Higgs production and decay in SUSY with CP violation

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based on

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Outline

- Introduction
  - MSSM with complex parameters
  - Higgs sector in complex MSSM
- Di-photon decay $H_1 \rightarrow \gamma\gamma$ in complex MSSM
  - Focus on $\text{BR}(H_1 \rightarrow \gamma\gamma)$
  - Impact of light SUSY particles
  - Dependence on SUSY parameters
- Outlook
  - Full production and decay $gg \rightarrow H_i \rightarrow \gamma\gamma$ at LHC
  - CP-violating NMSSM
Introduction

MSSM with complex parameters

- General MSSM:
  Many parameters can be complex

- Explicit 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]

- Global U(1) symmetries: some phases eliminated
  → e.g. phase of one gaugino mass parameter $M_i$

- Physical phases in Higgs sector
  $\mu$: Higgs-higgsino mass parameter
  $A_f$: trilinear couplings of sfermions
Introduction

Higgs sector in complex MSSM

- MSSM: 2 Higgs doublets
  → 5 physical Higgs particles at tree-level ($h, H, A, H^\pm$)

- $\tilde{t}$ and $\tilde{b}$ loops ⇒ 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
  → 3 neutral mass eigenstates ($H_1, H_2, H_3$), mixing matrix $O$

- Impact on Higgs search
  [LEP Higgs Working Group, hep-ex/0602042]
  → MSSM Higgs search at LEP: no universal limit on $m_{H_1}$

- Spectrum calculation (masses $m_{H_i}$ and mixing matrix $O$)
  - CP*SUPERH
    [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]
$H_1 \rightarrow \gamma\gamma$

- $pp \rightarrow H \rightarrow \gamma\gamma$: important search channel at LHC for $m_H \lesssim 150$ GeV

- Decay at 1-loop via $f, W, H^\pm, \tilde{f}, \tilde{\chi}^\pm$ loops in MSSM

- CP violation (CPV) enters via phase dependence of
  - Masses $m_{H_i} \rightarrow$ small
  - Mixing matrix $O \leftrightarrow H_i$ couplings (also to SM particles)
  - $\tilde{f}, \tilde{\chi}^\pm$ sector (masses, couplings to $H_i$)
\[ H_1 \rightarrow \gamma\gamma \] Production and decay in CPV MSSM

- Production \( gg \rightarrow H_i \) at LHC
  \[ \rightarrow \text{factor 2–5 enhancement/reduction of } \sigma \text{ with } \varphi_\mu \text{ and } \varphi_{A_t} \]

- \( gg \rightarrow H_i \rightarrow \gamma\gamma \) at LHC in CPV MSSM
  - Heavy sparticles (\( \tilde{f}, \tilde{\chi}^\pm \))
    \[ \leftrightarrow \text{CPV in } H_i \text{ couplings} \]
  - \( \mathcal{O}(10^2–10^3) \) suppression of \( \text{BR}(H_1 \rightarrow \gamma\gamma) \) possible
  \[ \Rightarrow \text{suppression of } \sigma \times \text{BR} \]

for
\[ M_{\tilde{Q},\tilde{U},\tilde{D}} = m_{\tilde{g}} = M_{\text{SUSY}} = 0.5 \text{ TeV}, \]
\[ |A_t| = |A_b| = \kappa M_{\text{SUSY}}, |\mu| = 2|A_t|, \]
\[ \Phi = \text{Arg}(A_t \mu) = \text{Arg}(A_b \mu) \]

[Choi, Lee, '99; Dedes, Moretti, '99]
[Choi, Hagiwara, Lee, '01]

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Analysis of Branching Ratio

Here:

- Investigate possible effects of light sparticles
- Calculation of $m_{H_i}$, $O$, $\Gamma(H_i)$, $\text{BR}(H_i)$ with CP SUPERH
- Detailed discussion of $A_f$, $\mu$, $\tan \beta$ dependence
- Leading contributions to $(h, H)$-$A$ mixing $\propto \text{Im}(\mu A_f)$

$$\phi_{\text{eff}} = \phi_\mu + \phi_{A_f}$$

→ Choosing $A_f$ real, analyzing $\phi_{\text{eff}} = \phi_\mu$ effects in the following

First step: analysis of $\text{BR}(H_1 \rightarrow \gamma\gamma)$

Scan over MSSM parameters [Moretti, Munir, Poulose, ’07]

→ in average $\sim 50\%$ deviation between CPV and CPC case possible for parameter points with $m_{H_1}$ in bins of size 4 GeV
$H_1 \rightarrow \gamma\gamma$

**Numerical results**

\[ \text{BR}(H_1 \rightarrow \gamma\gamma) \text{ as function of } m_{H_1} \]

for $M(\tilde{Q}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3) = 1 \text{ TeV}$, $|\mu| = 1 \text{ TeV}$, $A_f = 1.5 \text{ TeV}$, $\tan \beta = 20$

\[ \rightarrow M_{\tilde{U}_3} = 1 \text{ TeV (no light sparticles)} \]

\[ \rightarrow \text{CP effects from } H_1 \text{ couplings to } W, t, b \text{ in loops} \]

\[ \rightarrow M_{\tilde{U}_3} = 250 \text{ GeV } (m_{\tilde{t}_1} \sim 200 \text{ GeV}) \]

\[ \rightarrow \text{additional effects from light } \tilde{t}_1 \]
**Numerical results**

$m_{H_1}$ as function of $m_{H^\pm}$

for $M(\tilde{Q}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3) = 1$ TeV, $|\mu| = 1$ TeV, $A_f = 1.5$ TeV, $\varphi_\mu = 0$, $\varphi_\mu = 90^\circ$

→ deviations $\Delta m_{H_1}(\varphi_\mu)$ within experimental uncertainty
\( H_1 \rightarrow \gamma \gamma \)

**Numerical results**

\[ BR(H_1 \rightarrow \gamma \gamma) \] as function of \( m_{H^\pm} \)

for \( M(\tilde{Q}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3) = 1 \) TeV, \( |\mu| = 1 \) TeV, \( A_f = 1.5 \) TeV, \( \tan \beta = 20 \)

\( \rightarrow M_{\tilde{U}_3} = 1 \) TeV (no light sparticles)

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

\( \rightarrow \) additional effects from light \( \tilde{t}_1 \)
\( H_1 \rightarrow \gamma\gamma \)

Numerical results

\[
\text{BR}(H_1 \rightarrow \gamma\gamma) \text{ as function of } m_{H^\pm}
\]

for \( M(\tilde{Q}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3) = 1 \text{ TeV}, \ |\mu| = 1 \text{ TeV}, \ A_f = 0.5 \text{ TeV}, \ \tan \beta = 20 \)

\[
\rightarrow M_{\tilde{U}_3} = 1 \text{ TeV (no light sparticles)}
\]

\[
\rightarrow M_{\tilde{U}_3} = 250 \text{ GeV (} m_{\tilde{t}_1} \sim 200 \text{ GeV)}
\]

\[
\rightarrow \text{strong } A_f \text{ dependence}
\]
$H_1 \rightarrow \gamma\gamma$

Summary: SUSY parameter dependence

$\text{BR}(H_1 \rightarrow \gamma\gamma)$ in CP-violating MSSM

- Impact of light sparticles
  - light stops ($\tilde{t}_1$): possibly large effect
  - other light sparticles ($\tilde{b}_1, \tilde{\tau}_1, \tilde{\chi}_1^\pm$): small effect

- Strong $A_f$ dependence

- $|\mu|$ dependence
  - $\varphi_\mu$ dependence decreases for smaller $|\mu| = 500$ GeV

- $\tan \beta$ dependence
  - sensitivity to $\varphi_\mu$ considerably reduced for smaller $\tan \beta = 5$

- Conclusion: Strong phase dependence of $\text{BR}(H_1 \rightarrow \gamma\gamma)$
  - Increase or decrease depends on SUSY scenario
Outlook

Projects within

New connections between Experiment and Theory
(NExT) Institute
(Southampton University ↔ PPD, RAL)

http://www.hep.phys.soton.ac.uk/next/NEXT_web/NEXT_web.htm

- Analysis of full production + decay process $gg \rightarrow H_i \rightarrow \gamma\gamma$
  - Enhancement or cancellation between production + decay?
  - Impact of Higgs mixing in propagator [Ellis, Lee, Pilaftsis, '04]
  - Net effect for Higgs search at LHC

- Explicit CP violation in NMSSM Higgs sector
  - 3 CP-even and 2 CP-odd Higgs states mix \Rightarrow 5 mass eigenstates