CP violation in SUSY particle and Higgs production and decay

SHEP Southampton High Energy Physics

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NExT

based on

Bartl, SH, Hidaka, Kernreiter, Porod, PRD **70** (2004) 035003 [hep-ph/0311338]

Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, JHEP **0408** (2004) 038 [hep-ph/0406190]

Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, JHEP **0601** (2006) 170 [hep-ph/0510029]

Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, hep-ph/0608065, accepted in EPJC

Eriksson, SH, Rathsman, hep-ph/0612198

UKBSM 2007, Liverpool, 30 March, 2007

Outline

- Introduction
  - Supersymmetry with complex parameters
  - Complex parameters in sfermion and chargino/neutralino sectors
  - Higgs sector
- Aim: deriving the phases and analysing the CP structure of the theory
- CP-even observables

  $\longrightarrow$ Production cross sections and branching ratios
- CP-odd observables

  $\longrightarrow$ Asymmetries via triple products and transverse beam polarization

  $\longrightarrow$ Rate asymmetries
- Summary and outlook

- General MSSM:

  Many parameters can be complex

- New sources 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]
[Oshima, Nihei, Fujita, '05; Pospelov, Ritz, '05; Olive, Pospelov, Ritz, Santoso, '05]
[Abel, Lebedev, '05; Yaser Ayazi, Farzan, '06, '07]

- Physical phases of the parameters

  A_f : trilinear couplings of sfermions

  μ : Higgs-higgsino mass parameter

  M_1 : U(1) gaugino mass parameter

  M_3 : SU(3) gaugino mass parameter (gluino mass)

Introduction

Complex parameters in $\tilde{q}$ sector

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

with $\rightarrow M^2_{\tilde{t}_{RL}} = (M^2_{\tilde{t}_{LR}})^* = m_t \left(|A_t| e^{i\varphi_{A_t}} - \frac{|\mu| e^{-i\varphi_\mu}}{\tan\beta} \right)$ for stops $\tilde{t}$

$\rightarrow M^2_{\tilde{b}_{RL}} = (M^2_{\tilde{b}_{LR}})^* = m_b \left(|A_b| e^{i\varphi_{A_b}} - |\mu| e^{-i\varphi_\mu} \tan\beta \right)$ for sbottoms $\tilde{b}$

A_q : trilinear couplings of squarks ($\tan\beta = \frac{v_2}{v_1}$: ratio of Higgs VEVs)

μ : Higgs-higgsino mass parameter

- Diagonalization: $\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \mathcal{R}^{\tilde{q}} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$ $\rightarrow$ complex mixing matrix $\mathcal{R}^{\tilde{q}}$

- $\mathcal{R}^{\tilde{q}}$ enters squark couplings $\rightarrow \varphi_{A_q}, \varphi_\mu$ dependence of σ, Γ, BR

Introduction

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

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

- Neutralino ($\tilde{\chi}^0$) mass matrix:

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

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

μ : Higgs-higgsino mass parameter

(M_2 : SU(2) gaugino mass parameter)

M_1 : U(1) gaugino mass parameter

- Diagonalisation $\Rightarrow$ complex mixing matrices $\longrightarrow$ enter $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$ couplings $\longrightarrow$ φ_{M_1}, φ_μ dependence of σ, Γ, BR

Introduction Higgs sector

- MSSM: 2 Higgs doublets

  $\longrightarrow$ 5 physical Higgs particles at tree-level ($h, H, A, H^{\pm}$)

- $\tilde{t}$ and $\tilde{b}$ loops $\Rightarrow$ explicit CP violation in Higgs sector [Pilaftsis, '98]

  [Pilaftsis, Wagner, '99; Demir, '99, Carena, Ellis, Pilaftsis, Wagner, '00, '01; Choi, Drees, Lee, '00]

- CP-even (h, H) and CP-odd (A) neutral Higgs mix

  $\longrightarrow$ 3 neutral mass eigenstates (H_1, H_2, H_3), mixing matrix O

- Impact on Higgs search [LEP Higgs Working Group, hep-ex/0602042]

  $\longrightarrow$ MSSM Higgs search at LEP: no universal limit on m_{H_1}

- Spectrum calculation (masses m_{H_i} and mixing matrix O)

  - CPsuperH [Carena, Ellis, Pilaftsis, Wagner '00]

    [Lee, Pilaftsis, Carena, Choi, Drees, Ellis, Wagner '03; Ellis, Lee, Pilaftsis, '06]

  - FeynHiggs [Heinemeyer '01; Frank, Heinemeyer, Hollik, Weiglein '02]

    [Frank, Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, '06]

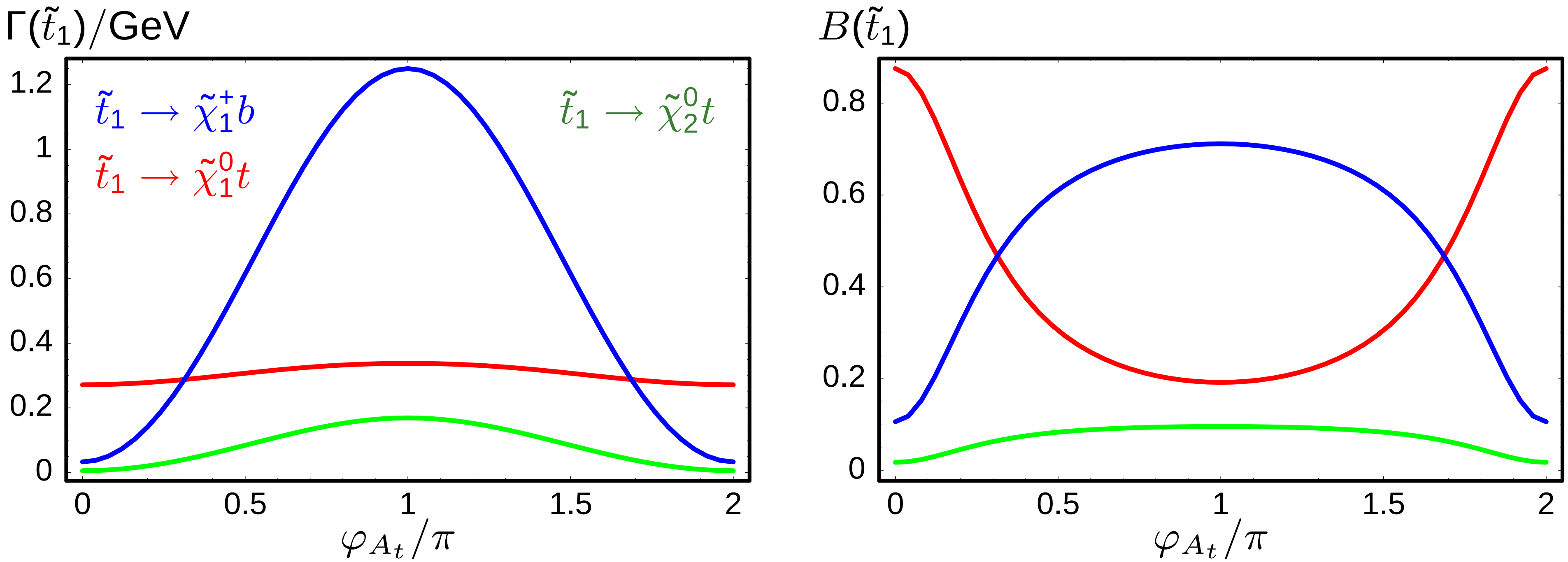
Branching ratios of squarks

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

[Bartl, SH, Hidaka, Kernreiter, Porod, '03]

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



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

Branching ratios of squarks

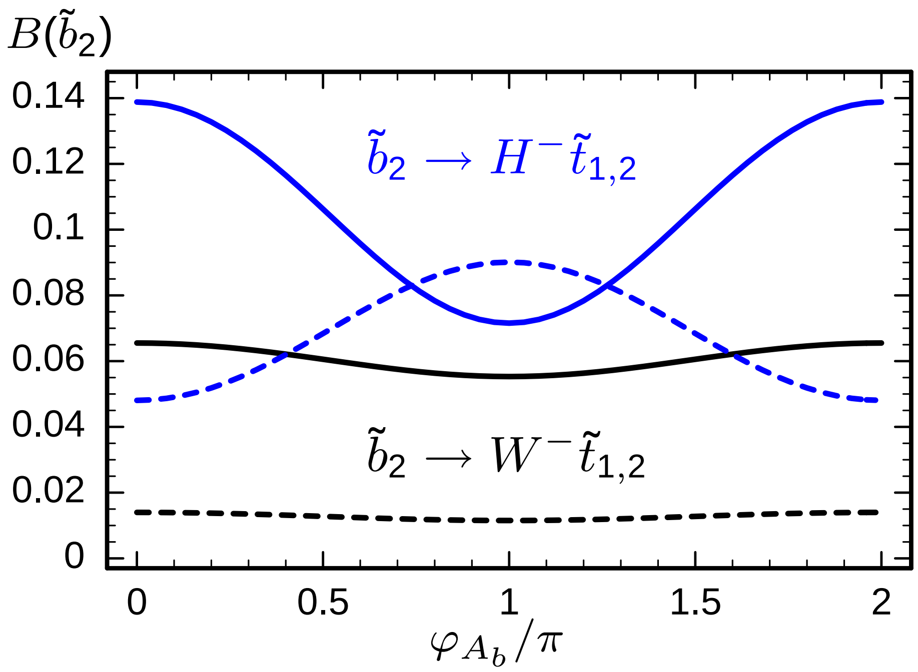
Branching ratios $B(\tilde{b}_2)$ [Bartl, SH, Hidaka, Kernreiter, Porod, '03]

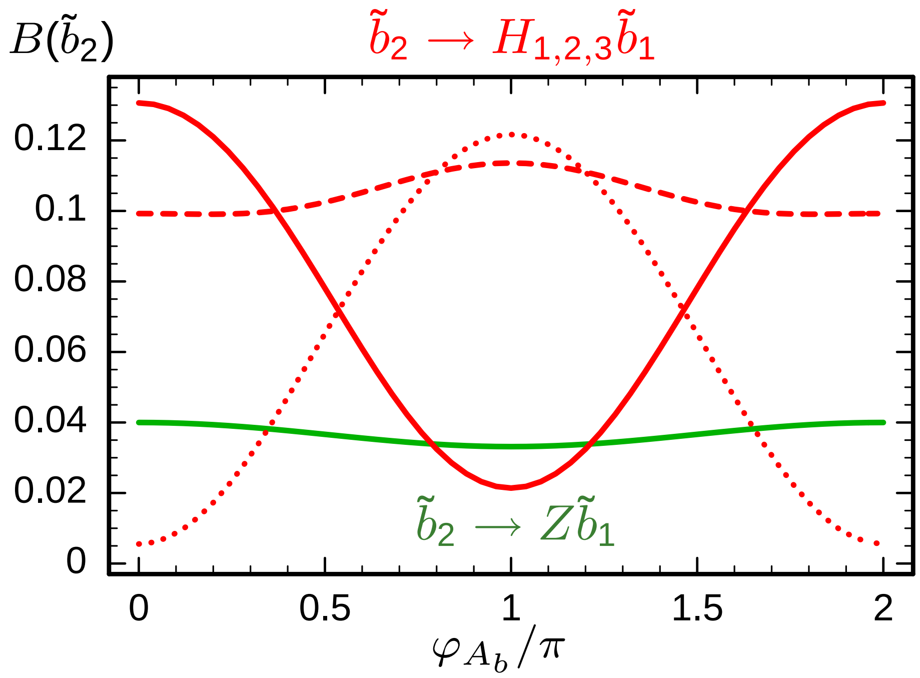
in scenario:

$M_Q < M_D$, $m_{\tilde{b}_1}$ = 350 GeV , $m_{\tilde{b}_2}$ = 700 GeV, $m_{\tilde{t}_1}$ = 170 GeV, $|A_t|$ = $|A_b|$ = 600 GeV,

$\varphi_{A_t} = \pi$, $|\mu|$ = 300 GeV, $\varphi_\mu = \pi$, M_2 = 200 GeV, $|M_1|/M_2 = 5/3 \tan^2\theta_W$, $\varphi_{M_1} = 0$,

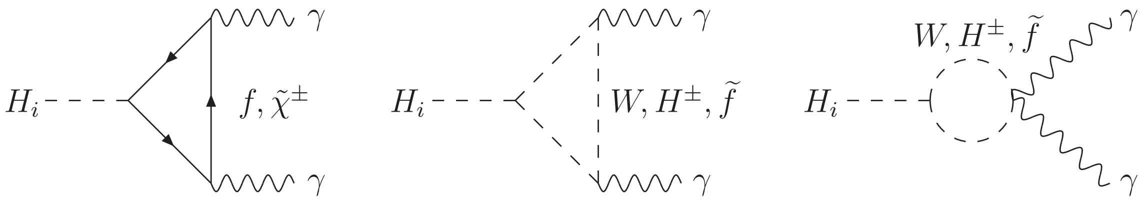
$\tan\beta$ = 30, $m_{H^\pm}$ = 150 GeV





Branching ratio of $H_1 \to \gamma\gamma$

- Impact of φ_μ on BR($H_1 \to \gamma\gamma$) [Moretti, Munir, Poulose, '07]
- Decay at 1-loop via f, W, $H^\pm$, $\tilde{f}$, $\tilde{\chi}^\pm$ loops



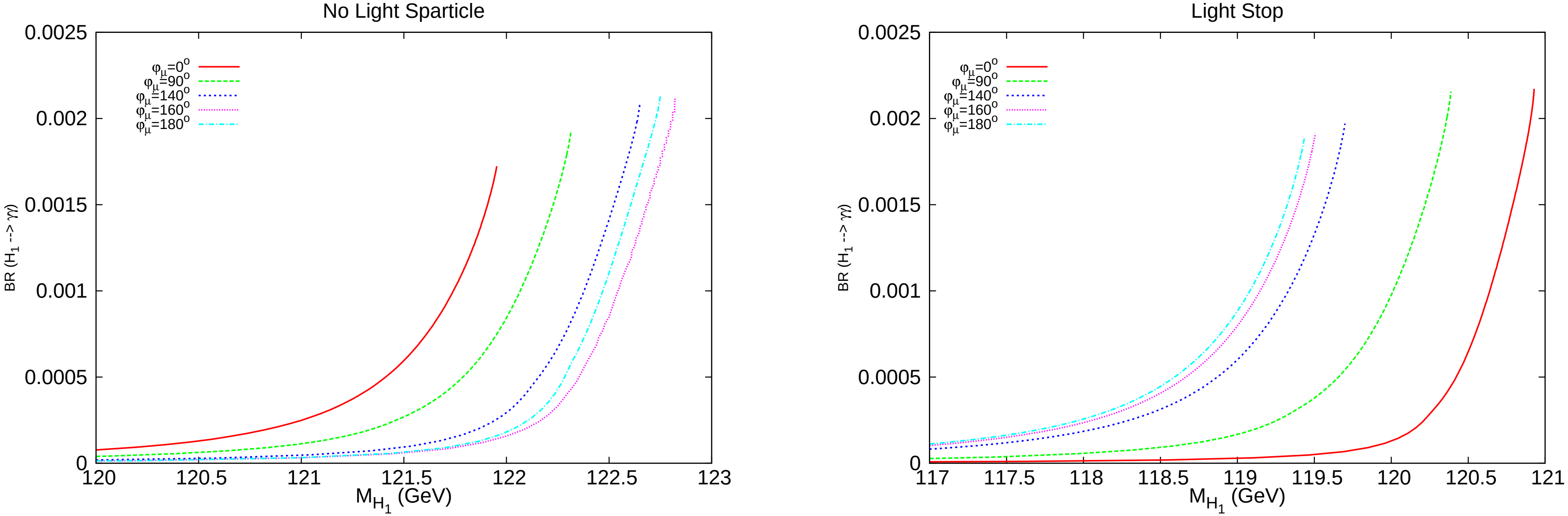
- CPV enters via phase dependence of
  - $m_{H_1} \longrightarrow$ small
  - H_i couplings (also to SM particles)
  - $\tilde{f}$, $\tilde{\chi}^\pm$ sector (masses, couplings to H_i)
- Scan over MSSM parameters
  $\longrightarrow$ in average $\sim$ 50% deviation between CPV and CPC case possible
  for parameter points with m_{H_1} in bins of size 4 GeV

Branching ratio of $H_1 \to \gamma\gamma$

- Results

  for $M_{(\tilde{Q}_3,\tilde{D}_3,\tilde{L}_3,\tilde{E}_3)}$ = 1 TeV, $|\mu|$ = 1 TeV, $|A_f|$ = 1.5 TeV,

  tan β = 20, M_1 = 100 GeV, $M_2 = M_3$ = 1 TeV



$\longrightarrow$ $M_{\tilde{U}_3}$ = 1 TeV

$\longrightarrow$ CP effects from H_i couplings to W, t, b in loops

$\longrightarrow$ $M_{\tilde{U}_3}$ = 250 GeV ($m_{\tilde{t}_1} \sim$ 200 GeV))

$\longrightarrow$ additional effects from light $\tilde{t}_1$

- Detailed discussion of SUSY parameter dependence

  [SH, Moretti, Munir, Poulose, in preparation]

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 $|T|^2 = PD + \sum_{a=1}^{3} \Sigma_P^a \Sigma_D^a$

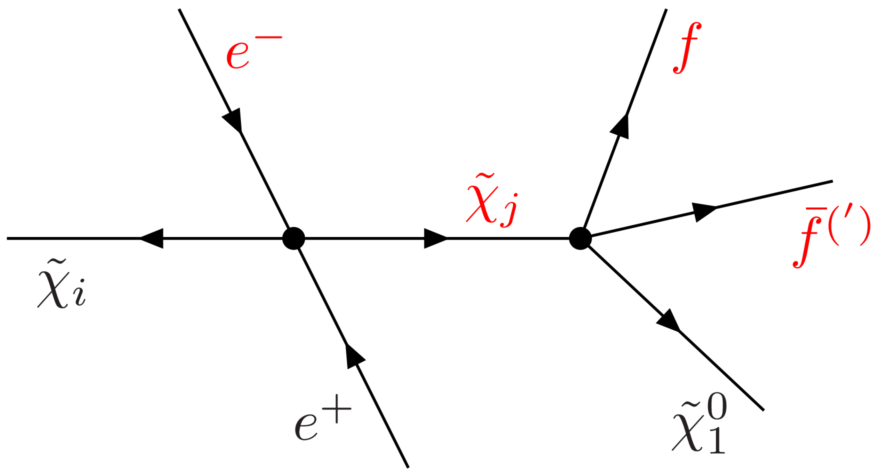
- In Σ_P^a and Σ_D^a: products like $\boxed{i\epsilon_{\mu\nu\rho\sigma} p_i^\mu p_j^\nu p_k^\rho p_l^\sigma}$

  $\Rightarrow$ 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 $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_f)$



$\longrightarrow$ 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

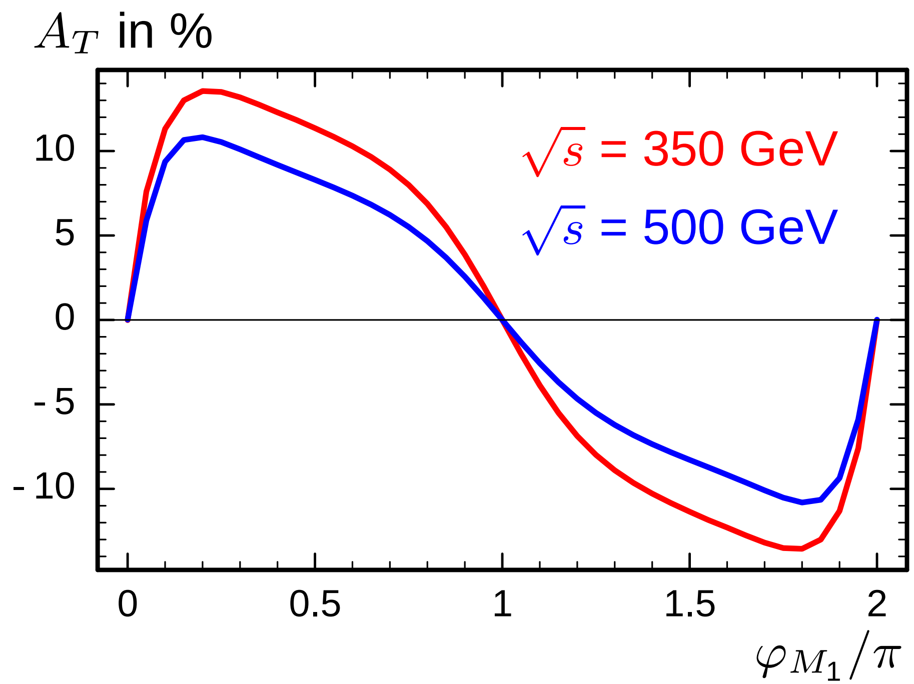
T-odd asymmetry in $\tilde{\chi}^0$ sector

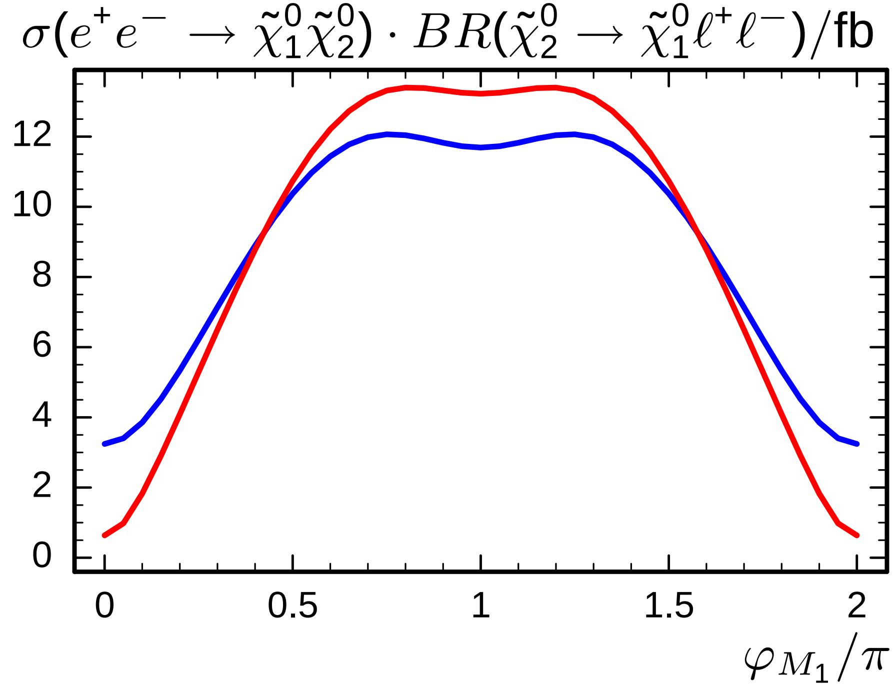
Asymmetry A_T for $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+\ell^-$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$

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

$\tan\beta$ = 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)

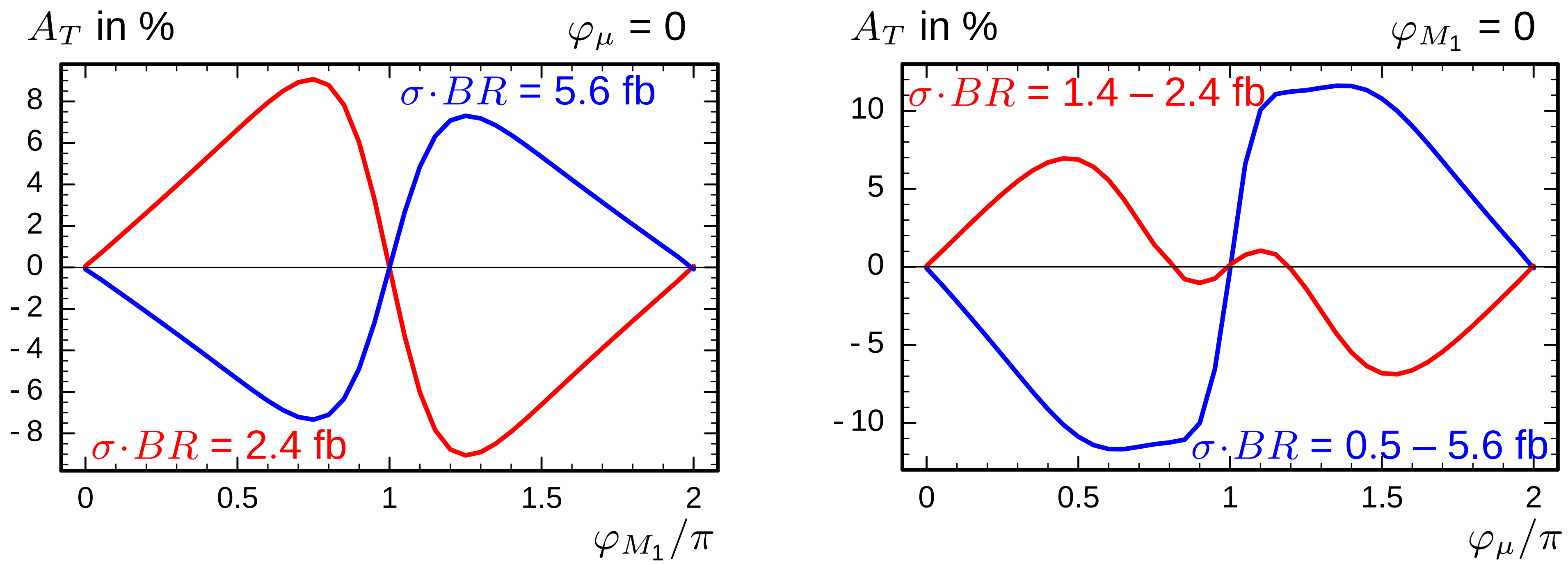
T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

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

[Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, '06]

$\longrightarrow$ tagging of c jet important

$\tan\beta$ = 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, $P_{e^-} = -0.8$, $P_{e^+} = +0.6$, $P_{e^-} = +0.8$, $P_{e^+} = -0.6$



Transverse beam polarization

Chargino/neutralino production

$$e^+e^- \longrightarrow \tilde{\chi}_i + \tilde{\chi}_j$$

with transverse beam polarization (4-vector $t^\mu_\pm$, polarization degree $\mathcal{P}^T_{e^\pm}$)

- Terms in amplitude squared $|T|^2 = P$ depending on $\mathcal{P}^T_{e^\pm}$:

  $P_T \sim \mathcal{P}^T_{e^-}\mathcal{P}^T_{e^+}\,[f_1\Delta_1 r_1 + f_2\Delta_2 r_2]$

  f_i: couplings; Δ_i: propagators; r_i: products of $t_\pm$ and momenta

  $\Rightarrow$ both beams have to be polarized (in limit $m_e = 0$!)

  [POWER report, hep-ph/0507011]

- r_1 is real; r_2 is imaginary, consisting of products like $i\epsilon_{\mu\nu\rho\sigma} t^\mu_\pm p^\nu_i p^\rho_j p^\sigma_k$

  $\Rightarrow$ with complex couplings f_2: real contributions to observables

  $\Rightarrow$ CP-odd terms $\sim \mathrm{Im}(f_2\Delta_2)\mathrm{Im}(r_2)$ at tree level

Transverse beam polarization

- Chargino production:

  Dirac particles: couplings $f_2\Delta_2$ have to be real (CPT invariance)

  $\Rightarrow$ CP-odd terms $f_2\Delta_2 r_2$ vanish [Bartl, Hohenwarter-Sodek, Kernreiter, Rud, '04]

  $\longrightarrow$ CP-even asymmetries can be defined with help of $f_1\Delta_1 r_1$

- Neutralino production:

  Majorana particles: t and u channels contribute

  $\Rightarrow$ CP-odd terms $f_2\Delta_2 r_2 \neq 0$ allowed

  $\Rightarrow$ CP-odd observables can be defined

Transverse beam polarization

- $f_2 \Delta_2 r_2 \sim \sin(\eta - 2\phi)$

  with ϕ: azimuthal angle of scattering plane; η: orientation of transverse polarizations

- CP-odd asymmetry

  - ϕ integration:

$$A_{CP}(\theta) = \frac{1}{\sigma}\left[\int_{\frac{\eta}{2}}^{\frac{\pi}{2}+\frac{\eta}{2}} - \int_{\frac{\pi}{2}+\frac{\eta}{2}}^{\pi+\frac{\eta}{2}} + \int_{\pi+\frac{\eta}{2}}^{\frac{3\pi}{2}+\frac{\eta}{2}} - \int_{\frac{3\pi}{2}+\frac{\eta}{2}}^{2\pi+\frac{\eta}{2}}\right] \frac{d^2\sigma}{d\phi\, d\theta} d\phi$$

  - θ integration:

$$A_{CP} = \left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi}\right] A_{CP}(\theta)\, d\theta$$

$\longrightarrow$ 8 sectors with alternating sign

Transverse beam polarization

Asymmetry A_{CP} for $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$

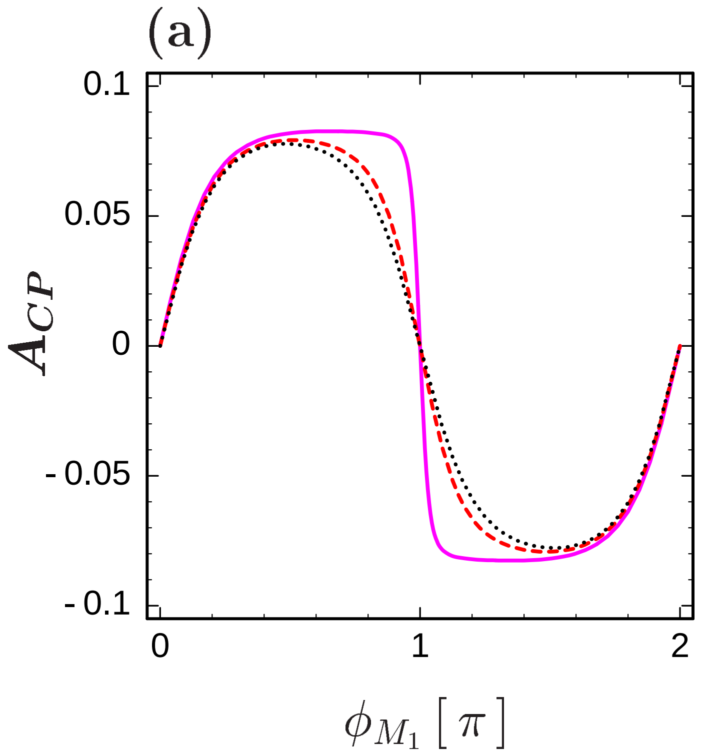
[Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, '05]

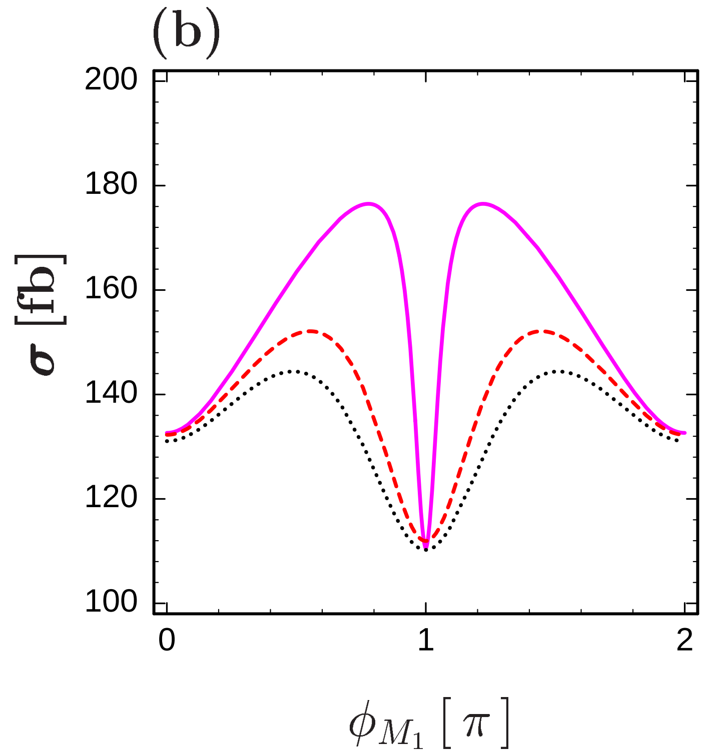
$\longrightarrow$ reconstruction of $\vec{p}_{\tilde{\chi}^0_2}$ necessary

M_2 = 245 GeV, $|M_1|$ = 123.3 GeV, $|\mu|$ = 160 GeV, ϕ_μ = 0, $m_{\tilde{e}_L}$ = 400 GeV, $m_{\tilde{e}_R}$ = 150 GeV

$\sqrt{s}$ = 500 GeV, $(\mathcal{P}^T_{e^-}, \mathcal{P}^T_{e^+})$ = (100%, 100%)

$\tan\beta$ = 3, 10, 30

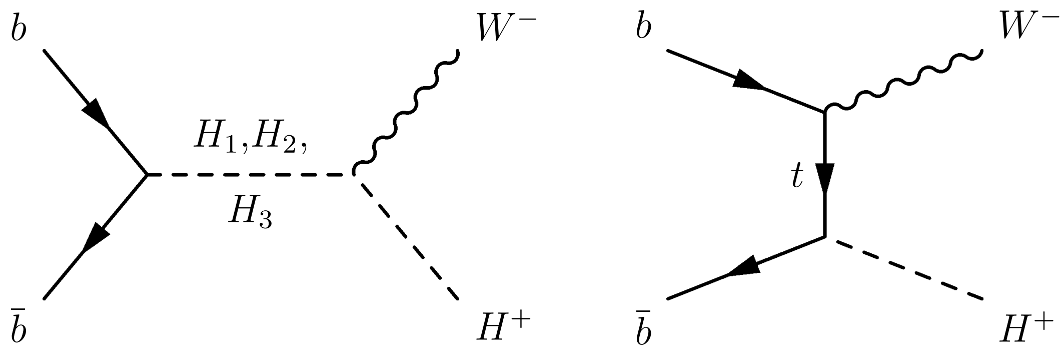




Rate asymmetry in $H^\pm$ production

LHC: $pp \to H^\pm + W^\mp \to \tau\nu + jj$ [Eriksson, SH, Rathsman, '06]

- Scenarios with large tan $\beta \Rightarrow$ large $B(H \to \tau\nu)$
  $\to b\bar{b}$ annihilation dominates:



- $g_{H_i H^- W^+} = O_{2i} \cos\beta - O_{1i} \sin\beta + \mathrm{i}\, O_{3i}$, $\quad g_{H_i \bar{b} b} = O_{1i} + \mathrm{i}\, O_{3i} \sin\beta$

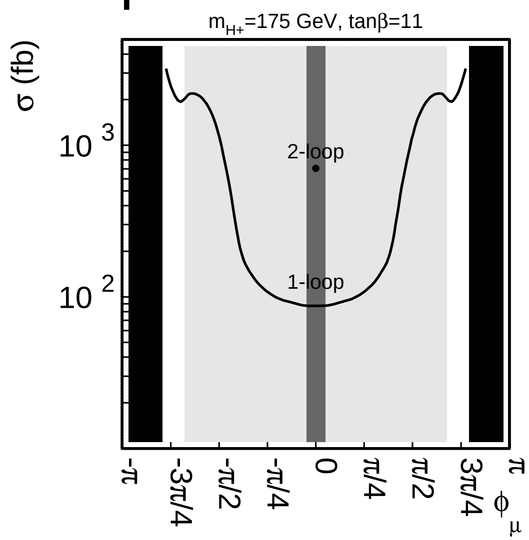
- Rate asymmetry: $$A_{\mathrm{CP}} = \frac{\sigma(b\bar{b} \to H^+W^-) - \sigma(b\bar{b} \to H^-W^+)}{\sigma(b\bar{b} \to H^+W^-) + \sigma(b\bar{b} \to H^-W^+)}$$

- In general CP-violating 2-Higgs-Doublet Models:
  Large A_{CP} possible in resonant scenarios with
  $m_{H_2} > m_{H^\pm} + m_W$ and $m_{H_3} > m_{H^\pm} + m_W$ [Akeroyd, Baek, '01]

Rate asymmetry in $H^{\pm}$ production

- In typical MSSM scenarios:
  - $m_{H_2} \sim m_{H_3} \sim m_{H^{\pm}} \Rightarrow$ $A_{\text{CP}} \lesssim 1\%$
  - small mixing between CP-even and CP-odd Higgs bosons
    $\Rightarrow$ weak φ_{A_t} and φ_μ dependence of cross section
- Resonant scenarios with $m_{H_3} > m_{H^{\pm}} + m_W$ [Akeroyd, Beak, '02]
  - Possible in scenarios with $|\mu| > 4M_{\text{SUSY}}$ or $|A_t|, |A_b| > 4M_{\text{SUSY}}$
  - Stronger phase dependence of cross section possible

$m_{H^{\pm}}$ = 175 GeV, tan β = 11
$|\mu|$ = 3300 GeV, M_2 = M_3 = 500 GeV
M_L^3 = M_E^3 = 500 GeV
M_Q^3 = M_U^3 = 250 GeV, M_D^3 = 400 GeV
A_t = A_b = 0



  - However: A_{CP} remains small

Summary and outlook

- Aim: revealing the CP structure of the underlying model
- CP-even observables: BR and σ of squarks and Higgs bosons
  $\longrightarrow$ strong dependence on SUSY phases possible
- CP-odd observables
  - Triple products, transverse beam polarization: asymmetries $\mathcal{O}$(10%)
  - Rate asymmetry in $H^{\pm}W^{\mp}$ production: small in MSSM
- Outlook: Projects within NExT Institute
  (Southampton University $\leftrightarrow$ PPD, RAL)
  `http://www.hep.phys.soton.ac.uk/next/NEXT_web/NEXT_web.htm`
  - Analysis of CPV in MSSM for LHC Higgs search
    $\longrightarrow$ Implications of light Higgs ($m_{H_1} \sim$ 50 GeV) $\leftrightarrow$ NMSSM
  - Analysis of explicit CP violation in NMSSM