\tilde{\chi}^0} N^{-1}$$

- we obtain 4 mass eigenstates – Majorana fermions
- in the CP-conserving case:
  $\Rightarrow$ elements of matrix N are either purely real or purely imaginary
  $\Rightarrow$ neutralinos have intrinsic CP parity $\eta = \pm i$

Renormalization scheme

We work in the on-shell scheme:

- regularization by dimensional reduction
- physical masses are input parameters
- renormalization conditions defined at the pole masses
- renormalization is performed after rotation of fields to mass eigenstate basis
- introduce renormalization constants for fields and mixing matrices
- attention needed: the number of observable masses exceeds the number of free parameters
  - $\Rightarrow$ e.g. in chargino/neutralino sector in the CP conserving case we have 4 parameters (M_1, M_2, μ, $\tan\beta$) and 6 masses
- counter terms added to *FeynArts* model file

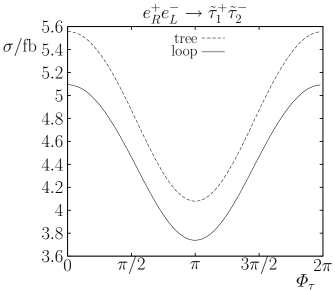
CP-sensitive observables

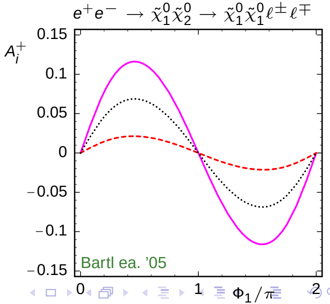
CP-even:

- U-shape dependence on complex phase
- cross-sections, decay rates or branching ratios
- threshold behavior of cross section or decay distribution

CP-odd:

- sinusoidal dependence on the phase
- asymmetries in production cross sections in CP-conjugated modes
- asymmetries in decay rates of particle and antiparticle
- triple products of momenta and/or spins
- angular distributions in production+decay



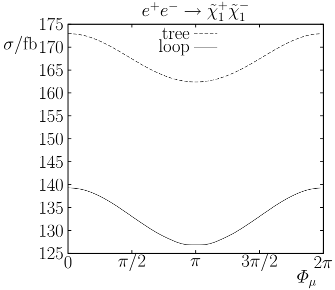


Outline

Cross sections dependence

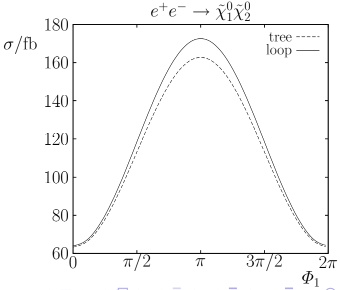
chargino production:

- a few % sensitivity to the phase of μ parameter
- large radiative corrections



neutralino production:

- strong dependence on the phase of M_1 parameter
- relative size of corrections strongly depends on Φ_1



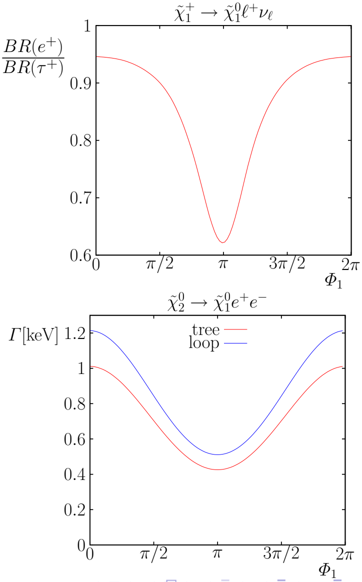
Decay widths

chargino decays:

- branching ratios for $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu_e$ and $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \tau^+ \nu_\tau$
- sensitive to the phase of M_1 and μ parameters

neutralino decays:

- decay width for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+ e^-$
- strong dependence on the phase of M_1 parameter

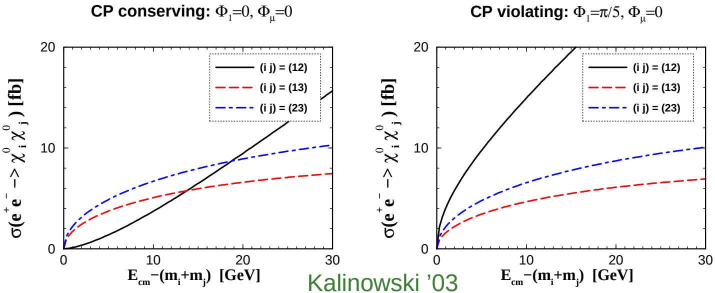


Threshold behavior in neutralino production

- orbital momentum L selection rule at the threshold for pair production of neutralinos $\{ij\}$ with CP parities η_i and η_j

$$1 = \eta_i \eta_j (-1)^L$$

- in the CP-conserving theory same (opposite) parities give P (S) wave excitation
- in the CP-violating theory there is always S-wave excitation



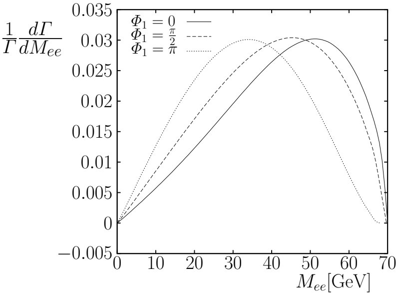
Kalinowski '03

Threshold behavior in neutralino three-body decay

- consider 3-body neutralino decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$
- orbital momentum L selection rule at the threshold for neutralino $\tilde{\chi}_1^0$ and lepton pair with neutralino CP parities η_2 and η_1

$$1 = -\eta_2 \eta_1 (-1)^L$$

- in the CP-conserving theory same (opposite) parities give S (P) wave excitation; in the CP-violating theory we have S-wave excitation

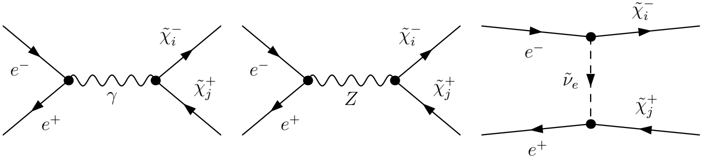


- note: if both decay and production of $\tilde{\chi}_2^0 \tilde{\chi}_1^0$ exhibit S-wave excitation ⇒ CPV phases are present

Outline

Chargino production

- 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

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

- 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

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

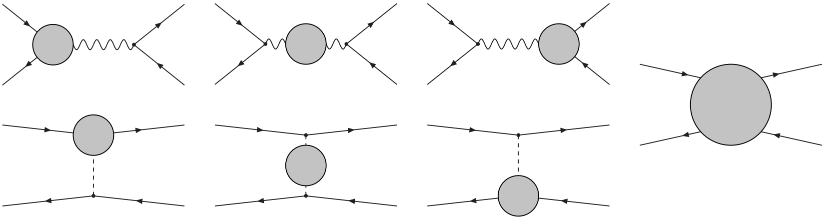
- in center of mass frame: $\mathbf{p}_1=-\mathbf{p}_2$ and $\mathbf{k}_1=-\mathbf{k}_2$

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

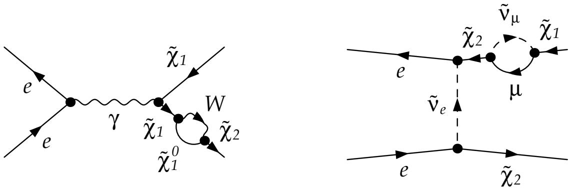
- no CP violation in diagonal chargino final states $\tilde{\chi}_1^-\tilde{\chi}_1^+$, $\tilde{\chi}_2^-\tilde{\chi}_2^+$
- at tree level for non-diagonal chargino pair production

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

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

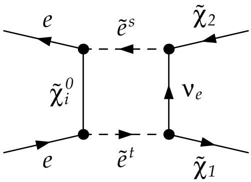


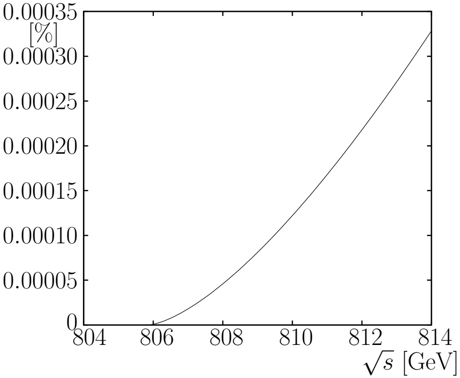
Source of CP asymmetries

- 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

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

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

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

- 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

Chosen parameters

- gaugino mass parameters

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

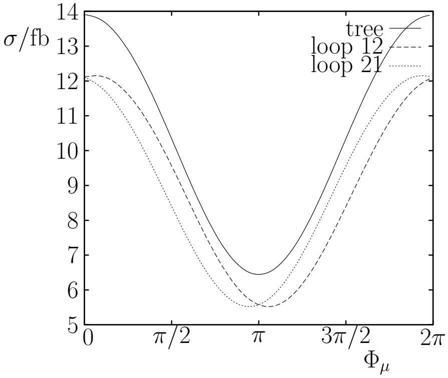
- sfermion parameters

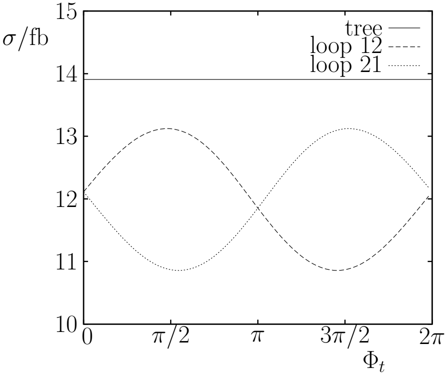
$$m_{\tilde{q}} \equiv M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = 450 \text{ GeV}$$
$$M_{\tilde{Q}} \equiv M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 300 \text{ GeV}$$
$$m_{\tilde{l}} \equiv M_{\tilde{L}_{1,2,3}} = M_{\tilde{E}_{1,2,3}} = 150 \text{ GeV}$$
$$A \equiv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

- 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

Cross section at one loop

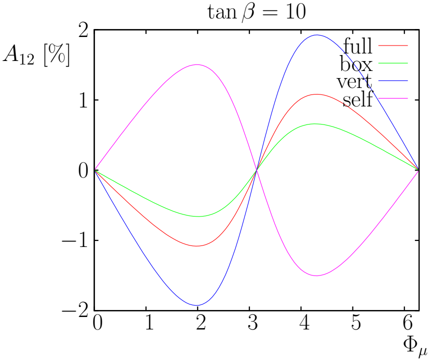


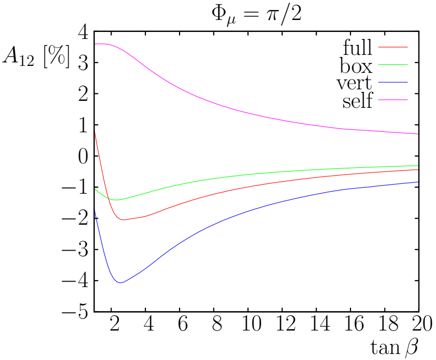


- significant difference between corrections in two production channels ⇒ asymmetry can be observed

Asymmetry for $\Phi_\mu \neq 0$

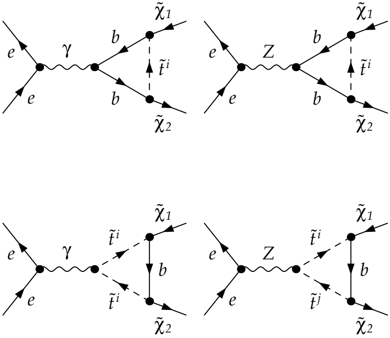
- dependence of asymmetry on the phase of μ parameter
- large cancelations between different contributions
- for low and high $\tan\beta$, asymmetry small due to small value of imaginary parts of couplings

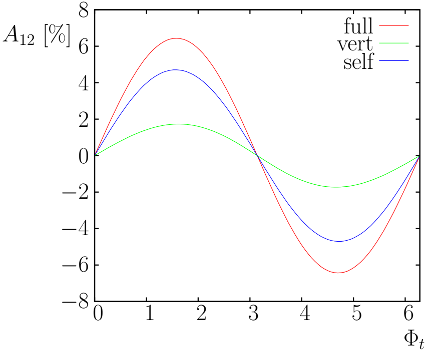




Asymmetry for $A_t \neq 0$

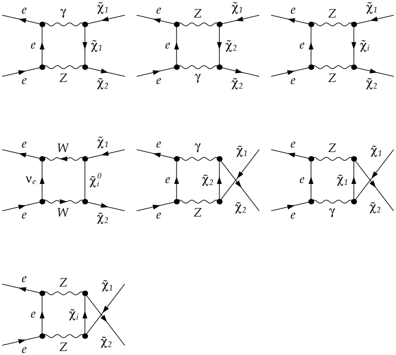
- only contributions from diagrams with stop exchange enter
- asymmetry can reach 6%
- gives access to CP violation in stop sector

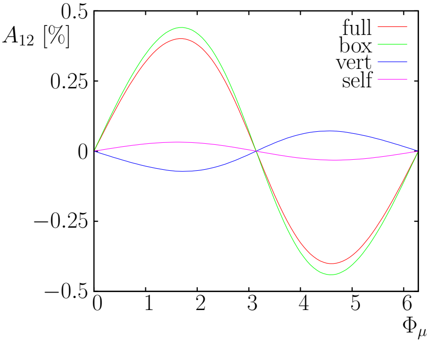




Case of heavy sfermions

- 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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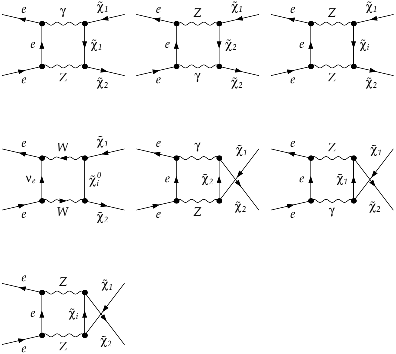
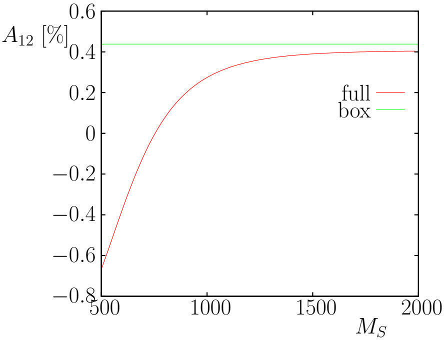
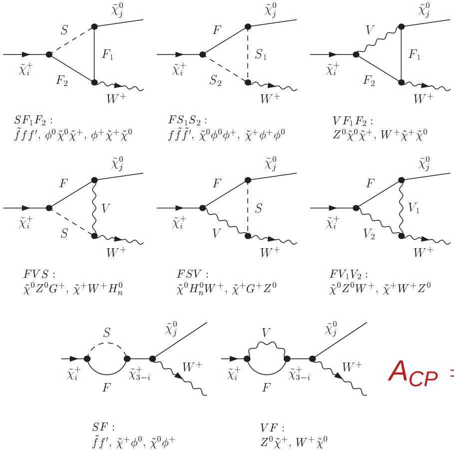




Loop corrections to $\tilde{\chi}_i^{\pm} \to W^{\pm}\tilde{\chi}_1^0$

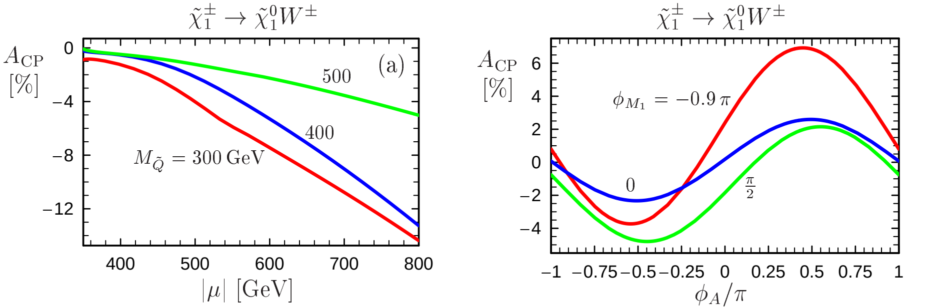


[Eberl, Gajdosik, Majerotto, Schrausser; Yang, Du]

- branching ratios $\sim 5\%$
- possible detection at LHC - charginos from decay chains of $\tilde{g}$ and $\tilde{q}$
- asymmetry

$$A_{CP} = \frac{\Gamma(\tilde{\chi}_i^+ \to W^+\tilde{\chi}_1^0) - \Gamma(\tilde{\chi}_i^- \to W^-\tilde{\chi}_1^0)}{\Gamma(\tilde{\chi}_i^+ \to W^+\tilde{\chi}_1^0) + \Gamma(\tilde{\chi}_i^- \to W^-\tilde{\chi}_1^0)}$$

CP asymmetries in $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$



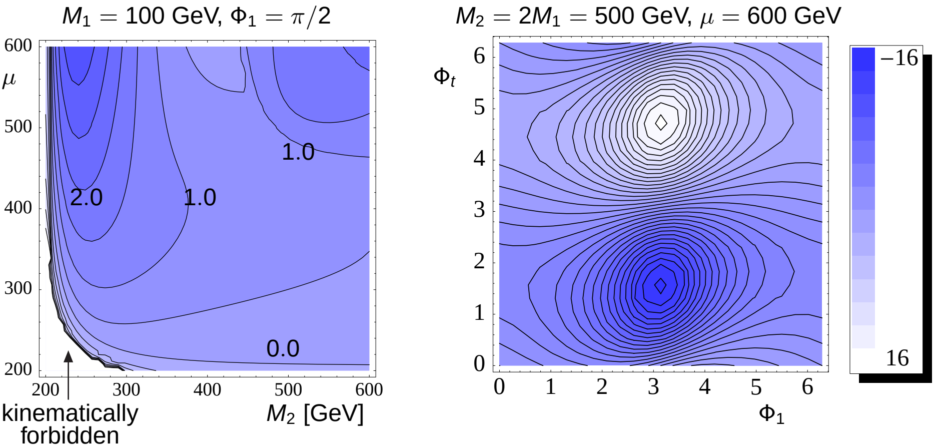
$M_2 = 500$ GeV, $|A| = 400$ GeV,
$\Phi_t = -\pi/4$, $\Phi_1 = 3\pi/4$

$M_2 = 500$ GeV, $|A| = 400$ GeV,
$\mu = 600$ GeV, $M_{\tilde{Q}} = 400$ GeV

- asymmetry sensitive to the phases of stop trilinear coupling A_t and bino mass M_1
- can be of the order of $\sim 10\%$

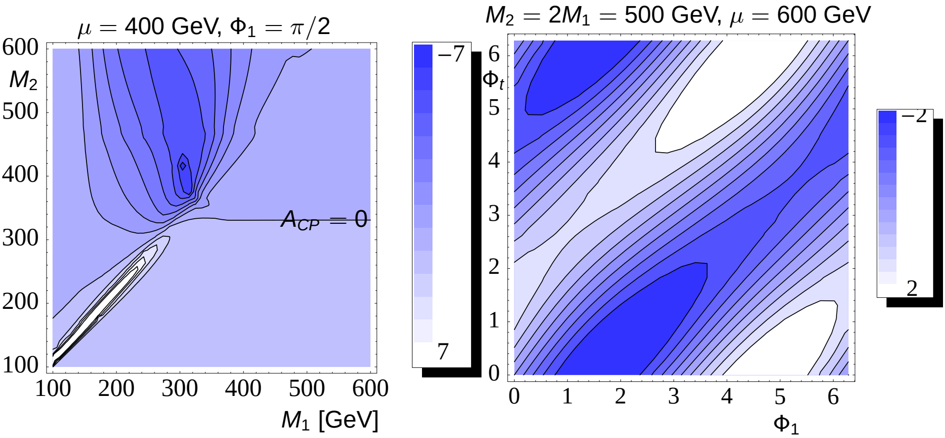
[Eberl, Gajdosik, Majerotto, Schrausser]

$A_{CP}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0)$



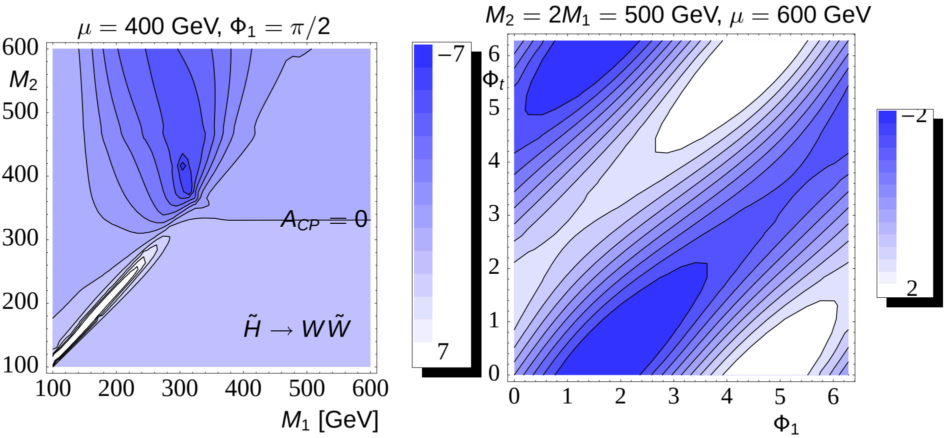
- stop parameters: $|A| = 400$ GeV, $m_{\tilde{Q}} = 300$ GeV
- maximal asymmetry $\sim 16\%$ for $\Phi_1 = \pi$

$A_{CP}(\tilde{\chi}_2^{\pm} \to W^{\pm}\tilde{\chi}_1^0)$



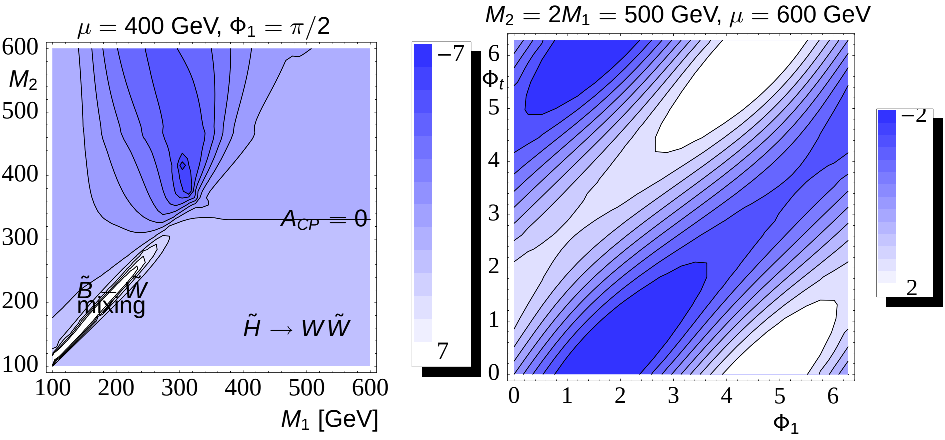
- stop parameters: $|A| = 400$ GeV, $m_{\tilde{Q}}$ = 300 GeV
- Φ_1 and Φ_t effects correlated

$A_{CP}(\tilde{\chi}_2^{\pm} \to W^{\pm}\tilde{\chi}_1^0)$



- stop parameters: $|A| = 400$ GeV, $m_{\tilde{Q}} = 300$ GeV
- Φ_1 and Φ_t effects correlated

$A_{CP}(\tilde{\chi}_2^\pm \to W^\pm \tilde{\chi}_1^0)$



- stop parameters: $|A| = 400$ GeV, $m_{\tilde{Q}}$ = 300 GeV
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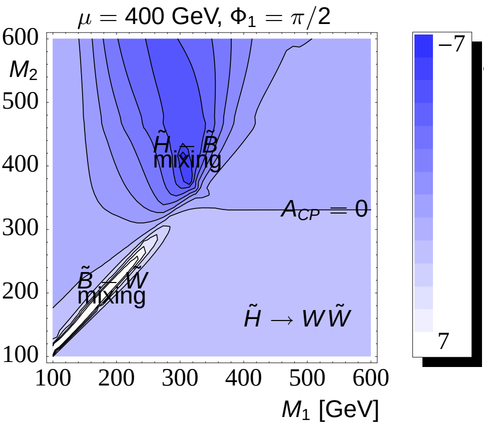
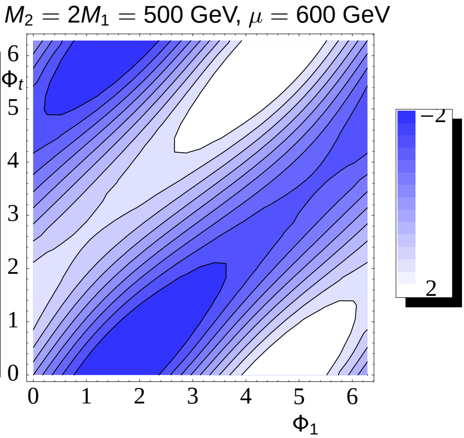
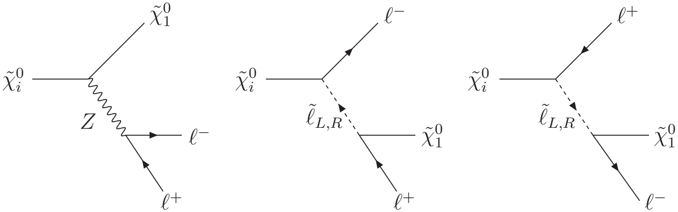




- stop parameters: $|A| = 400$ GeV, $m_{\tilde{Q}}$ = 300 GeV
- Φ_1 and Φ_t effects correlated

Three-body neutralino decay

- 3-body decay of polarized $\tilde{\chi}^0_2(\hat{n}) \to \tilde{\chi}^0_1(p) + \ell^+(q_+) + \ell^-(q_-)$



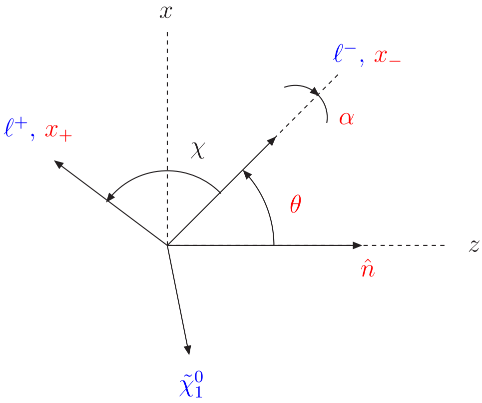
- differential decay rate at tree level

Choi, Chung, Kalinowski, Kim, KR '05

$$\frac{d^4\Gamma}{dx_- dx_+ d\cos\theta\, d\varphi} = \frac{\alpha^2 m_2}{16\pi^2}\Big[F_0(x_-,x_+) + (\hat{q}_- \cdot \hat{n})\, F_1(x_-,x_+) + (\hat{q}_+ \cdot \hat{n})\, F_2(x_-,x_+) + \hat{n}\cdot(\hat{q}_- \times \hat{q}_+)\, F_3(x_-,x_+)\Big]$$

- with kinematic functions $F_i(x_-,x_+)$ and $x_\pm = 2E_{\ell^\pm}/m_2$
- Majorana nature of neutralinos leads to $F_3(x_-,x_+) \xrightarrow{CP} -F_3(x_+,x_-)$

Kinematical configuration



CP transformation:

$$x_\pm \stackrel{CP}{\longrightarrow} +x_\mp, \quad \vec{q}_\pm \stackrel{CP}{\longrightarrow} -\vec{q}_\mp,$$

$$\hat{q}_\pm \cdot \hat{n} \stackrel{CP}{\longrightarrow} -\hat{q}_\mp \cdot \hat{n},$$

$$\hat{n} \cdot (\hat{q}_- \times \hat{q}_+) \stackrel{CP}{\longrightarrow} -\hat{n} \cdot (\hat{q}_- \times \hat{q}_+)$$

CPT transformation:

$$x_\pm \stackrel{CPT}{\longrightarrow} +x_\mp, \quad \vec{q}_\pm \stackrel{CPT}{\longrightarrow} +\vec{q}_\mp,$$

$$\hat{q}_\pm \cdot \hat{n} \stackrel{CPT}{\longrightarrow} -\hat{q}_\mp \cdot \hat{n},$$

$$\hat{n} \cdot (\hat{q}_- \times \hat{q}_+) \stackrel{CPT}{\longrightarrow} +\hat{n} \cdot (\hat{q}_- \times \hat{q}_+)$$

CP asymmetry in the neutralino decay

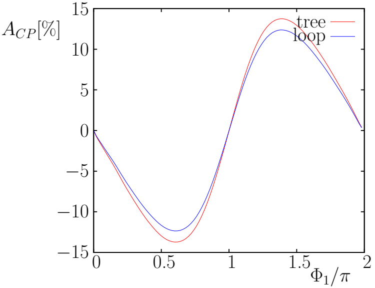
- a CP-odd and CPT-even distribution

$$F_{\rm CP}(x_-, x_+) = \frac{1}{2}\left[F_3(x_-, x_+) + F_3(x_+, x_-)\right]$$

- a CP-odd quantity related to the above CP-odd distribution

$$O_{\rm CP} = \hat{n} \cdot (\hat{q}_+ \times \hat{q}_-)$$

$$A_{\rm CP} \equiv \frac{N(O_{\rm CP} > 0) - N(O_{\rm CP} < 0)}{N(O_{\rm CP} > 0) + N(O_{\rm CP} < 0)} = \frac{\int_{\mathcal{D}} \frac{1}{2} \sin\chi \, F_{\rm CP}(x_-, x_+)\, dx_- dx_+}{\int_{\mathcal{D}} F_0(x_-, x_+)\, dx_- dx_+}$$



Outline

Summary

- many possible CP-even and CP-odd observables can give information about complex phases of μ, M_1, A_t, A_τ
- unambiguous detection will require combining data from different channels/sectors
- some asymmetries are induced by loop effects
- could be of the order of a few % for phases of μ, M_1, A_t
  $\Rightarrow$ access to CP properties of chargino, neutralino and stop sectors
- Outlook:
  full analysis of production+decay required at one loop for precision physics at the ILC