CP Violation in SUSY

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Outline

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- Summary

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
  A_f : trilinear couplings of sfermions
  $m_{\tilde{g}}$: gluino mass
- Introduction of CP violation
  - may help to explain baryon asymmetry of universe
  - constraints from electric dipole moments (EDMs) of e, n, Hg, Tl

[Barger, Falk, Han, Jiang, Li, Plehn, hep-ph/0101106]

[Abel, Khalil, Lebedev, hep-ph/0103320]

Introduction

Complex parameters in mass mixing

- Sfermion mass matrix:

$$\mathcal{L}_M^{\tilde{f}} = -(\tilde{f}_L^*, \tilde{f}_R^*) \begin{pmatrix} M^2_{\tilde{f}_{LL}} & M^2_{\tilde{f}_{LR}} \\ M^2_{\tilde{f}_{RL}} & M^2_{\tilde{f}_{RR}} \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix}$$

with

$$M^2_{\tilde{f}_{RL}} = (M^2_{\tilde{f}_{LR}})^* = m_f \left(A_f - \mu^* (\tan\beta)^{-2T_f^3} \right)$$

A_f : trilinear couplings of sfermions $\rightarrow |A_f|, \varphi_{A_f}$

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

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

- 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

CP conserving observables

- Recent study of SUSY phases at linear colliders

  [Choi, Drees, Gaissmaier, hep-ph/0403054]

  - impact on chargino, neutralino and selectron production
  - detailed analysis of EDM constraints on phases
    $\longrightarrow$ cancellations $\Rightarrow$ correlation between phases
  - direct evidence for CP violation from $\vec{s}_\perp(\tilde{\chi})$

- Production of charginos/neutralinos at linear colliders
  $\longrightarrow$ Determination of $|\mu|$, φ_μ, $|M_1|$, φ_{M_1}, M_2, $\tan\beta$

  [Choi, Djouadi, Song, Zerwas, hep-ph/9812236]
  [Kneur, Moultaka, hep-ph/9907360, hep-ph/9910267]
  [Barger, Han, Li, Plehn, hep-ph/9907425]
  [Choi, Guchait, Kalinowski, Zerwas, hep-ph/0001175]
  [Choi, Djouadi, Guchait, Kalinowski, Song, Zerwas, hep-ph/0002033]
  [Choi, Kalinowski, Moortgat-Pick, Zerwas, hep-ph/0108117, hep-ph/0202039]
  [Gounaris, Mouël, hep-ph/0204152]

CP conserving observables

Branching ratios of 3rd generation sfermions

- Impact of phases φ_{A_f}, φ_{M_1}, φ_μ on two-body decays of $\tilde{\tau}$, $\tilde{t}$ and $\tilde{b}$

  $\rightarrow$ emphasis on φ_{A_τ}, φ_{A_t}, φ_{A_b}

  $\rightarrow$ possible determination of $|A_f|$, φ_{A_f} or Re(A_f), Im(A_f)

- Phase in sfermion sector:

$$\varphi_{\tilde{f}} = \arg\left[M^2_{\tilde{f}_{RL}}\right] = \arg\left[A_f - \mu^*(\tan\beta)^{-2T^3_f}\right]$$

CP conserving observables $B(\tilde{\tau})$

$\tilde{\tau}$ sector

[Bartl, Hidaka, Kernreiter, Porod, hep-ph/0204071, hep-ph/0207186]

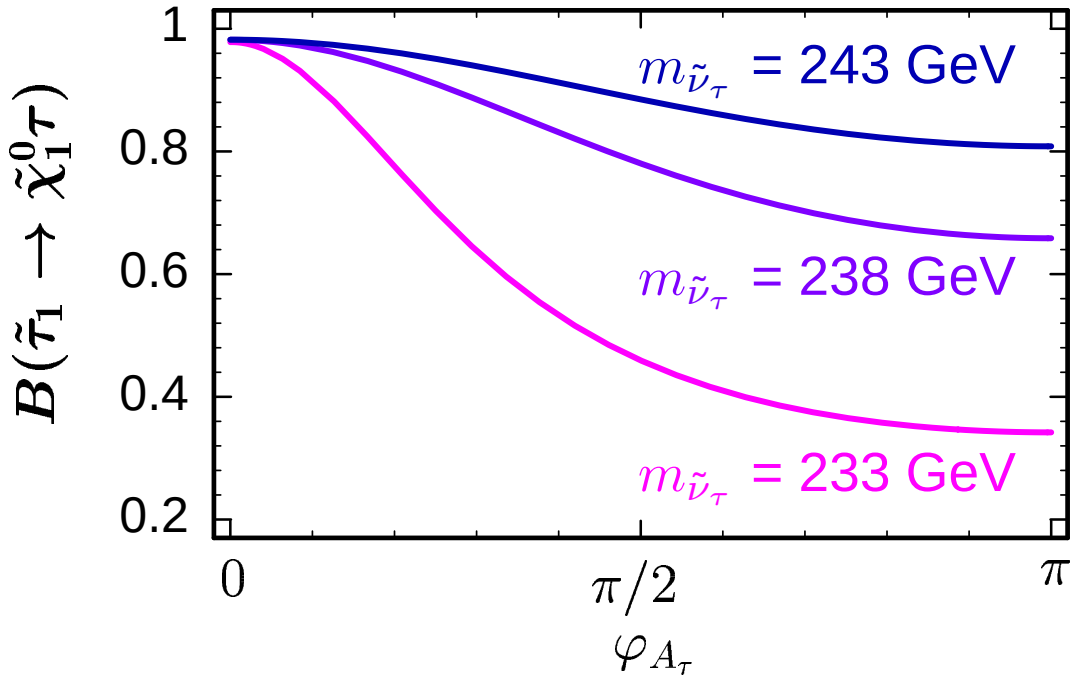
- Branching ratio $B(\tilde{\tau}_1 \to \tilde{\chi}_1^0 \tau)$ in scenario:
  $m_{\tilde{\tau}_1}$ = 240 GeV, $|A_\tau|$ = 1 TeV, $|\mu|$ = 300 GeV, φ_μ = 0,
  M_2 = 200 GeV, $|M_1| = M_2 5/3 \tan^2\theta_W$, φ_{M_1} = 0, $\tan\beta$ = 3

$\to$ strong phase dependence

$\to$ caused by mixing angle

$\to$ $\tilde{\tau}_1$: $\tilde{\tau}_R \to \tilde{\tau}_L$ for $m_{\tilde{\nu}_\tau}$ = 233 GeV

$\to$ occurs for $M_{\tilde{\tau}_{LL}} \approx M_{\tilde{\tau}_{RR}}$ *and* $|A_\tau| \approx |\mu| \tan\beta$



CP conserving observables $B(\tilde{\tau})$

- Global fit of many observables

  $\rightarrow$ masses, branching ratios, production cross sections $\sigma(e^+e^- \rightarrow \tilde{\tau}_i\tilde{\tau}_j)$

  for $\sqrt{s}$ = 800 GeV and polarized beams in scenario:
  $m_{\tilde{\tau}_1}$ = 150 GeV, $m_{\tilde{\tau}_2}$ = 350 GeV, $|A_\tau|$ = 800 GeV, φ_{A_τ} = $3/4\pi$
  $|\mu|$ = 250 GeV, φ_μ = 0, M_2 = 280 GeV, $|M_1|$ = $M_2 5/3 \tan^2\theta_W$, φ_{M_1} = 0

  $\Rightarrow$ tan β = 3: $\delta(\mathrm{Im}(A_\tau))/|A_\tau|$ = 9 %, $\delta(\mathrm{Re}(A_\tau))/|A_\tau|$ = 22 %

  tan β = 30: $\delta(\mathrm{Im}(A_\tau))/|A_\tau|$ = 3 %, $\delta(\mathrm{Re}(A_\tau))/|A_\tau|$ = 7 %

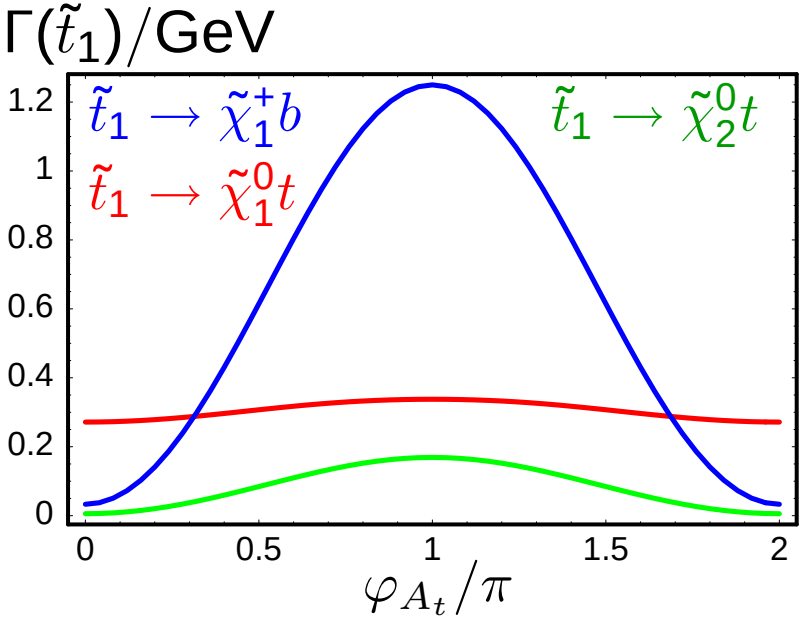
CP conserving observables $B(\tilde{t})$, $B(\tilde{b})$

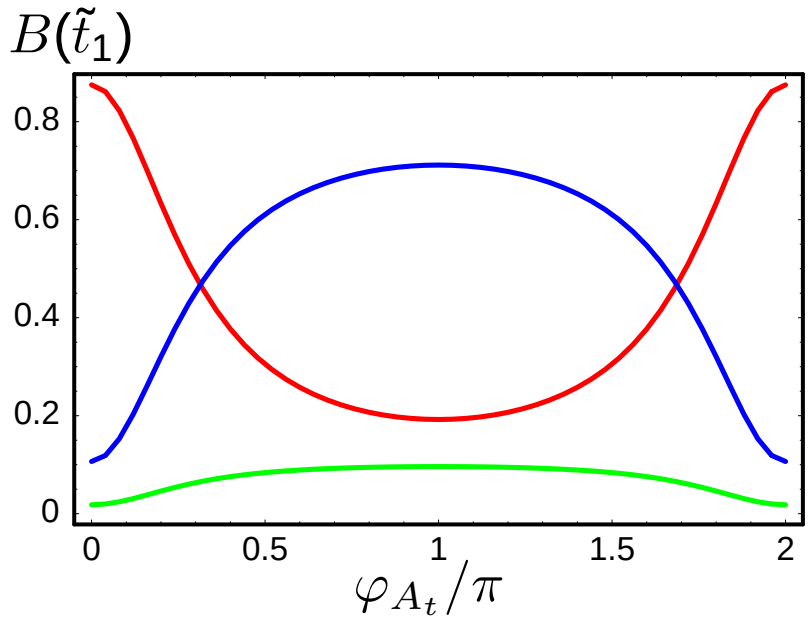
$\tilde{t}$ and $\tilde{b}$ sectors

[Bartl, SH, Hidaka, Kernreiter, Porod, hep-ph/0306281, hep-ph/0307317, hep-ph/0311338]

- $\tilde{t}_1$ partial decay widths and branching ratios in scenario:

  $m_{\tilde{t}_L} > m_{\tilde{t}_R}$, $m_{\tilde{t}_1}$ = 379 GeV , $m_{\tilde{t}_2}$ = 575 GeV, $m_{\tilde{b}_1}$ = 492 GeV, (SPS 1a inspired)
  $|A_t|$ = 466 GeV, $|A_b|$ = 759 GeV, φ_{A_b} = 0, $|\mu|$ = 352 GeV, φ_μ = 0,
  M_2 = 193 GeV, $|M_1| = M_2 5/3 \tan^2\theta_W$, φ_{M_1} = 0, $\tan\beta$ = 10





$\to$ pronounced phase dependence of $\Gamma(\tilde{t}_1 \to \tilde{\chi}_1^+ b)$: effect of $\varphi_{\tilde{t}} \sim \varphi_{A_t}$

CP conserving observables $B(\tilde{t})$, $B(\tilde{b})$

- Global fit of many observables

  $\rightarrow$ masses, branching ratios, production cross sections $\sigma(e^+e^- \rightarrow \tilde{q}_i\tilde{q}_j)$

  for $\sqrt{s}$ = 2 TeV and polarized beams in scenarios:

  tan β = 6, M_D = 169.6 GeV, M_U = 408.8 GeV, M_Q = 623.0 GeV, $|A_t|$ = $|A_b|$ = 800 GeV, φ_{A_t} = φ_{A_b} = $\pi/4$, M_2 = 300 GeV, μ = -350 GeV, $m_{\tilde{g}}$ = 1000 GeV, m_{H^+} = 900 GeV

  tan β = 30, M_D = 360.0 GeV, M_U = 198.2 GeV, M_Q = 691.9 GeV, $|A_t|$ = 600 GeV, φ_{A_t} = $\pi/4$, $|A_b|$ = 1000 GeV, φ_{A_b} = $3\pi/2$, M_2 = 200 GeV, μ = -350 GeV, $m_{\tilde{g}}$ = 1000 GeV, m_{H^+} = 350 GeV

$\Rightarrow$ $\delta(\mathrm{Im}(A_t))/|A_t| = 2-3\,\%$, $\delta(\mathrm{Re}(A_t))/|A_t| = 2-3\,\%$

$\delta(\mathrm{Im}(A_b))/|A_b| \sim 50\,\%$, $\delta(\mathrm{Re}(A_b))/|A_b| \sim 50\,\%$

CP conserving observables $A_\phi(\tilde{\chi}^\pm)$

Azimuthal asymmetries in chargino production

[Bartl, Hohenwarter-Sodek, Kernreiter, Rud, hep-ph/0403265]

Chargino production with subsequent two-body decays at linear collider with transverse beam polarization

$$e^+e^- \longrightarrow \tilde{\chi}_i^+ + \tilde{\chi}_j^-, \qquad \tilde{\chi}_j^- \longrightarrow \ell^-\tilde{\nu}_\ell, \quad \tilde{\chi}_j^- \longrightarrow W^-\tilde{\chi}_1^0$$

$\rightarrow$ Azimuthal asymmetry:

$$A_\phi = \frac{1}{\sigma}\left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi}\right]\frac{d\sigma}{d\phi}d\phi$$

with $\vec{s}_\perp^{\,e^-} \perp \vec{s}_\perp^{\,e^+}$ and $\phi = \angle(\vec{s}_\perp^{\,e^-}, \vec{p}_\perp^{\,\ell^-})$ or $\angle(\vec{s}_\perp^{\,e^-}, \vec{p}_\perp^{\,W^-})$

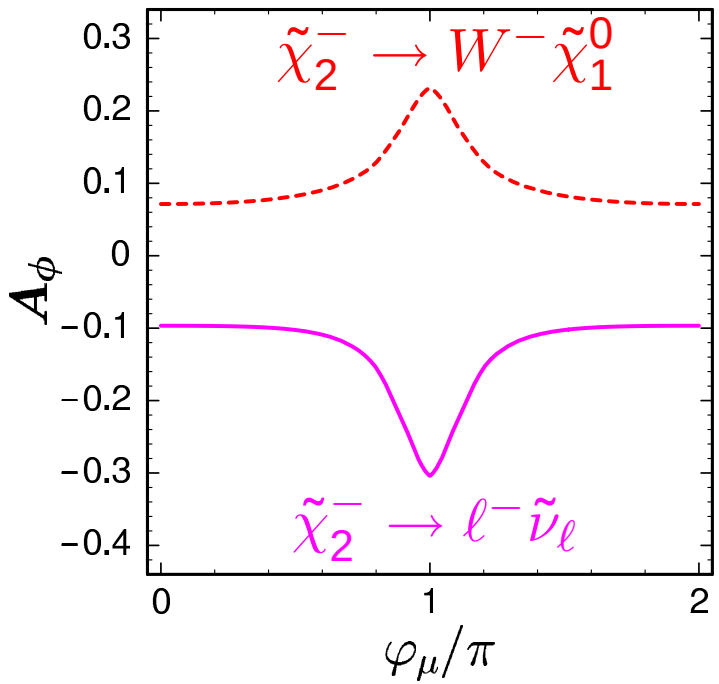
CP conserving observables $A_\phi(\tilde{\chi}^\pm)$

Azimuthal asymmetry A_ϕ for $e^+e^- \to \tilde{\chi}_1^+ + \tilde{\chi}_2^-$

in scenario:

$|\mu|$ = 400 GeV, M_2 = 200 GeV, φ_{M_1} = 0,
tan β = 3, $m_{\tilde{\nu}}$ = 150 GeV

$\sqrt{s}$ = 800 GeV



Possible CP sensitive observables:

→ Triple product correlations including transverse beam polarization:
e.g. for $\vec{s}_\perp \cdot (\vec{p}_1 \times \vec{p}_2)$

However:

correlations vanish if at least one subsequent chargino decay is ignored

CP sensitive observables $A_T(\tilde{\chi}^0)$, 3-body

CP asymmetry in neutralino production and leptonic three-body decay

[Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, '04]

$$e^+e^- \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_1^0 \ell^+\ell^- \qquad (\ell = e, \mu)$$

$\longrightarrow$ with full spin correlation between production and decay

[Moortgat-Pick, Fraas, hep-ph/9708481]
[Moortgat-Pick, Fraas, Bartl, Majerotto, hep-ph/9903220]
[Choi, Song, Song, hep-ph/9907474]

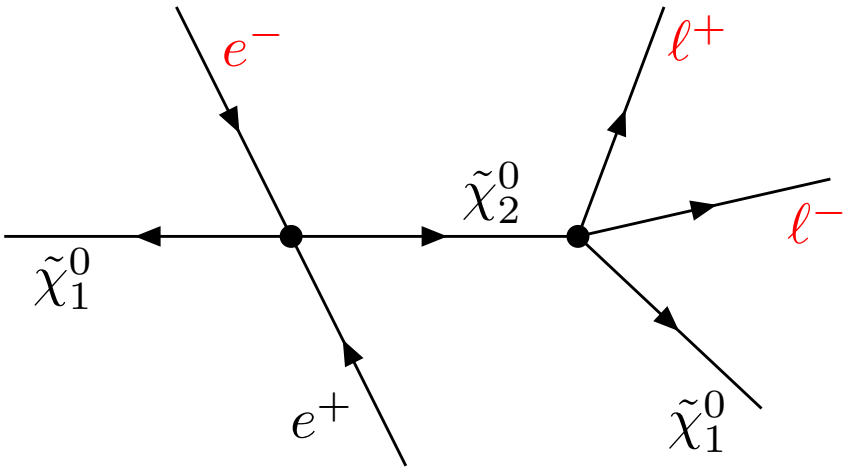
$\longrightarrow$ amplitude squared $|T|^2 = PD + \Sigma_P^a \Sigma_D^a$

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

$\Rightarrow$ CP violation at tree level

CP sensitive observables $A_T(\tilde{\chi}^0)$, 3-body

Triple product between $\vec{p}_{e^-}, \vec{p}_{\ell^-}$ and $\vec{p}_{\ell^+}$: $\boxed{\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})}$



→ T-odd asymmetry:

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

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

CP sensitive observables $A_T(\tilde{\chi}^0)$, 3-body

Contours of A_T in $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell^+\ell^-$

in scenario:

$\tan\beta$ = 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,

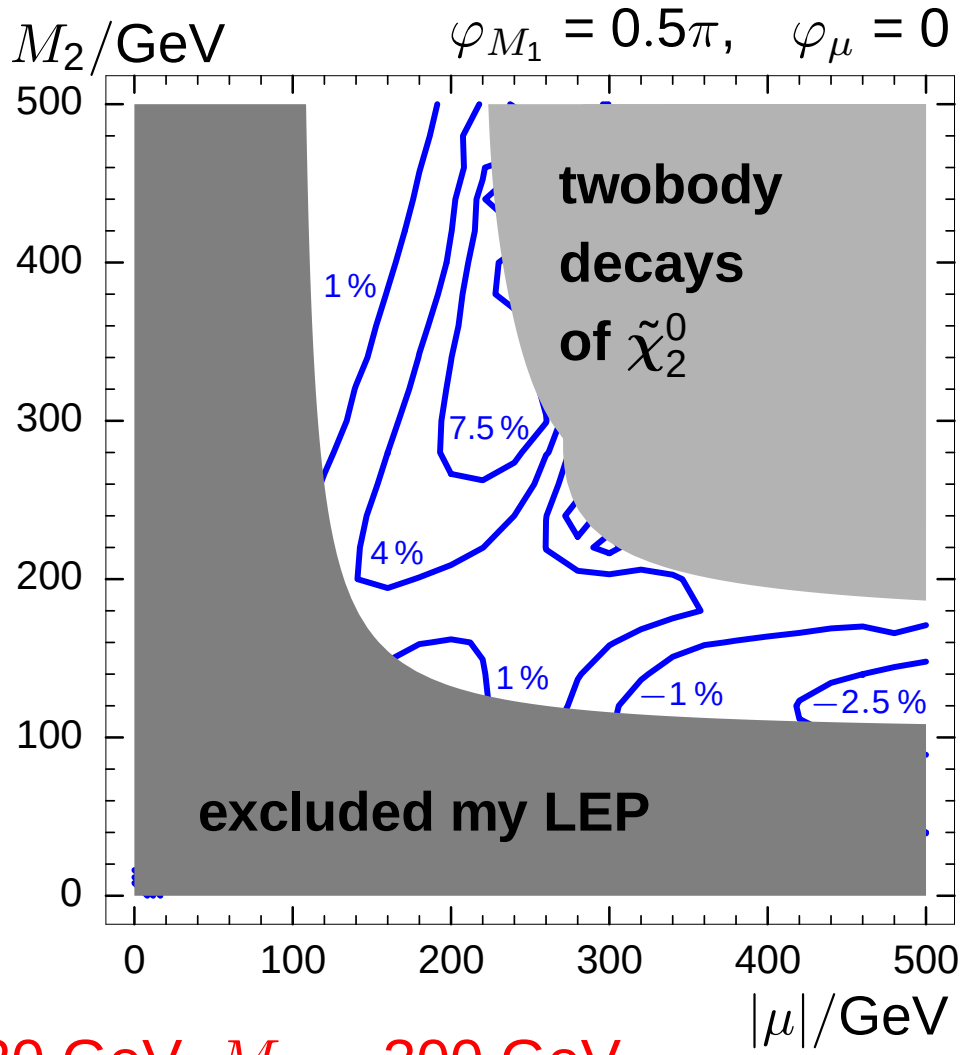
P_{e^-} = −0.8, P_{e^+} = +0.6

Dark shaded area:

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

Light shaded area:

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



$A_T > 7.5\,\%$ for $|\mu| \sim 220$ GeV, $M_2 \sim 300$ GeV

CP sensitive observables

Monte Carlo

Recent Monte Carlo studies of triple product asymmetries

[Aguilar-Saavedra, hep-ph/0403243, hep-ph/0404104]

→ in SPS 1a inspired scenario

→ including ISR, beamstrahlung, detector resolution and background

- $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$
- $e^+e^- \to \tilde{e}_L\tilde{e}_{R,L}, \quad \tilde{e}_L \to e\tilde{\chi}_2^0 \to e\tilde{\chi}_1^0\mu^+\mu^-$

⇒ $A_T \sim$ 10 % observable after few years of running

CP sensitive observables $A_T(\tilde{\chi})$, 2-body

CP asymmetry in chargino/neutralino production and two-body decay

- triple products in 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]
- CP asymmetries using tau polarization for $\ell = \tau$
  [Bartl, Kernreiter, Kittel, hep-ph/0309340]
  [Choi, Drees, Gaissmaier, Song, hep-ph/0310284]
- triple products in 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]

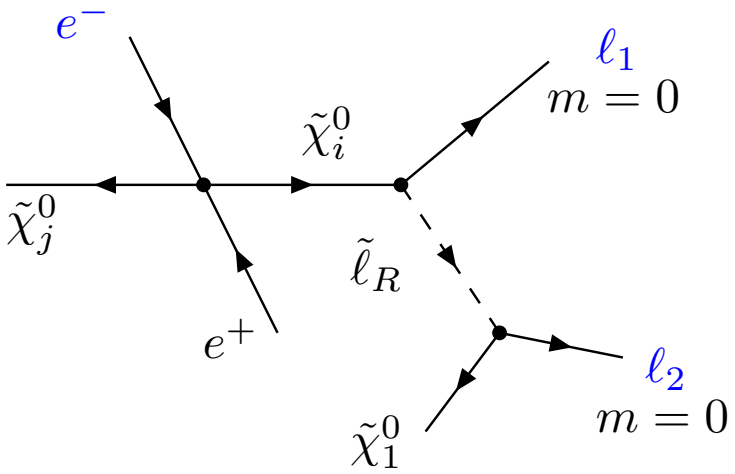
CP sensitive observables $A_T(\tilde{\chi}^0)$, 2-body

CP asymmetry A_T in leptonic two-body decay of neutralinos

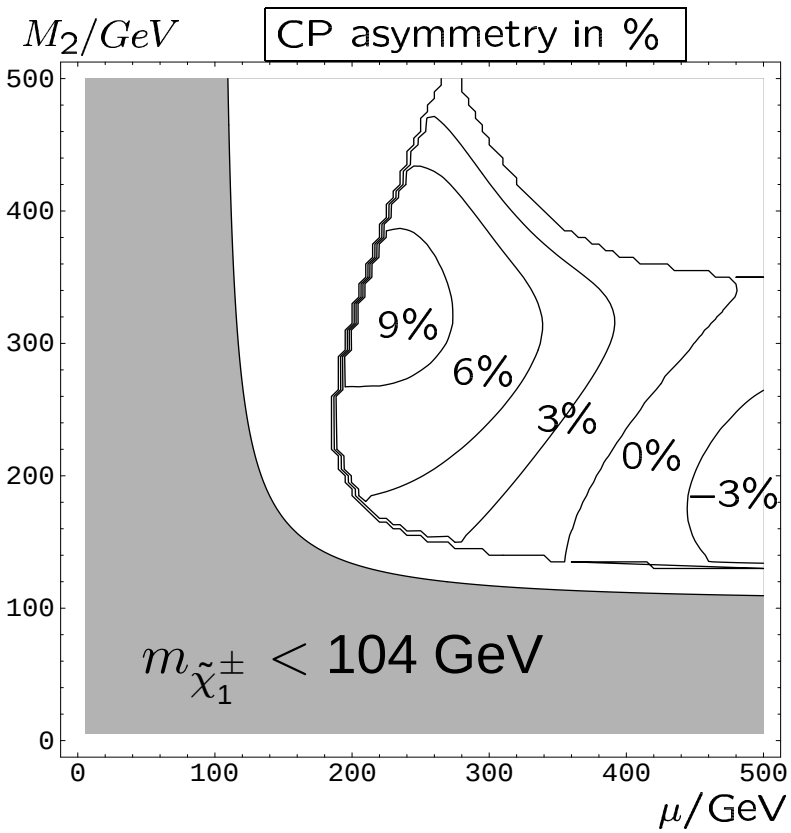
[Bartl, Fraas, Kittel, Majerotto, hep-ph/0308141, hep-ph/0308143]

$e^+e^- \longrightarrow \tilde{\chi}_1^0 + \tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_1^0 + \tilde{\ell}_R l_1, \quad \tilde{\ell}_R \longrightarrow \tilde{\chi}_1^0 l_2$

$\rightarrow$ triple product: $\mathcal{T} = \vec{p}(e^-) \cdot \left[\vec{p}(\ell_1) \times \vec{p}(\ell_2)\right]$



$\varphi_{M_1} = 0.5\pi, \quad \varphi_\mu = 0$



in scenario:

$|M_1| = M_2 5/3 \tan^2\theta_W$, $\tan\beta = 10$, $m_0 = 100$ GeV

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

$\sigma \gtrsim 60$ fb for $|\mu| \sim 220$ GeV, $M_2 \sim 300$ GeV

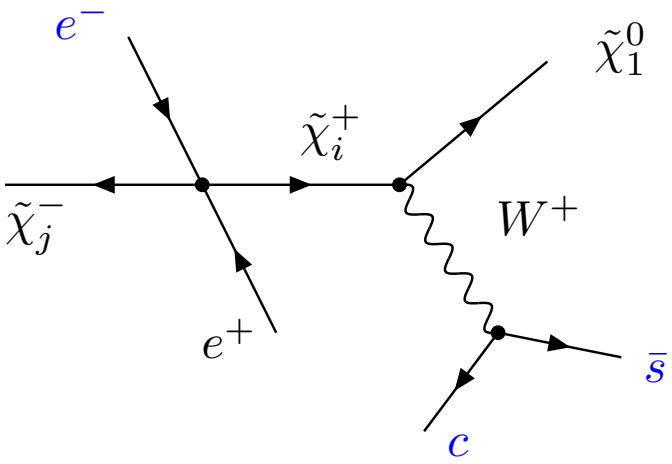
CP sensitive observables $A_T(\tilde{\chi}^{\pm})$, 2-body

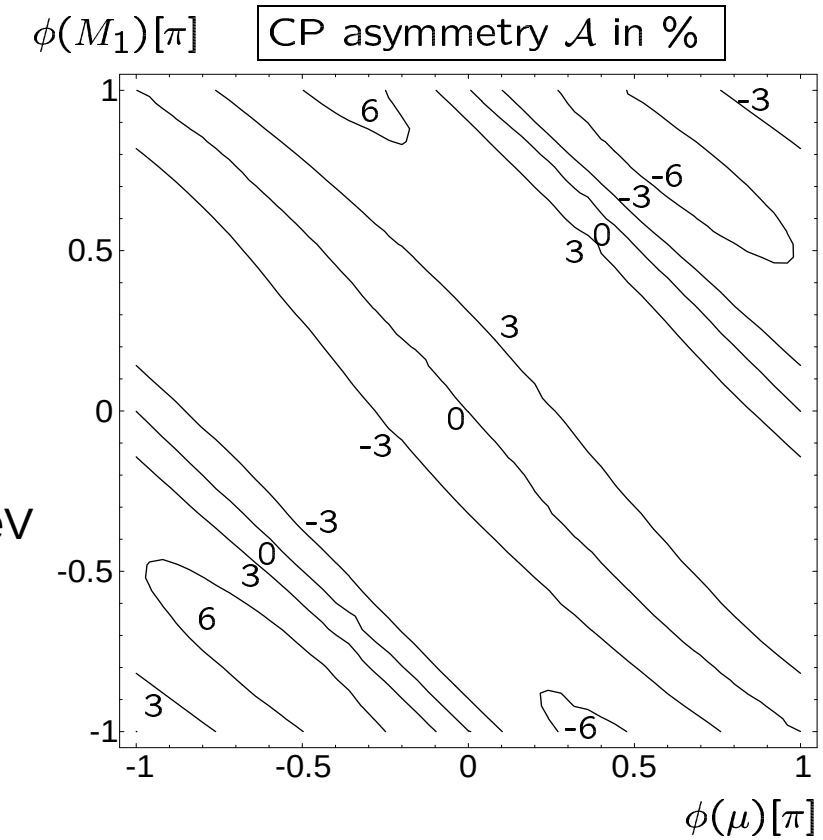
CP asymmetry A_T in two-body decay of charginos into W

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

$$e^+e^- \longrightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+ \longrightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^0 W^+, \quad W^+ \longrightarrow c\bar{s}$$

$\rightarrow$ triple product: $\mathcal{T} = \vec{p}(e^-) \cdot \left[\vec{p}(c) \times \vec{p}(\bar{s})\right]$





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

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

σ = 66 fb – 74 fb

Summary

- CP even observables
  - branching ratios of 3rd generation sfermions

    $\longrightarrow$ pronounced φ_{A_t} dependence of $\tilde{t}_i$ branching ratios

    $\longrightarrow$ estimation of expected accuracy by global fit:

    M_E, M_L: error $\sim$ 1 %; A_τ: error 5 – 20 %

    M_D, M_U, M_Q, A_t: error 2 – 3 %; A_b: error 50 – 100 %;
  - azimuthal asymmetry in chargino production with transverse beam polarization

    $\longrightarrow$ strong φ_μ dependence
- CP sensitive observables
  - triple product correlations in neutralino/chargino production + decay

    $\longrightarrow$ asymmetries $\sim$ 10 %, observable at linear colliders