# One-loop corrections in chargino sector with CP violating phases

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# Outline

1. Introduction
2. CP violation in chargino production
3. CP violation in chargino decays
4. Summary and outlook

# Motivation

- radiative corrections in MSSM could be of order 20%
- so far only CP-conserving case at one loop thoroughly examined
- MSSM with CP violating phases:
  $M_1 = |M_1| e^{i\Phi_1}$, $\mu = |\mu| e^{i\Phi_\mu}$, $A_f = |A_f| e^{i\Phi_f}$
  - $\rightarrow$ strong bounds on these phases from EDMs exist, however
  - $\rightarrow$ large phases possible if accidental cancelations occur
  - $\rightarrow$ or 1st and 2nd generation of squarks are heavy
  - $\rightarrow$ $\Phi_1$ poorly constrained
- calculation of radiative corrections to CP violating observables, e.g. asymmetries in decay widths, asymmetries in sparticles production, asymmetries of triple products of momenta and/or spins
  - $\rightarrow$ such observables provide unambiguous way of detecting CP violating phases
- here we analyze gaugino/higgsino sectors 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

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

# 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

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

- mass eigenstates - Weyl spinors $\chi_i^0$ and Majorana spinors $\tilde{\chi}_i^0$ $(i = 1, 2, 3, 4)$

$$\begin{pmatrix} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \end{pmatrix} = N \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix} \qquad \tilde{\chi}_i^0 = \begin{pmatrix} \chi_i^0 \\ \bar{\chi}_i^0 \end{pmatrix}$$

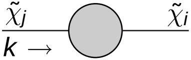
# Renormalization scheme

We work in the on-shell scheme:

- regularization by dimensional reduction
- physical masses are input parameters
- renormalization conditions defined at the pole masses
- no mixing between particles on-shell
- 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 ($M_1$, $M_2$, $\mu$, $\tan\beta$) and 6 masses

# Renormalization of charginos and neutralinos

- 1PI renormalized Green's function




$$= \hat{\Gamma}^{\tilde{\chi}}_{ij} = i(\not{k} - m_{\tilde{\chi}_i})\delta_{ij} + i\hat{\Sigma}^{\tilde{\chi}}_{ij}(k^2)$$

- substitute in Lagrangian wave function and mass counter terms

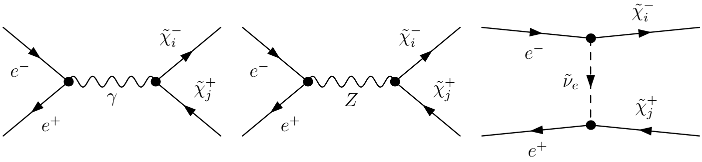
$$\tilde{\chi}_i \rightarrow (\delta_{ij} + \frac{1}{2}\delta\tilde{Z}^L_{ij}P_L + \frac{1}{2}\delta\tilde{Z}^R_{ij}P_R)\tilde{\chi}_j, \qquad m_{\tilde{\chi}_i} \rightarrow m_{\tilde{\chi}_i} + \delta m_{\tilde{\chi}_i}$$

- renormalization conditions:
  $\Rightarrow$ poles at $k^2 = m^2_{\tilde{f}}$, residues equal 1 and no mixing on-shell
- introduce counterterms for mixing matrices

$$\delta U_{ij} = \frac{1}{4}\sum_{k=1}^{2}\left(\delta\tilde{Z}^{\pm,R}_{ik} - (\delta\tilde{Z}^{\pm,R}_{ki})^*\right)U_{kj} \qquad \delta V_{ij} = \frac{1}{4}\sum_{k=1}^{2}\left(\delta\tilde{Z}^{\pm,L}_{ik} - (\delta\tilde{Z}^{\pm,L}_{ki})^*\right)V_{kj}$$

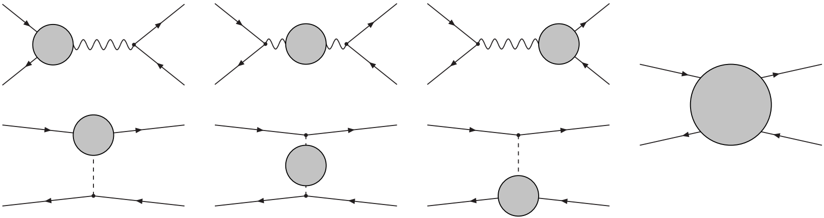
$$\delta N_{ij} = \frac{1}{4}\sum_{k=1}^{4}\left(\delta\tilde{Z}^{0,L}_{ik} - \delta\tilde{Z}^{0,R}_{ki}\right)N_{kj}$$

# Chargino production at the tree-level

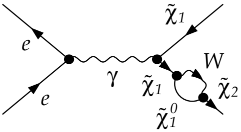


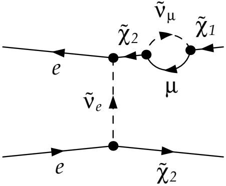

- tree-level cross-section conserves CP
- CP violating effects can be probed by observables sensitive to the chargino polarization component normal to the production plane [Choi ea.]
- CP effects appear also for polarized initial beams when one takes into account also chargino decays [Bartl ea., Kittel ea.]
- for non-diagonal chargino pair production $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ at the one-loop level one can construct CP sensitive observable without polarization of electron/positron beams [Osland, Vereshagin]

# Structure of corrections



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



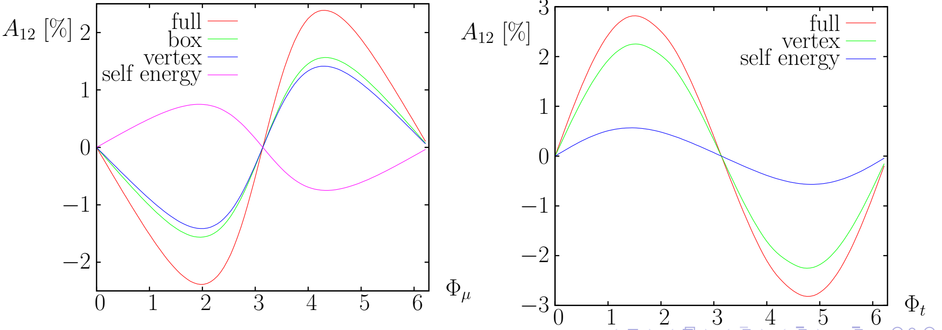



# CP asymmetry in $e^+e^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$

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

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

- $A_{12}$ is sensitive to the phase of $\mu$ and $A_t$



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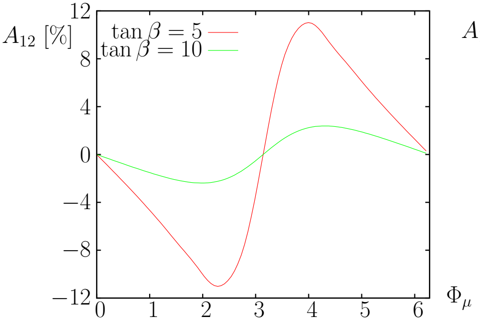
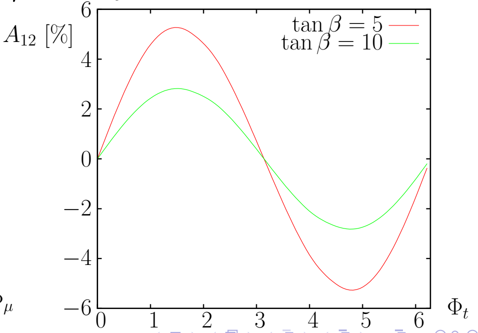
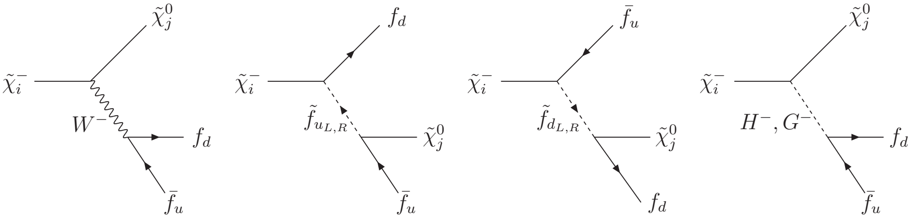


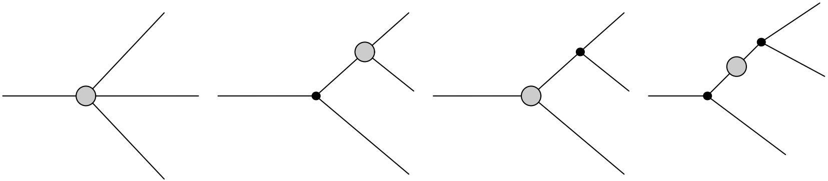



# Chargino decays at the tree-level

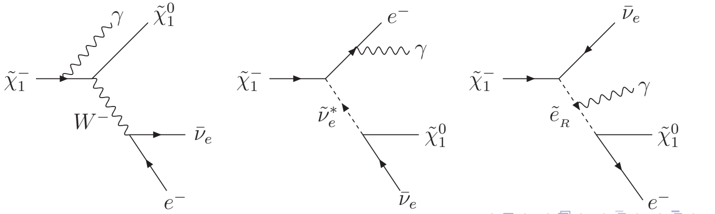



- here we consider only genuine 3-body decays
  - $\Rightarrow$ sleptons heavier than chargino: $m_{\tilde{\ell}}, m_{\tilde{\nu}} > m_{\chi_1^\pm}$
  - $\Rightarrow$ mass difference between chargino and neutralino smaller than $m_W$
- in lepton channel only one particle detectable
- diagrams with Higgs exchange relevant only for heavy fermions
- shape of the decay distributions important at ILC for measurement of chargino and lightest neutralino masses

# Structure of corrections



- three types of one-loop contributions: box, vertex and self-energy diagrams $\Rightarrow$ use *FeynArts/FormCalc/LoopTools*
- to obtain physically meaningful result inclusion of soft and hard photon bremsstrahlung necessary



# Decay width

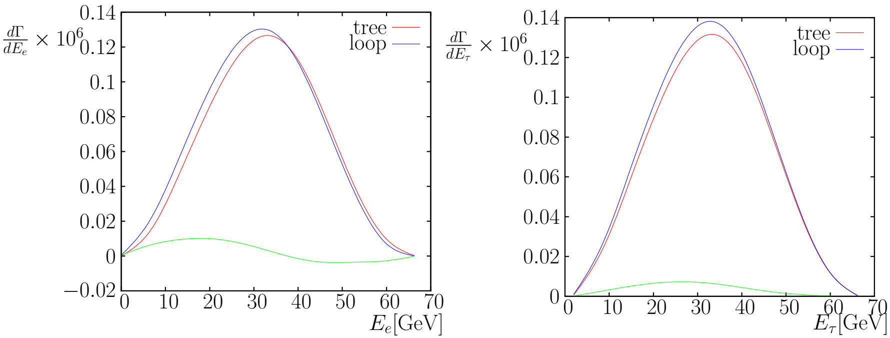
- numerical analysis for the following scenario:

| particle | $\tilde{\chi}_1^{\pm}$ | $\tilde{\chi}_1^0$ | $\tilde{e}_L$ | $\tilde{e}_R$ | $\tilde{\nu}_e$ |
|---|---|---|---|---|---|
| mass [GeV] | 165.3 | 97.9 | 287.9 | 221.9 | 276.6 |
| particle | $\tilde{\tau}_1$ | $\tilde{\tau}_2$ | $\tilde{q}_L$ | $\tilde{q}_R$ | $H^{\pm}$ |
| mass [GeV] | 211.9 | 289.0 | 561.3 | 544.3 | 436.4 |

- only genuine 3-body decays allowed: $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu_e$, $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \mu^+ \nu_\mu$, $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \tau^+ \nu_\tau$, $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 u\bar{d}$, $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 c\bar{s}$
- correction in leptonic modes typically of the order of 5%

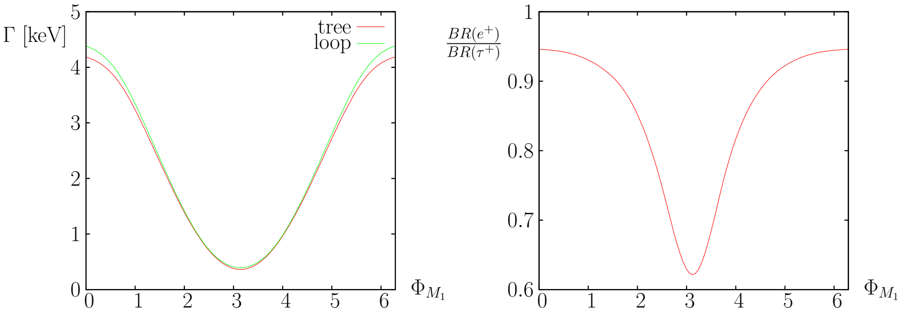
| decay mode | tree-level width | one-loop width |
|---|---|---|
| $e\nu_e\tilde{\chi}_1^0$ | 4.18 keV | 4.38 keV |
| $\mu\nu_\mu\tilde{\chi}_1^0$ | 4.18 keV | 4.38 keV |
| $\tau\nu_\tau\tilde{\chi}_1^0$ | 4.38 keV | 4.61 keV |

# Lepton energy distribution



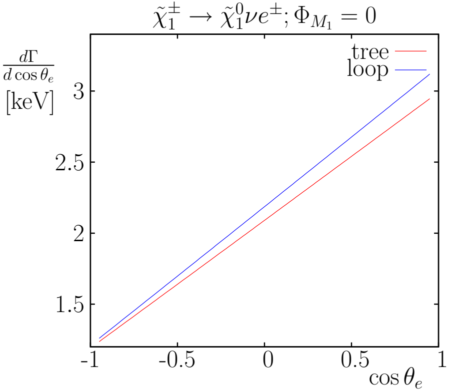

- one-loop corrections to electron and $\tau$ energy distributions in 3-body chargino decays
- electron distribution shifted slightly towards lower energies due to photonic corrections

# $\Phi_{M_1}$ dependence




- width $\Gamma(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu)$ and ratio of branching fractions $BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu)/BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \tau^+ \nu_\tau)$ show strong dependence on the phase $\Phi_{M_1}$
- radiative corrections more significant around $\Phi_{M_1} = 0$

# Angular distribution




- angular distribution of $e^+/e^-$ with respect to chargino spin vector
- for $\Phi_{M_1} = \pi/2$ significant difference between corrections to $e^+$ and $e^-$ distributions

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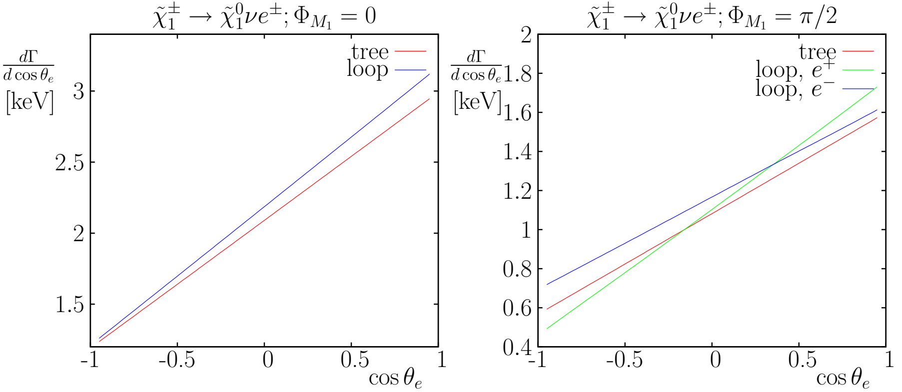


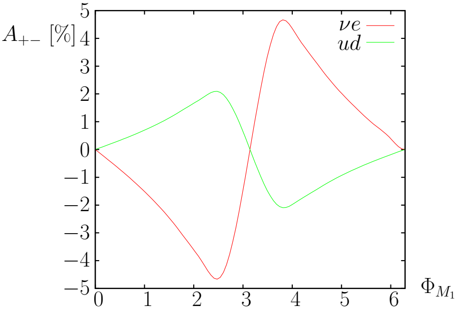

- angular distribution of $e^+/e^-$ with respect to chargino spin vector
- for $\Phi_{M_1} = \pi/2$ significant difference between corrections to $e^+$ and $e^-$ distributions

# Charge asymmetry

- asymmetry in decay widths between $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^-$

$$A_{+-}^{e\nu} = \frac{\Gamma(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu_e) - \Gamma(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}_e)}{\Gamma(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu_e) + \Gamma(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}_e)}$$

- sensitive to the CP phase of the bino mass parameter $M_1$




- easy:
  - $\longrightarrow$ counting experiment
  - $\longrightarrow$ large chargino production rate ($\sigma \sim$ 200 fb)
- accurate determination of asymmetry possible
- access to CP properties of neutralino sector

# Summary and outlook

- One-loop corrections to leptonic chargino decays calculated - important for ILC physics
- Loop corrections induce significant CP violation effects in chargino production and decays which are not present at the tree-level
- Might be useful for determination of CP phases in chargino/neutralino/stop sector

- Outlook:
  Full analysis of production+decay required at one-loop for precision physics at the ILC
  $\Rightarrow$ Tania Robens' talk