T-odd Asymmetries in Chargino and Neutralino Production and Decay

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Outline

- Introduction
  - MSSM with complex parameters
  - complex parameters in chargino and neutralino sectors
- Aim: deriving the phases and analysing the CP structure of the theory
- T-odd asymmetries in chargino and neutralino sectors
  - full spin correlations between production and decay
  - triple products and T-odd asymmetries
  - for three-body and two-body decays
- Conclusions and outlook

Introduction MSSM with complex parameters

- General MSSM:

  Complex parameters in Higgs potential and soft SUSY breaking terms

- Physical phases of the parameters

  μ : Higgs-higgsino mass parameter

  M_1 : U(1) gaugino mass parameter

  $m_{\tilde{g}}$: gluino mass

  A_f : trilinear couplings of sfermions

- Introduction of CP violation
  - may help to explain baryon asymmetry of universe
  - constraints from electric dipole moments (EDMs)of e, n, Hg, Tl

    [Ibrahim, Nath, '99; Barger, Falk, Han, Jiang, Li, Plehn, '01; Abel, Khalil, Lebedev, '01]

Introduction

Complex parameters in $\tilde{\chi}^{\pm,0}$ sectors

- Chargino mass matrix: $X = \begin{pmatrix} M_2 & \sqrt{2}\, m_W s_\beta \\ \sqrt{2}\, m_W c_\beta & \mu \end{pmatrix}$
- Neutralino mass matrix:

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

$s_\beta \equiv \sin\beta$, $c_\beta \equiv \cos\beta$

μ : Higgs-higgsino mass parameter $\rightarrow |\mu|, \varphi_\mu$

M_1 : U(1) gaugino mass parameter $\rightarrow |M_1|, \varphi_{M_1}$

M_2 : SU(2) gaugino mass parameter

$\tan\beta = \dfrac{v_2}{v_1}$: ratio of Higgs vevs

T-odd asymmetries in $\tilde{\chi}^{\pm}, \tilde{\chi}^{0}$ sectors

Chargino/neutralino production with subsequent three-body decays

$$e^+e^- \longrightarrow \tilde{\chi}_i + \tilde{\chi}_j \longrightarrow \tilde{\chi}_i + \tilde{\chi}_1^0 f \bar{f}^{(\prime)}$$

- full spin correlation between production and decay

  [Moortgat-Pick, Fraas, '97; Moortgat-Pick, Fraas, Bartl, Majerotto, '98, '99; Choi, Song, Song, '99]

- amplitude squared $|T|^2 = PD + \Sigma_P^a \Sigma_D^a$

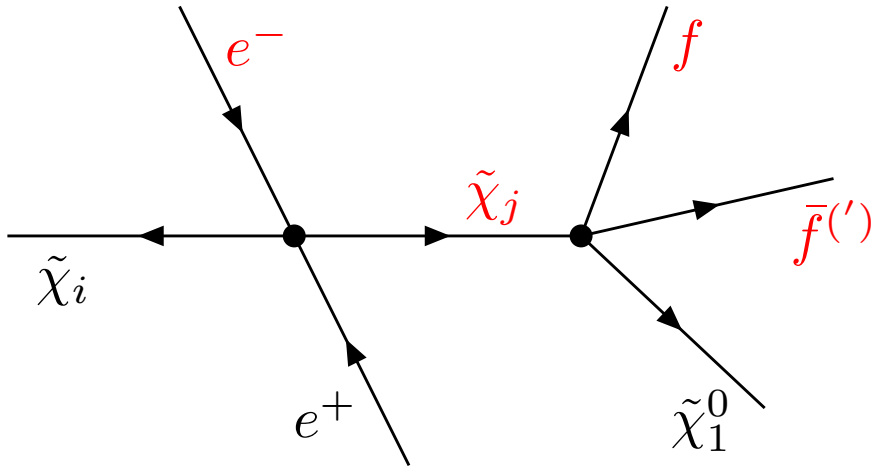
- in Σ_P^a and Σ_D^a: products like $i\epsilon_{\mu\nu\rho\sigma} p_i^\mu p_j^\nu p_k^\rho p_l^\sigma$

  $\Rightarrow$ with complex couplings: real contributions to observables

  $\Rightarrow$ CP violation at tree level

T-odd asymmetries in $\tilde{\chi}^{\pm}, \tilde{\chi}^{0}$ sectors

Triple products: $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_f \times \vec{p}_{\bar{f}^{(\prime)}})$ or $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_f)$



→ T-odd asymmetry:

$$A_T = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)} = \frac{\int \text{sign}(\mathcal{T}) |T|^2 d\text{Lips}}{\int |T|^2 d\text{Lips}}$$

→ CP-odd, if final state interactions and finite-widths effects can be neglected

T-odd asymmetry in $\tilde{\chi}^0$ sector

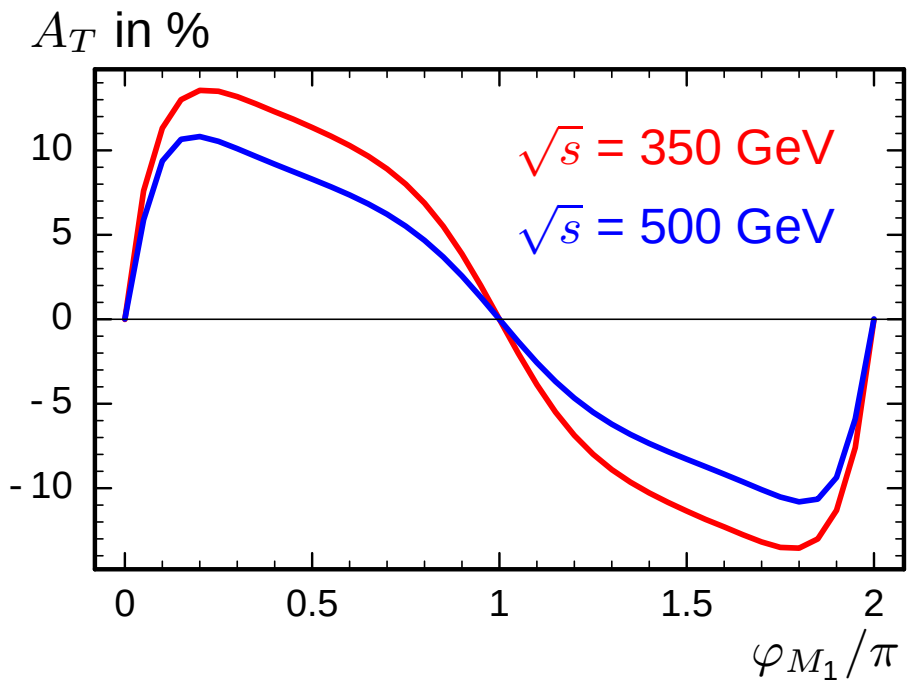
Asymmetry A_T for $e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_2^0 \to \tilde{\chi}_i^0\tilde{\chi}_1^0\ell^+\ell^-$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$

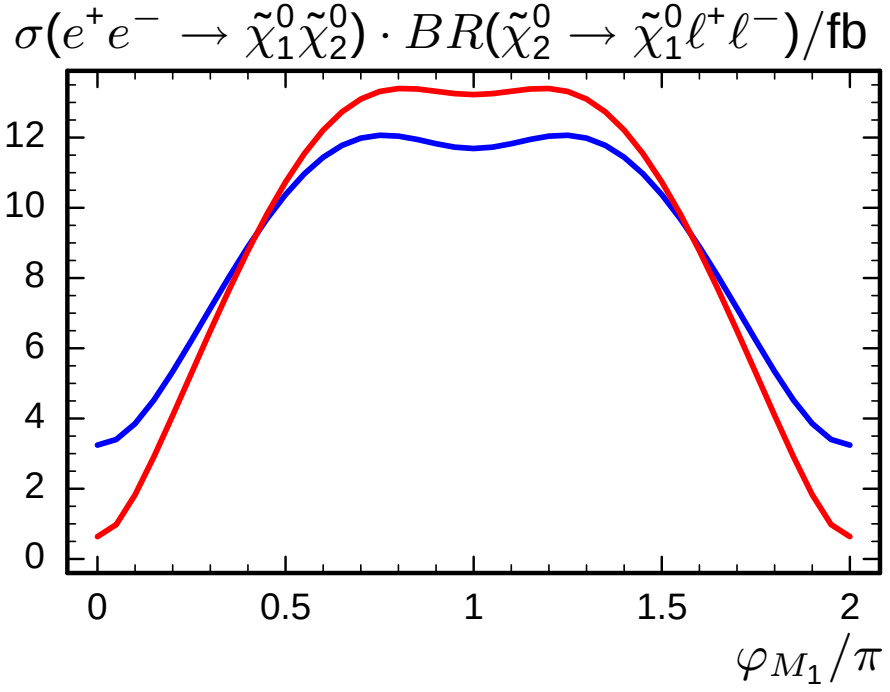
[Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, hep-ph/0406190]

- $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$ for

  $\tan\beta$ = 10, M_2 = 300 GeV, $|M_1|$ = 150 GeV, $|\mu|$ = 200 GeV, φ_μ = 0

  $m_{\tilde{e}_L}$ = 267.6 GeV, $m_{\tilde{e}_R}$ = 224.4 GeV, P_{e^-} = −0.8, P_{e^+} = +0.6





$\to A_T$ larger closer to threshold (spin correlations)

T-odd asymmetry in $\tilde{\chi}^0$ sector

- $e^+e^- \to \tilde{\chi}^0_3\tilde{\chi}^0_2 \to \tilde{\chi}^0_3\tilde{\chi}^0_1\ell^+\ell^-$

Contours of A_T [in %] for

$\tan\beta$ = 10, $|M_1| = M_2\, 5/3 \tan^2\theta_W$,

$m_{\tilde{e}_L}$ = 267.6 GeV, $m_{\tilde{e}_R}$ = 224.4 GeV

$\sqrt{s}$ = 500 GeV, $P_{e^-} = -0.8$, P_{e^+} = +0.6

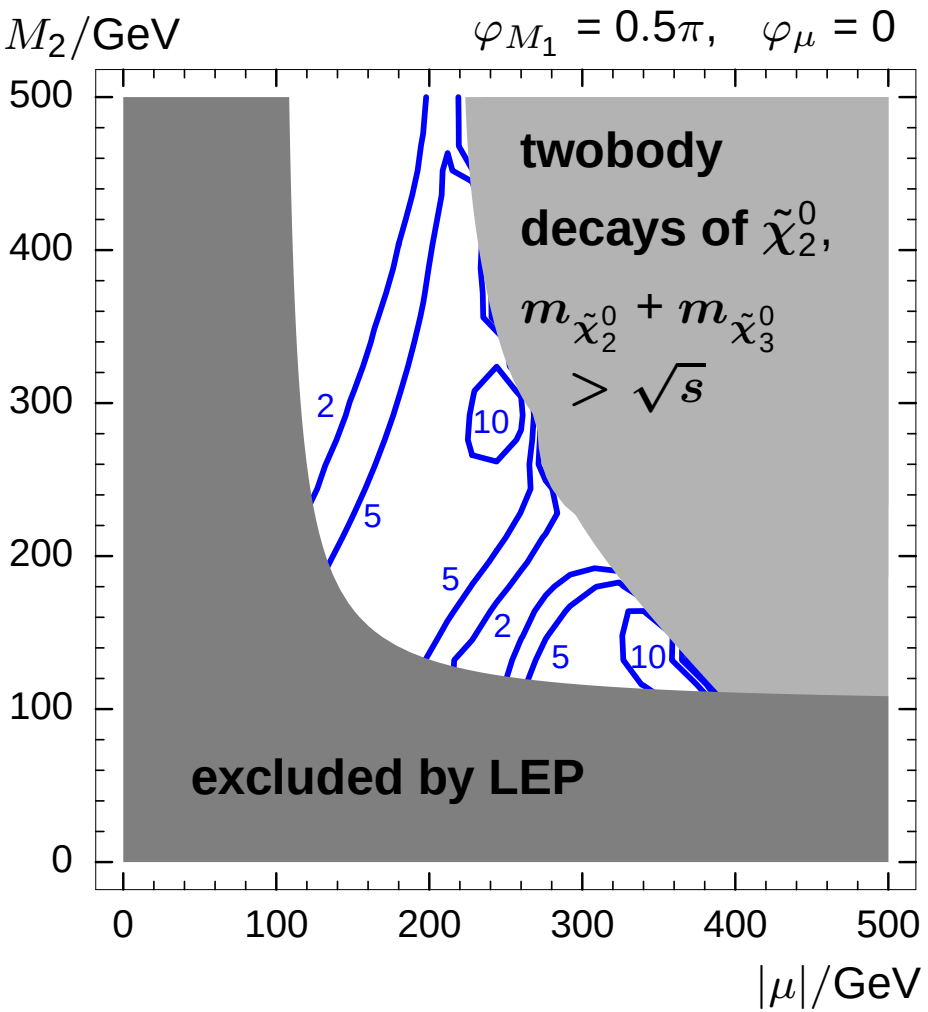
Dark shaded area:

$m_{\tilde{\chi}^\pm_1} < 103$ GeV

Light shaded area:

$m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} > m_Z$, $m_{\tilde{\chi}^0_2} > m_{\tilde{e}_R}$ or

$m_{\tilde{\chi}^0_2} + m_{\tilde{\chi}^0_3} > \sqrt{s}$



- $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2 \to \tilde{\chi}^0_2\tilde{\chi}^0_1\ell^+\ell^-$: $A_T = \mathcal{O}(1\,\%)$
- $e^+e^- \to \tilde{\chi}^0_4\tilde{\chi}^0_2 \to \tilde{\chi}^0_4\tilde{\chi}^0_1\ell^+\ell^-$: $\sigma \cdot BR \lesssim 1$ fb

T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

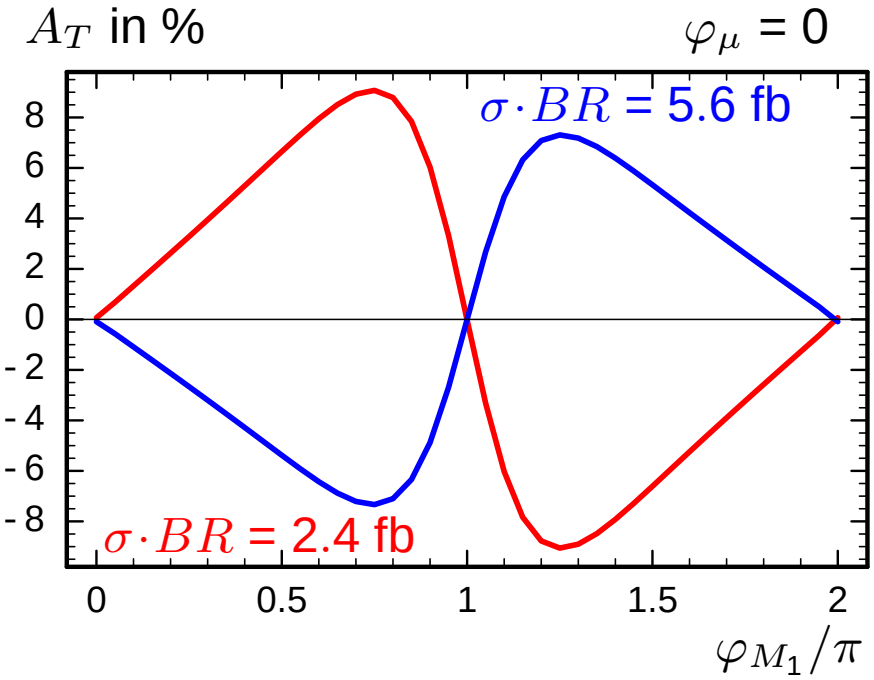
Asymmetry A_T for $e^+e^- \to \tilde{\chi}_j^- \tilde{\chi}_1^+ \to \tilde{\chi}_j^- \tilde{\chi}_1^0 c\bar{s}$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\bar{s}} \times \vec{p}_c)$

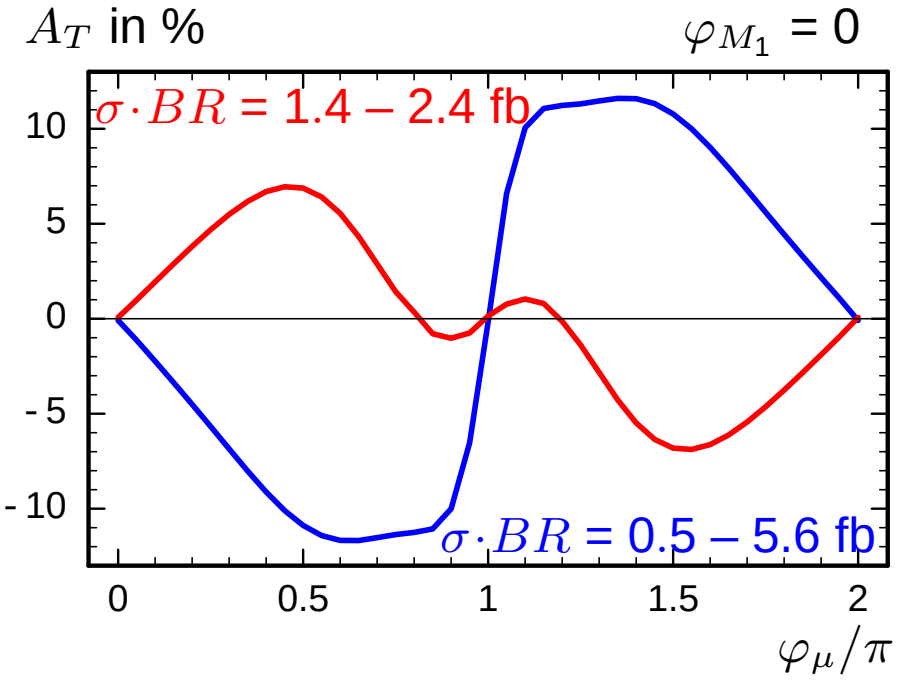
$\to$ tagging of c jet important

- $e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_1^+ \to \tilde{\chi}_2^- \tilde{\chi}_1^0 c\bar{s}$ for

  $\tan\beta = 5$, $M_2 = 150$ GeV, $|M_1| = M_2\, 5/3 \tan^2\theta_W$, $|\mu| = 320$ GeV, $m_{\tilde{\nu}} = 250$ GeV,

  $m_{\tilde{u}_L} = 500$ GeV, $\sqrt{s} = 500$ GeV, $P_{e^-} = -0.8$, $P_{e^+} = +0.6$, $P_{e^-} = +0.8$, $P_{e^+} = -0.6$





T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

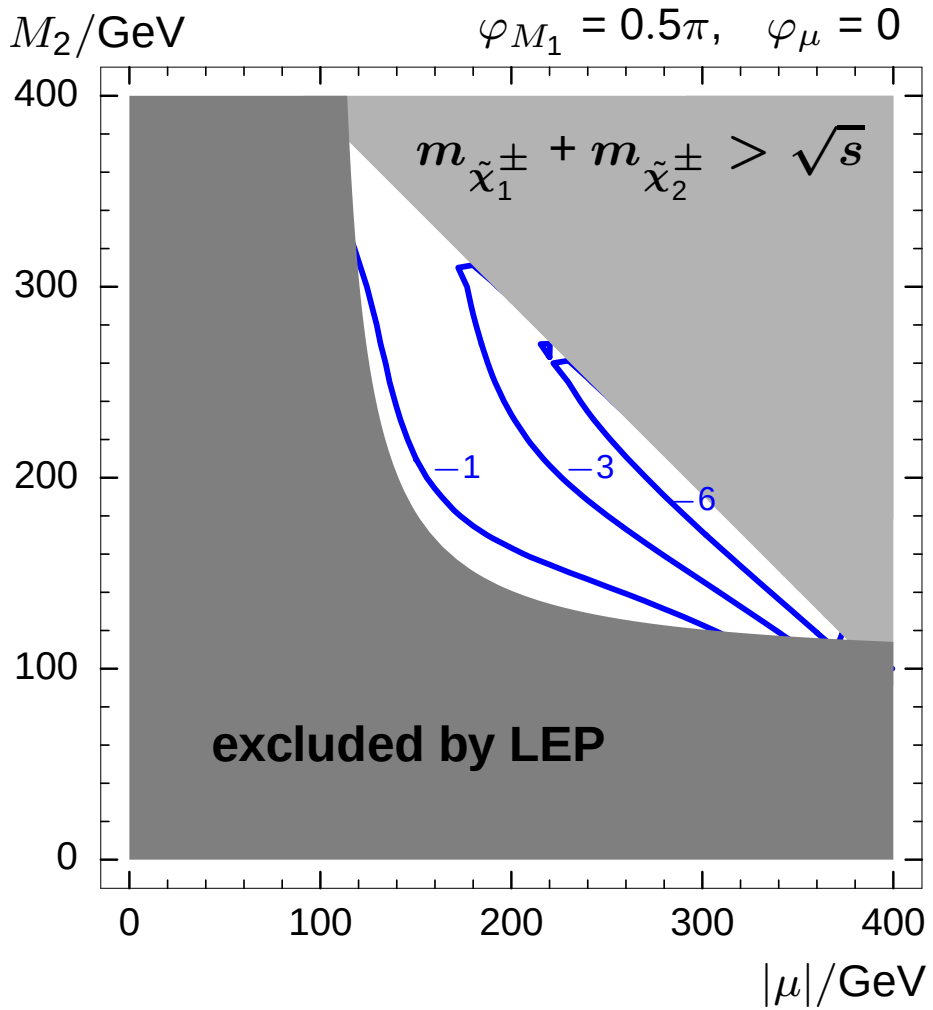
- Contours of A_T [in %] for $e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_1^+ \to \tilde{\chi}_2^- \tilde{\chi}_1^0 c\bar{s}$

$\tan\beta = 5$, $|M_1| = M_2\, 5/3 \tan^2\theta_W$,
$m_{\tilde{\nu}} = 250$ GeV, $m_{\tilde{u}_L} = 500$ GeV

$\sqrt{s} = 500$ GeV, $P_{e^-} = -0.8$, $P_{e^+} = +0.6$

Dark shaded area:
$m_{\tilde{\chi}_1^\pm} < 103$ GeV

Light shaded area:
$m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_2^\pm} > \sqrt{s}$



T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

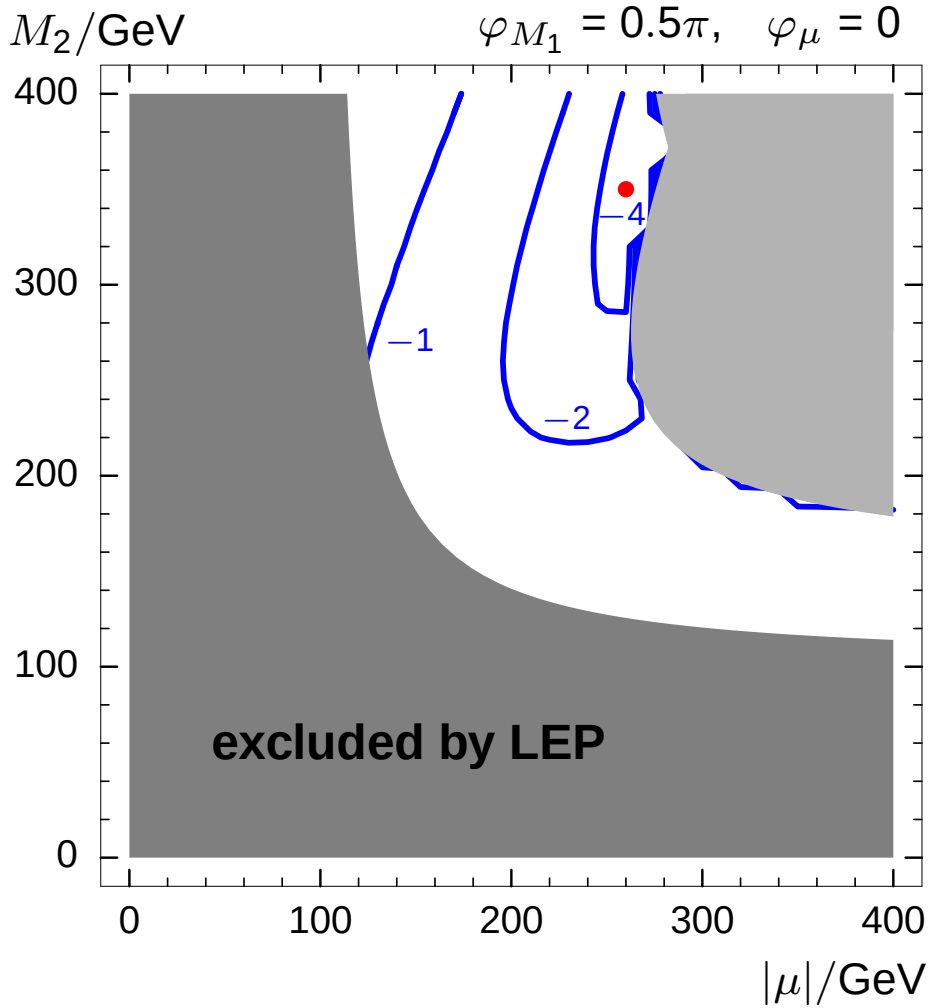
- Contours of A_T [in %] for $e^+e^- \to \tilde{\chi}_1^- \tilde{\chi}_1^+ \to \tilde{\chi}_1^- \tilde{\chi}_1^0 c\bar{s}$

tan β = 5, $|M_1| = M_2\, 5/3 \tan^2 \theta_W$,
$m_{\tilde{\nu}}$ = 250 GeV, $m_{\tilde{u}_L}$ = 500 GeV

$\sqrt{s}$ = 500 GeV, P_{e^-} = −0.8, P_{e^+} = +0.6

Dark shaded area:
$m_{\tilde{\chi}_1^\pm} < 103$ GeV

Light shaded area:
$2m_{\tilde{\chi}_1^\pm} > \sqrt{s}$ or
$m_{\tilde{\chi}_1^\pm} > m_W + m_{\tilde{\chi}_1^0}$



$|\mu|$ = 260 GeV, M_2 = 350 GeV: $\sigma(e^+e^- \to \tilde{\chi}_1^- \tilde{\chi}_1^+) \cdot BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 c\bar{s})$ = 117 fb

T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

Asymmetry A_T for $e^+e^- \to \tilde{\chi}_j^- \tilde{\chi}_1^+ \to \tilde{\chi}_j^- \tilde{\chi}_1^0 \ell^+ \nu$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_1^+} \times \vec{p}_{\ell^+})$

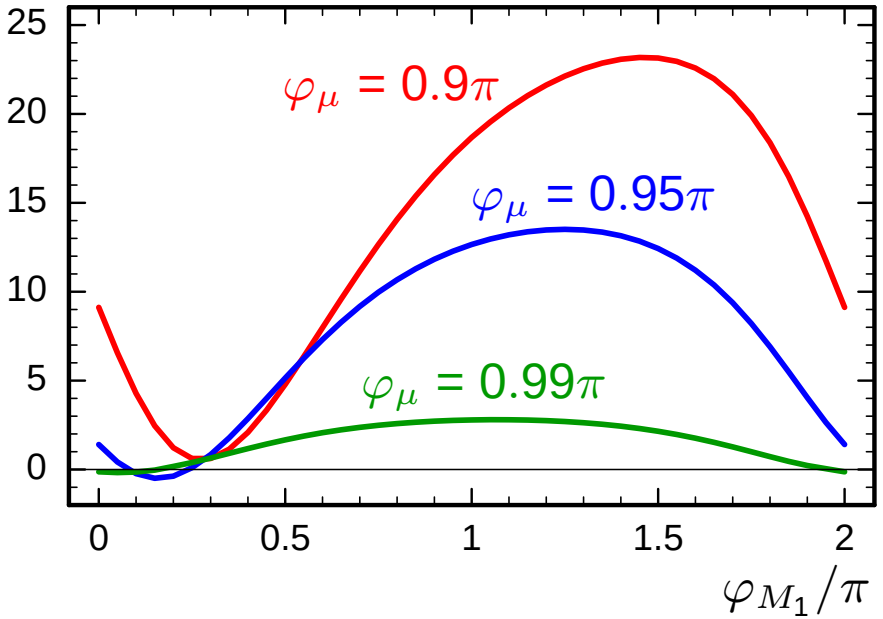
$\to$ reconstruction of $\vec{p}_{\tilde{\chi}_1^+}$ with information from $\tilde{\chi}_j^-$ decay

- $e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_1^+ \to \tilde{\chi}_2^- \tilde{\chi}_1^0 \ell^+ \nu$ for

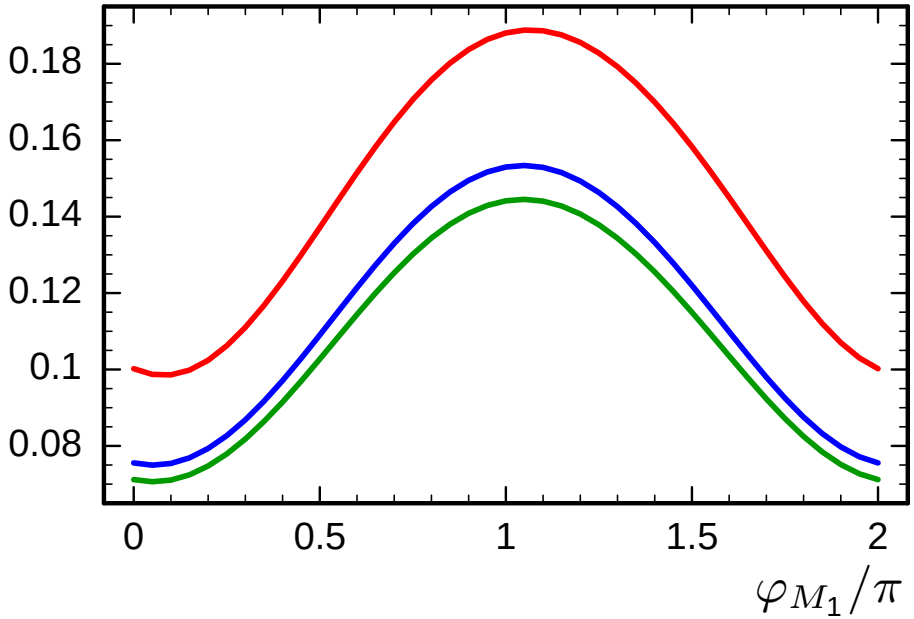
  $\tan\beta$ = 5, M_2 = 120 GeV, $|M_1| = M_2\, 5/3 \tan^2\theta_W$, $|\mu|$ = 320 GeV, $m_{\tilde{\nu}}$ = 250 GeV,

  $m_{\tilde{u}_L}$ = 500 GeV, $\sqrt{s}$ = 500 GeV, $P_{e^-} = -0.8$, P_{e^+} = +0.6

A_T in %



$\sigma(e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_1^+) \cdot BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \ell^+ \nu)$/fb



T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

- Contours of A_T [in %] for $e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_1^+ \to \tilde{\chi}_2^- \tilde{\chi}_1^0 \ell^+ \nu$

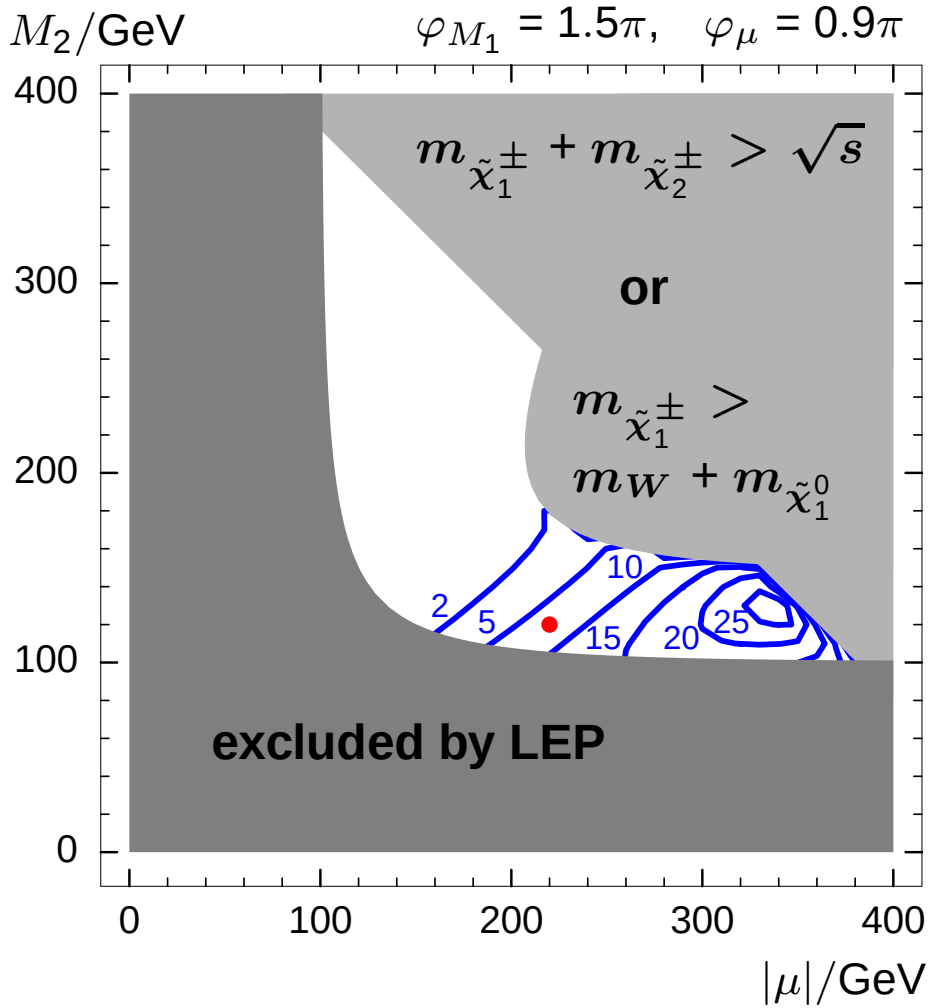
$\tan\beta = 5$, $|M_1| = M_2\, 5/3 \tan^2\theta_W$,
$m_{\tilde{\nu}} = 250$ GeV, $m_{\tilde{u}_L} = 500$ GeV

$\sqrt{s} = 500$ GeV, $P_{e^-} = -0.8$, $P_{e^+} = +0.6$

Dark shaded area:
$m_{\tilde{\chi}_1^\pm} < 103$ GeV

Light shaded area:
$m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_2^\pm} > \sqrt{s}$ or
$m_{\tilde{\chi}_1^\pm} > m_W + m_{\tilde{\chi}_1^0}$

$|\mu| = 220$ GeV, $M_2 = 120$ GeV:
$\sigma \cdot BR = 2.0$ fb



- $e^+e^- \to \tilde{\chi}_1^- \tilde{\chi}_1^+ \to \tilde{\chi}_1^- \tilde{\chi}_1^0 \ell^+ \nu$: $A_T = \mathcal{O}(1\,\%)$

T-odd asymmetries for two-body decays

Chargino/neutralino production with subsequent two-body decays

- Leptonic decays:

$$e^+e^- \to \tilde{\chi}_1^0 + \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \tilde{\ell}\ell_1, \quad \tilde{\ell} \to \tilde{\chi}_1^0 \ell_2 \qquad (\ell = e, \mu, \tau)$$

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0308141, hep-ph/0308143]

[Bartl, Fraas, Kernreiter, Kittel, W. Majerotto, hep-ph/0310011]

$$e^+e^- \to \tilde{\chi}_i^- + \tilde{\chi}_j^+ \to \tilde{\chi}_i^- + \tilde{\nu}\ell^+$$

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0406309]

- Decays into Z and W:

$$e^+e^- \to \tilde{\chi}_i^0 + \tilde{\chi}_j^0 \to \tilde{\chi}_i^0 + \tilde{\chi}_n^0 Z, \quad Z \to \ell\bar{\ell}, q\bar{q}$$

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0402016]

$$e^+e^- \to \tilde{\chi}_i^- + \tilde{\chi}_j^+ \to \tilde{\chi}_i^- + \tilde{\chi}_n^0 W^+, \quad W^+ \to c\bar{s}$$

[Bartl, Fraas, Kernreiter, Kittel, Majerotto, '04]

- CP asymmetries using tau polarisation for $\ell = \tau$

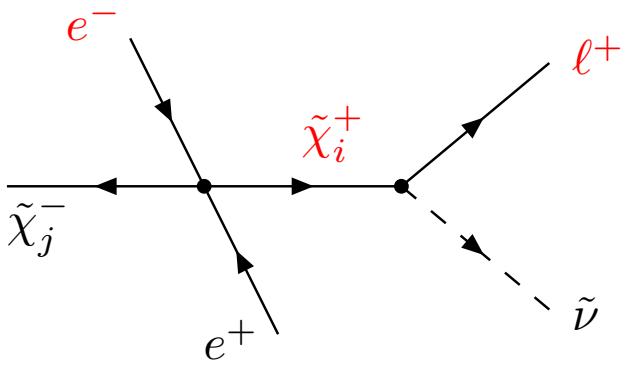
[Bartl, Kernreiter, Kittel, hep-ph/0309340; Choi, Drees, Gaissmaier, Song, hep-ph/0310284]

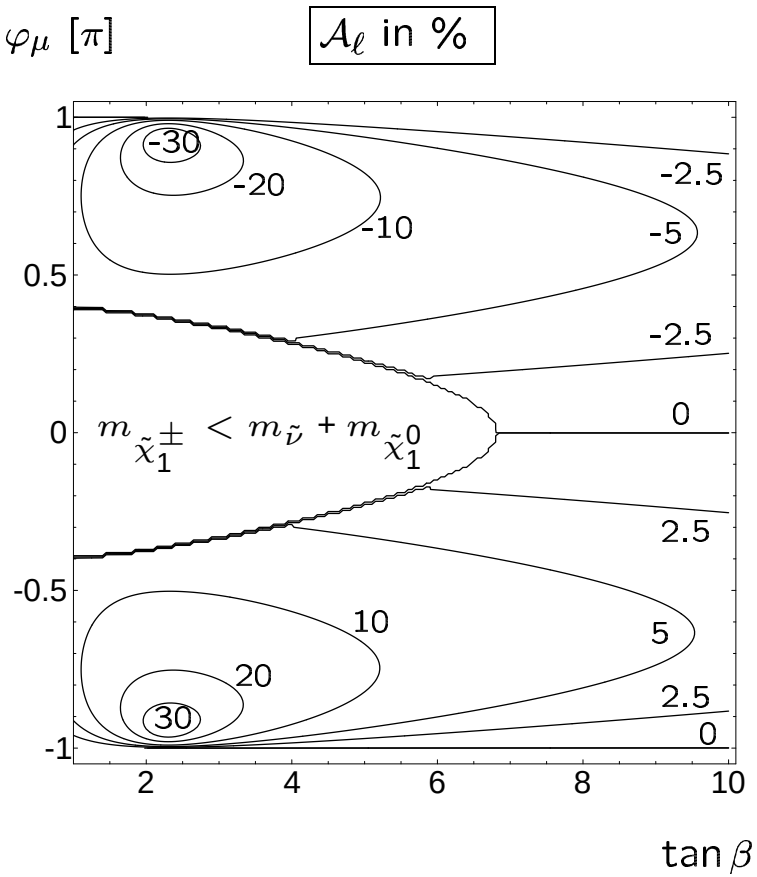
T-odd asymmetry for $\tilde{\chi}^{\pm}$ two-body decays

Asymmetry A_T for two-body decay of charginos into sneutrino

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0406309]

$e^+e^- \to \tilde{\chi}_2^- + \tilde{\chi}_1^+ \to \tilde{\chi}_2^- + \tilde{\nu}\ell^+, \qquad \mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_1^+} \times \vec{p}_{\ell^+})$





in scenario: M_2 = 200 GeV, $|\mu|$ = 400 GeV, $m_{\tilde{\nu}}$ = 185 GeV

$\sqrt{s}$ = 800 GeV, $P_{e^-} = -0.8$, $P_{e^+} = 0.6$

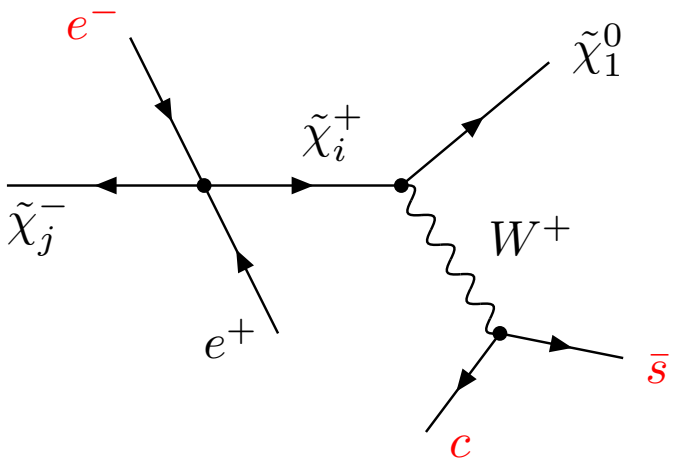
$\sigma \cdot BR$ = 2 fb – 20 fb

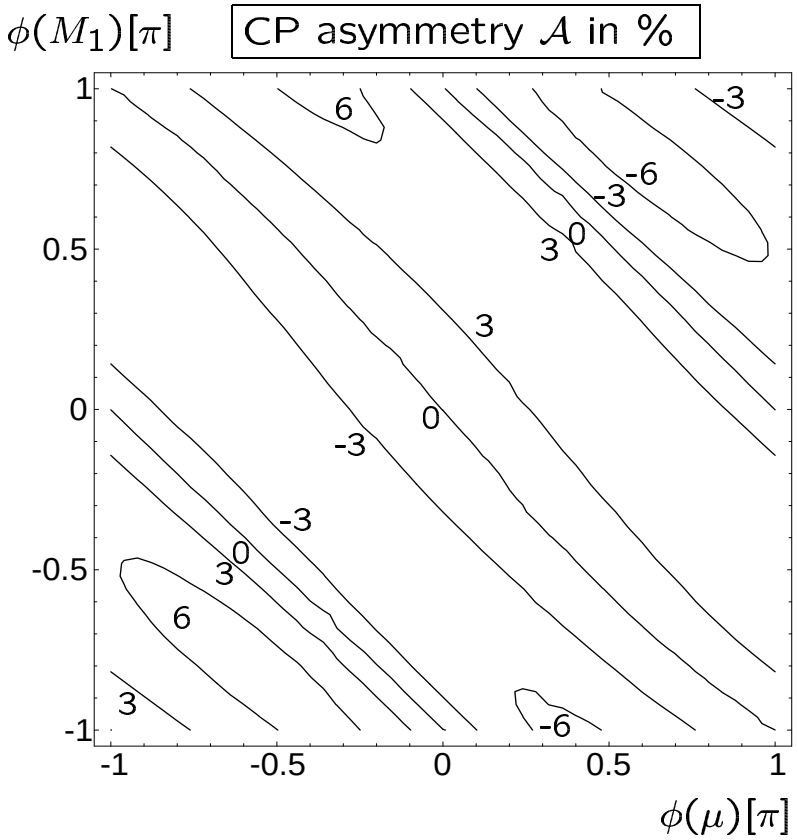
T-odd asymmetry for $\tilde{\chi}^{\pm}$ two-body decays

Asymmetry A_T for two-body decay of charginos into W

[Bartl, Fraas, Kernreiter, Kittel, Majerotto, '04]

$$e^+e^- \to \tilde{\chi}_1^- + \tilde{\chi}_1^+ \to \tilde{\chi}_1^- + \tilde{\chi}_1^0 W^+, \quad W^+ \to c\bar{s}, \qquad \mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_c \times \vec{p}_{\bar{s}})$$





in scenario: $|M_1|$ = 200 GeV, M_2 = 400 GeV, $|\mu|$ = 350 GeV
m_0 = 300 GeV, tan β = 10

$\sqrt{s}$ = 800 GeV, $P_{e^-} = -0.8$, $P_{e^+} = 0.6$

$\sigma \cdot BR$ = 66 fb – 74 fb

Conclusions and outlook

- Aim: revealing the CP structure of the underlying model
- T-odd asymmetries in chargino and neutralino sectors
  - based on triple product correlations
  - full spin correlations between production and decay necessary
  - for three-body and two-body decays
- Asymmetries of $\mathcal{O}(30\,\%)$ ($\tilde{\chi}^{\pm}$) and $\mathcal{O}(10\,\%)$ ($\tilde{\chi}^{0}$) possible

  $\Rightarrow$ important tool for $\rightarrow$ search for CP violation in SUSY

  $\rightarrow$ determination of SUSY phases
- Monte Carlo study in neutralino sector $\rightarrow$ next talk

  [Aguilar-Saavedra, hep-ph/0404104]
- Outlook: incorporation in strategies for parameter determination