CP Violation
in Sparticle Production and Decay

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Outline

- Introduction
  - MSSM with complex parameters
  - Constraints from EDMs and $B(b \to s\gamma)$
- Chargino/neutralino production and decay
  - Charginos/neutralinos at linear colliders
  - Triple product asymmetries
  - Charginos/neutralinos at Tevatron, LHC
- Squark/slepton production and decay
  - Branching ratios of third generation squark/sleptons
  - CP-odd asymmetries in their 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

  A_f : trilinear couplings of sfermions

  M_3 : SU(3) gaugino mass parameter

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

Introduction

Constraints

- Electric dipole moments (EDMs) of e, n, Hg, Tl

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

  - φ_μ, φ_{M_1}: one loop contributions of $\tilde{\chi}^0$, $\tilde{\chi}^\pm$
    $\Rightarrow$ strong constraints, especially on φ_μ
  - φ_{A_f}: two loop contributions $\Rightarrow$ constraints less severe

    [Chang, Keung, Pilaftsis ’99, Pilaftsis ’02]

- Measurements in B meson sector:

  E.g. branching ratio of $b \to s\gamma$: $2.0 \times 10^{-4} < B(b \to s\gamma) < 4.5 \times 10^{-4}$

  [Abe et. al (Belle) ’01; Chen at al. (Cleo) ’01]

  $\Rightarrow$ constraints on φ_{A_t} and φ_μ

  [Bertolini et al. ’91; Kagan, Neubert ’98; Hurth, Lunghi, Porod ’03]

Chargino/neutralino production & decay

- Chargino ($\tilde{\chi}^{\pm}$) mass matrix: $X = \begin{pmatrix} M_2 & \sqrt{2}\, m_W s_\beta \\ \sqrt{2}\, m_W c_\beta & \mu \end{pmatrix}$

- Neutralino ($\tilde{\chi}^0$) 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 $\longrightarrow |\mu|$, φ_μ

M_1 : U(1) gaugino mass parameter $\longrightarrow |M_1|$, φ_{M_1}

M_2 : SU(2) gaugino mass parameter

- Diagonalization $\longrightarrow$ masses depend on phases: $m_{\tilde{\chi}_i^\pm}(\varphi_\mu)$, $m_{\tilde{\chi}_i^0}(\varphi_{M_1}, \varphi_\mu)$

  $\longrightarrow$ complex mixing matrices $\longrightarrow$ enter $\tilde{\chi}^\pm$, $\tilde{\chi}^0$ couplings

Chargino/neutralino production & decay

Production of charginos/neutralinos at ILC

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

- Determination of parameters possible
- Example: [Choi, Kalinowski, Moortgat-Pick, Zerwas, hep-ph/0202039]

  Measurement of $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_{1,2}^0}$, $\sigma_{\text{pol}}(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$, $\sigma_{\text{pol}}(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$

  $\longrightarrow$ allows determination of $|\mu|$, φ_μ, $|M_1|$, φ_{M_1}, M_2, $\tan\beta$

  however: ambiguities in sign of $\sin\varphi_\mu$ and $\sin\varphi_{M_1}$
- Resolvable with CP-odd observables, e.g. normal $\tilde{\chi}_2^0$ polarization

Chargino/neutralino production & decay

T-odd/CP-odd asymmetries from triple product correlations

- Three-body decays

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

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

$$e^+e^- \to \tilde{\chi}_i^- \tilde{\chi}_1^+ \to \tilde{\chi}_i^- \tilde{\chi}_1^0 f \overline{f'}$$

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

- Two-body 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]

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

[Choi, Kim, hep-ph/0311037; Bartl, Fraas, Kittel, Majerotto, hep-ph/0402016]

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

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

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

[Kittel, Bartl, Fraas, Majerotto, hep-ph/0410054]

Chargino/neutralino production & decay

CP-odd observables

- Triple product correlations using tau polarization for $\ell = \tau$

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

- Monte Carlo studies for triple product asymmetries

  [Aguilar-Saavedra, hep-ph/0404104, hep-ph/0410068]

  including ISR, beamstrahlung, detector resolution and background

  $\Rightarrow$ Asymmetries $\sim$ 10 % observable after few years of running of ILC

- Threshold behavior of neutralino production and decay:

  [Choi, hep-ph/0308060]

  simultaneous steep S-wave excitations of $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ threshold and invariant mass distribution of f in $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 f\bar{f}$ $\Rightarrow$ CP violation

- CP-odd asymmetries with transverse beam polarization

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

  [Bartl, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, in preparation]

Charginos/neutralinos

Example: T-odd asymmetry for $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$ three-body decays

- $e^+e^- \to \tilde{\chi}_i + \tilde{\chi}_j \to \tilde{\chi}_i + \tilde{\chi}_1^0 f \bar{f}^{(\prime)}$
- Full spin correlation between production and decay

  [Moortgat-Pick, Fraas, ’97; Moortgat-Pick, Fraas, Bartl, Majerotto, ’98, ’99; Choi, Song, Song, ’99]
- Amplitude squared $|T|^2 = PD + \sum_{a=1}^{3} \Sigma_P^a \Sigma_D^a$
- In Σ_P^a and Σ_D^a: products like $i\epsilon_{\mu\nu\rho\sigma} p_i^\mu p_j^\nu p_k^\rho p_l^\sigma$

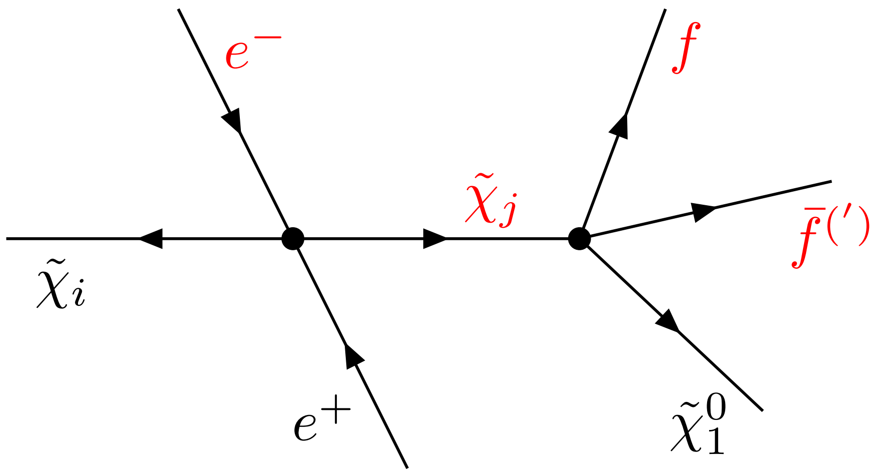
  $\Rightarrow$ with complex couplings: real contributions to observables

  $\Rightarrow$ CP violation at tree level

Charginos/neutralinos

T-odd asymmetry

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



$\longrightarrow$ T-odd asymmetry:

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

$\longrightarrow$ CP-odd, if final state interactions and finite-widths effects can be neglected

or define $A_{\text{CP}} = A_T - \bar{A}_T$

Charginos/neutralinos

T-odd asymmetry

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]

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

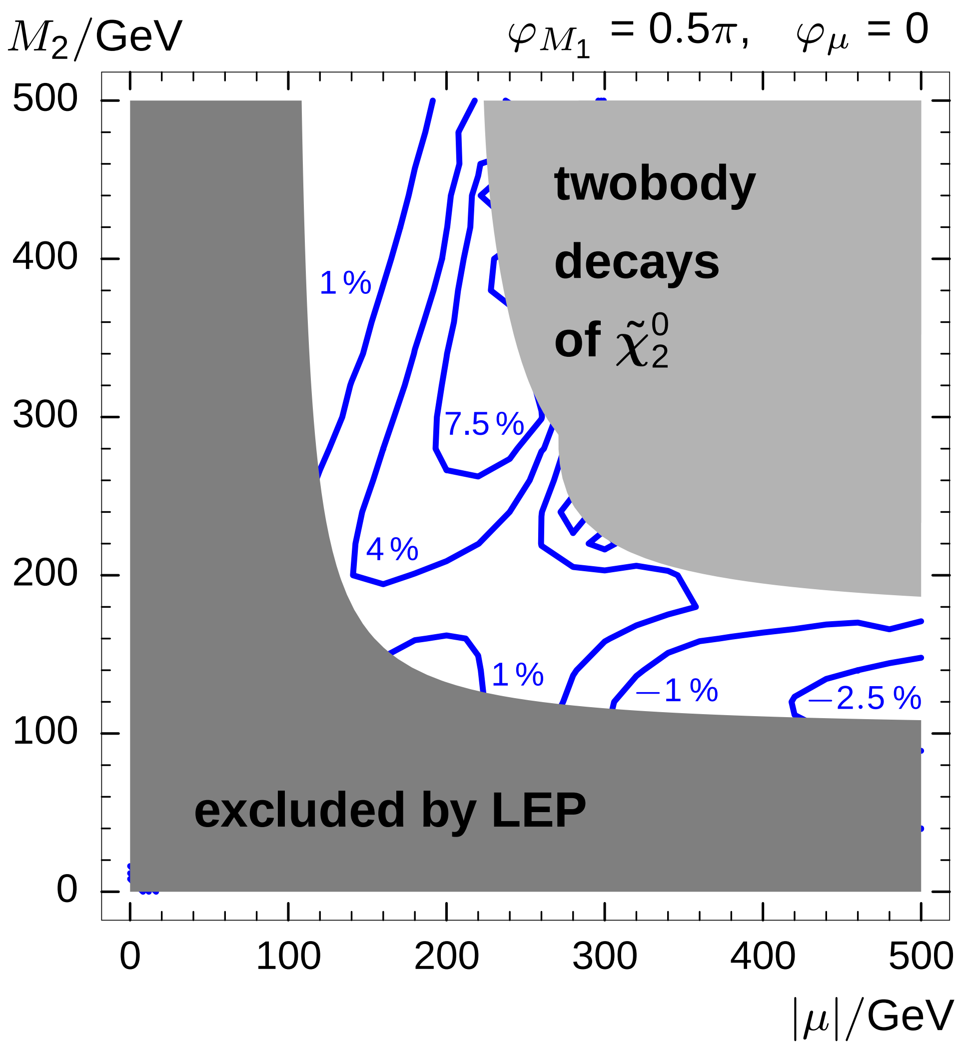
  Contours of A_T [in %] for
  $\tan\beta = 10$, $|M_1| = M_2\, 5/3 \tan^2\theta_W$,
  $m_{\tilde{e}_L} = 267.6$ GeV, $m_{\tilde{e}_R} = 224.4$ GeV

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

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

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

  large A_T and $\sigma \sim 10$ fb:
  $|\mu| \sim 240$ GeV, $M_2 \sim 300$ GeV



Charginos/neutralinos

T-odd asymmetry

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

  Contours of A_T [in %] for

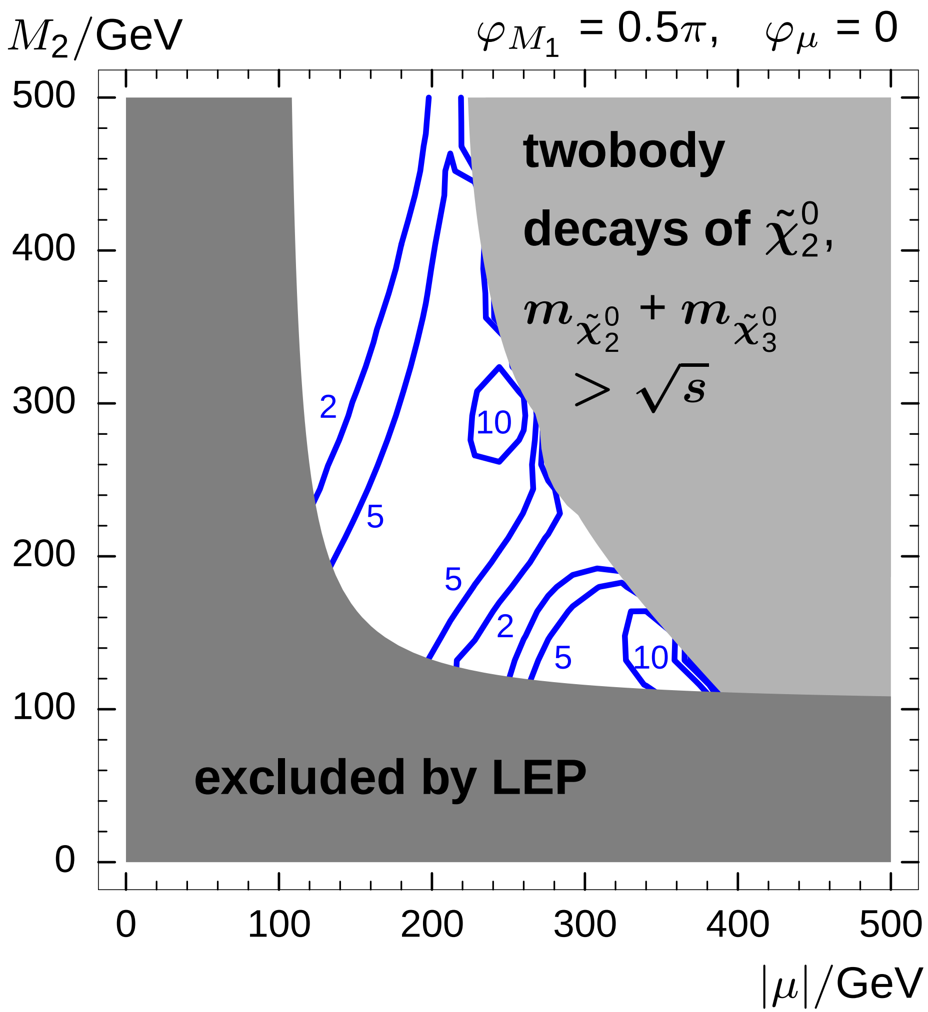
  $\tan\beta$ = 10, $|M_1|$ = $M_2\, 5/3 \tan^2\theta_W$,
  $m_{\tilde{e}_L}$ = 267.6 GeV, $m_{\tilde{e}_R}$ = 224.4 GeV

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

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

  Light shaded area:
  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} > m_Z$, $m_{\tilde{\chi}_2^0} > m_{\tilde{e}_R}$ or
  $m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_3^0} > \sqrt{s}$

  large A_T and $\sigma \sim 10$ fb:
  $|\mu| \sim 240$ GeV, $M_2 \sim 300$ GeV



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

Charginos/neutralinos — hadron colliders

- Impact of phases on trilepton signal at Tevatron
  $p\bar{p} \to \tilde{\chi}^\pm_1 \tilde{\chi}^0_2,\ \tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 \ell^\pm \nu,\ \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+ \ell^-$
  [Choi, Guchait, Song, Song, hep-ph/9904276, hep-ph/0007276]

  $\longrightarrow$ triple product asymmetries analyzed

- Production at LHC
  - Single and pair production of $\tilde{\chi}^0$
    $(q\bar{q} \to \tilde{\chi}^0_i \tilde{g},\ qg \to \tilde{\chi}^0_i \tilde{q},\ q\bar{q}' \to \tilde{\chi}^0_i \tilde{\chi}^\pm_j,\ q\bar{q} \to \tilde{\chi}^0_i \tilde{\chi}^0_j)$
    [e.g. Gounaris, Layssac, Porfyriadis, Renard, hep-ph/0404162, hep-ph/0411366]

    $\longrightarrow$ try triple product asymmetries (?)

  - Cascade decays of gluinos and squarks
    [e.g. Kawagoe, Nojiri, Polesello, hep-ph/0410160; Gjelsten, Miller, Osland, hep-ph/0410303]

    $\longrightarrow$ endpoints of kinematical distributions $\Rightarrow$ determination of masses

    $\longrightarrow$ CP-even observables $\Rightarrow$ ambiguities

    $\longrightarrow$ try triple product asymmetries with leptons in cascades (?)

Squark/slepton production & decay

- Squark/slepton 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 $\longrightarrow |A_f|, \varphi_{A_f}$

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

- Phase effects large in third generation: $\tilde{t}, \tilde{b}, \tilde{\tau}$
- Diagonalization $\longrightarrow$ masses depend on phases: $m_{\tilde{f}_i}(\varphi_{A_f}, \varphi_\mu)$

  $\longrightarrow$ complex mixing matrices $\longrightarrow$ enter $\tilde{f}$ couplings

Squark/slepton production & decay

- $\tilde{\tau}$, $\tilde{t}$, $\tilde{b}$ decays in complex MSSM

  [Bartl, Hidaka, Kernreiter, Porod, hep-ph/0204071, hep-ph/0207186]
  [Bartl, SH, Hidaka, Kernreiter, Porod, hep-ph/0306281, hep-ph/0307317, hep-ph/0311338]

  $\longrightarrow$ pronounced phase dependence of branching ratios possible

  $\longrightarrow$ parameter determination estimated by global fit

- One-loop corrections for $\tilde{t}$, $\tilde{b}$ decays: [Ibrahim, Nath, hep-ph/0411272]

  $\longrightarrow$ up to 30 % for $\Gamma(\tilde{t})$, smaller for $\Gamma(\tilde{b})$

- Polarization of final τ and t from $\tilde{\tau}$ and $\tilde{t}$ decays

  [Gajdosik, Godbole, Kraml, hep-ph/0405167]

  $\longrightarrow$ strong phase dependence possible

- CP-odd/T-odd triple product asymmetries in $\tilde{t}$, $\tilde{b}$, $\tilde{\tau}$ decays

  [Bartl, Kernreiter, Porod, hep-ph/0202198]
  [Bartl, Fraas, Kernreiter, Kittel, hep-ph/0306304]
  [Bartl, Christova, Hohenwarter-Sodek, Kernreiter, hep-ph/0409060]

  $\longrightarrow$ asymmetries up to 40 % possible

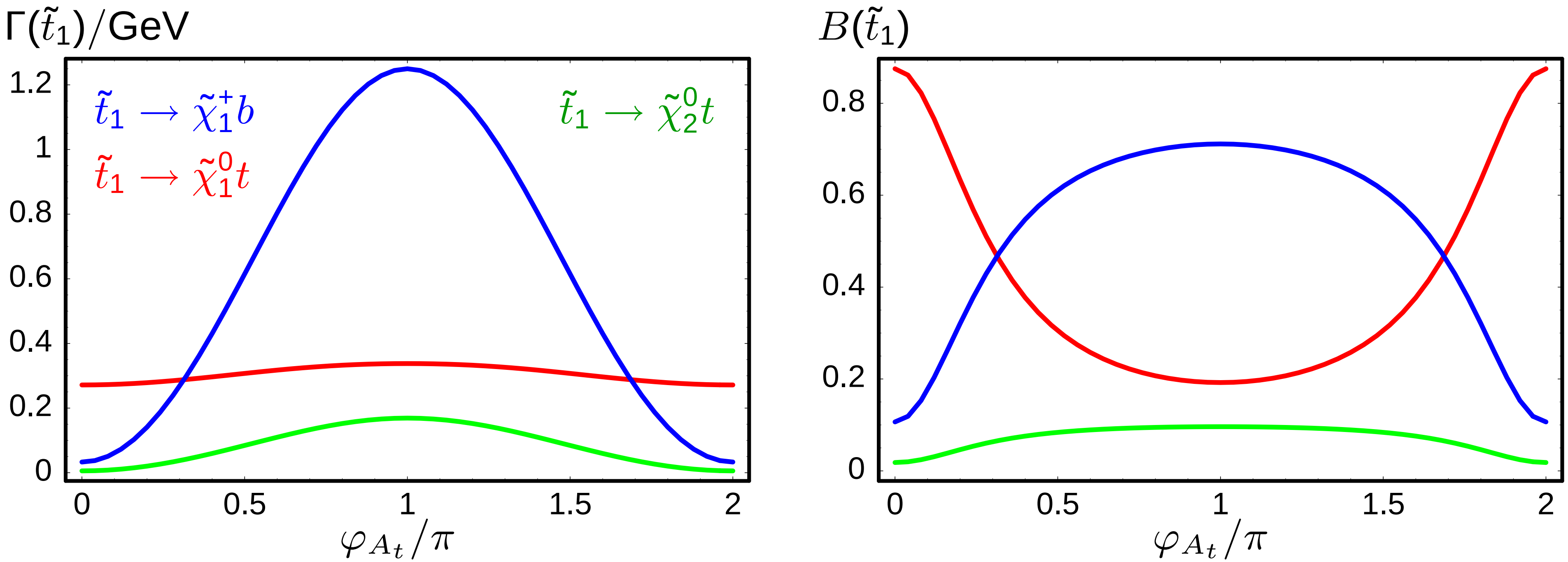
Branching ratios of $\tilde{t}_1$

Partial decay widths $\Gamma(\tilde{t}_1)$ and branching ratios $B(\tilde{t}_1)$

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

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,
$|A_t|$ = 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



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

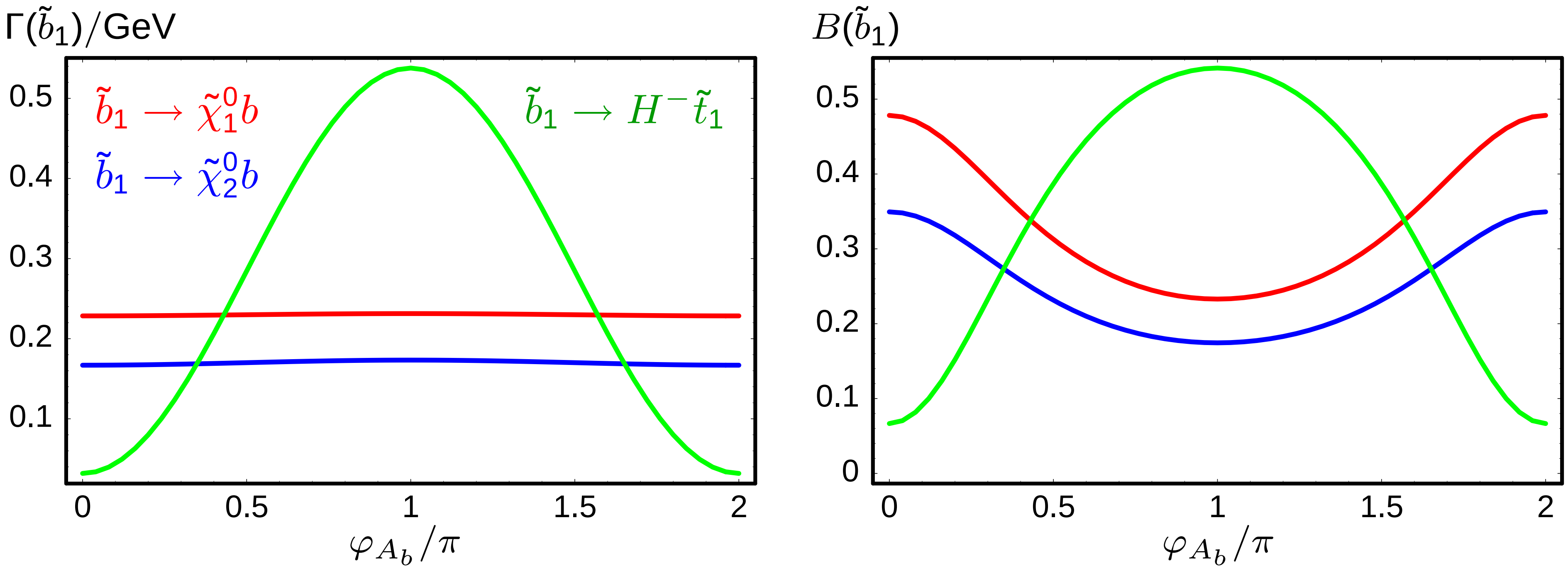
Branching ratios of $\tilde{b}_1$

Partial decay widths $\Gamma(\tilde{b}_1)$ and branching ratios $B(\tilde{b}_1)$

[Bartl, SH, Hidaka, Kernreiter, Porod, hep-ph/0311388]

in scenario:

$M_Q > M_D$, $m_{\tilde{b}_1}$ = 350 GeV , $m_{\tilde{b}_2}$ = 700 GeV, $m_{\tilde{t}_1}$ = 170 GeV, $|A_t| = |A_b|$ = 600 GeV,
φ_{A_t} = 0, $|\mu|$ = 300 GeV, $\varphi_\mu = \pi$, M_2 = 200 GeV, $|M_1|/M_2 = 5/3 \tan^2\theta_W$, φ_{M_1} = 0,
$\tan\beta$ = 30, $m_{H^\pm}$ = 150 GeV



$\longrightarrow$ strong phase φ_{A_b} dependence of $\Gamma(\tilde{b}_1 \to H^- \tilde{t}_1)$

Parameter determination in $\tilde{t}$, $\tilde{b}$ sector

Global fit in representative scenarios of many observables

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

- $\tilde{\tau}$ sector: $\sigma_{\text{pol}}(e^+e^- \to \tilde{\tau}_i\tilde{\tau}_j)$ for $\sqrt{s}$ = 800 GeV

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

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

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

- $\tilde{t}$, $\tilde{b}$ sector: $\sigma_{\text{pol}}(e^+e^- \to \tilde{q}_i\tilde{q}_j)$ for $\sqrt{s}$ = 2 TeV

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

  $\delta(\text{Im}(A_t))/|A_t|$ = 2 – 3 %, $\delta(\text{Re}(A_t))/|A_t|$ = 2 – 3 %

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

Triple product asymmetry in $\tilde{t}_1$ decay

Asymmetry A_T

for $\tilde{t}_1 \to t + \tilde{\chi}_2^0 \to bW^+ + \tilde{\ell}_1^- \ell_1^+ \to b\ell^+\nu + \tilde{\ell}_1^- \ell_1^+$ $(\ell = e, \mu)$, $\mathcal{T} = \vec{p}_{\ell_1^+} \cdot (\vec{p}_{\ell^+} \times \vec{p}_t)$

[Bartl, Christova, Hohenwarter-Sodek, Kernreiter, hep-ph/0409060]

Contours of A_T [in %] for

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

$M_Q > M_U$, $m_{\tilde{t}_1} = 400$ GeV, $m_{\tilde{t}_2} = 800$ GeV

$|A_t| = 1200$ GeV, $\varphi_{A_t} = 0.5\pi$, $\varphi_{M_1} = \varphi_\mu = 0$

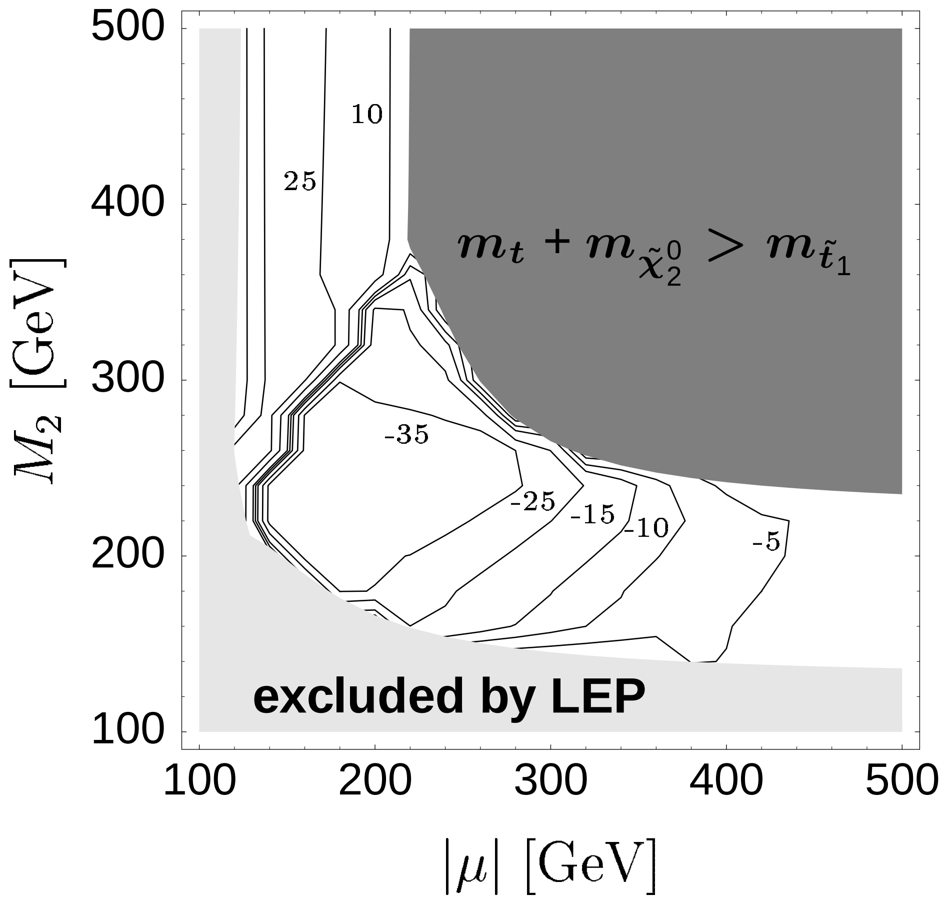
Light shaded area:

$m_{\tilde{\chi}_1^\pm} < 103$ GeV

Dark shaded area:

$m_t + m_{\tilde{\chi}_2^0} > m_{\tilde{t}_1}$

large A_T for $M_2 \sim |\mu|$



Conclusions and outlook

- CP-even observables (m, σ, BR)
  $\longrightarrow$ ambiguities in determining the phases
- Unambiguous determination of phases: CP-odd observables
- Chargino/neutralino production and decay
  - e^+e^- linear colliders: many analyses (CP-even and CP-odd)
  - LHC: try triple product asymmetries
    in single/pair production of $\tilde{\chi}^0$ and in cascades (?)
- Squark and slepton decays
  - Strong phase dependence of branching ratios
  - Large triple product asymmetries possible
  - Applicable to LC and LHC