Higgs at LHC in CP-Violating MSSM

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12 December 2008, ICTP, Trieste

Plan

- Higgs sector: MSSM
- Higgs sector: CPV MSSM
- $H_1 \to \gamma\gamma$
- Summary & Outlook

Higgs Sector: MSSM

- 2 Higgs doublets
  Of the 8 dof, 3 will be absorbed (after ssb) by W and Z, giving 5 physical dof:

  $h,\ H$: neutral scalar A : neutral pseudo-scalar $H^{\pm}$: charged

- At tree level, all masses and couplings depend on only two parameters.

  Traditional choice: $\tan\beta \equiv \frac{v_2}{v_1}$, and M_A

MSSM Higgs

LHC will discover CP conserving MSSM Higgs.

But CPV changes the phenomenology

CPV MSSM

CP-Violating phases:

Gaugino masses: $M_a, (a = 1, 2, 3a)$
the parameter: μ
the sof-bilinear term: $B\mu$
trilinear couplings: A_i could be complex

Too many couplings to do phenomenology, if all are independent.

CPV MSSM

Counting phases

- To avoid EDM constraints:
  Take sparticles of first two generations to be very heavy
  Set A_i's of first two generations to zero.
- Use the Pecci-Quinn type $U(1)$ symmetries to make
  M_a and $B\mu$ real

  We are left with complex $\mu, \quad A_{\tau,b,t}$
- What enters in the scalar-pseudoscalar mixing is the product of $\mu\, A_f$. Therefore effectively we are left with a single phase parameter.

Higgs sector in CPV MSSM

Complex parameters in Higgs-squark 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: $\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} = \mathcal{R}^{\tilde{q}} \begin{pmatrix} \tilde{q}_L \\ \tilde{q}_R \end{pmatrix}$ → complex mixing matrix $\mathcal{R}^{\tilde{q}}$

Higgs sector in CPV MSSM

- $\mathcal{R}^{\tilde{q}}$ and A_q and μ enters Higgs-squark-squark couplings.
- Consequence:
  Explicit CPV in Higgs sector at higher order (squark-loops)
  The Higgs mass eigenstates are CP-mixed states:

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = O \begin{pmatrix} \phi_1 \\ \phi_2 \\ a \end{pmatrix}$$

  O is the mixing matrix.
- Mixing is proportional to $Im\,(\mu A_i)$

Higgs sector in CPV MSSM

Effective neutral Higgs-squark couplings at tree-level

$$\mathcal{L}_{\tilde{q}\tilde{q}H} = -g\, C(\tilde{q}_k^\dagger H_i \tilde{q}_j)\, \tilde{q}_k^\dagger H_i \tilde{q}_j$$

$$\left(C(\tilde{q}_k^\dagger H_i \tilde{q}_j)\right) = \mathcal{R}^{\tilde{q}} \begin{pmatrix} C(\tilde{q}_L^\dagger H_i \tilde{q}_L) & C(\tilde{q}_L^\dagger H_i \tilde{q}_R) \\ C(\tilde{q}_R^\dagger H_i \tilde{q}_L) & C(\tilde{q}_R^\dagger H_i \tilde{q}_R) \end{pmatrix} \mathcal{R}^{\tilde{q}\dagger}$$

$\longrightarrow$ phases $\varphi_{A_q}, \varphi_\mu$ in $C(\tilde{q}_R^\dagger H_i \tilde{q}_L) = [C(\tilde{q}_L^\dagger H_i \tilde{q}_R)]^*$

for example for stops:

$$C(\tilde{t}_L^\dagger H_i \tilde{t}_R) \quad = \quad \frac{m_t}{2 m_W \sin\beta}\{-i\left(\cos\beta|A_t|e^{-i\varphi_{A_t}} + \sin\beta|\mu|e^{i\varphi_\mu}\right) O_{3i}$$

$$- \left(|\mu|e^{i\varphi_\mu} O_{1i} - |A_t|e^{-i\varphi_{A_t}} O_{2i}\right)\}$$

Higgs sector in CPV MSSM

Pheno Studies: Computational aides

- CPsuperH
  `http://www.hep.man.ac.uk/u/jslee/CPsuperH/html`
  (RG improved effective potential approach.)
- FeynHiggs
  `http://www.feynhiggs.de`
  (Feynman digramatic approach)

Computes (s)particle masses, couplings, decay widths, branching ratios, etc. for a set of input parameters.

CPV Higgs production and decay

- Resonant CP violation at LHC in $b\bar{b}, gg, W^+W^- \to H_i \to \tau^+\tau^-$

  Scenarios with $m_{H_1} \sim m_{H_2} \sim m_{H_3}$ [Ellis, Lee, Pilaftsis, '04, '05]

  $\longrightarrow$ CP effects largest for $W^+W^- \to H_i \to \tau^+\tau^-$

  $\longrightarrow$ σ: factor 2

  $\longrightarrow$ CP asymmetry using τ polarization: 50% possible

- $pp \to H^\pm H_1 \to 4b\ell + \not{E}_T$ at LHC [Gosh, Moretti, '04]

  CPX scenario with light H_1, suppressed H_1ZZ coupling

  $\longrightarrow$ $H_1H^\mp W^\pm$ coupling enhanced (sum rule)

  $\Rightarrow$ $pp \to H^\pm H_1 \to 4b\ell + \not{E}_T$ promising channel

- $pp \to H_i\tilde{q}_i\bar{\tilde{q}}_j$ [Li, Li, Li, '06]

  $\longrightarrow$ $\sigma(pp \to H_i\tilde{t}_i\bar{\tilde{t}}_j)$ can be several orders enhanced

CPV Higgs Production and Decay

- We consider $H_1 \to \gamma\gamma$, which is the important channel for the mass range $100 \lesssim m_{H_1} \lesssim 130$ GeV.
- Previous study of $H_1 \to \gamma\gamma$:
  restricted to the parameter space with no light (sparticles). CP violation enters entirely through scalar – pseudo-scalar mixing.

  BR suppressions of $10^2 - 10^3$

  . [Choi, Hagiwara, Lee '01]

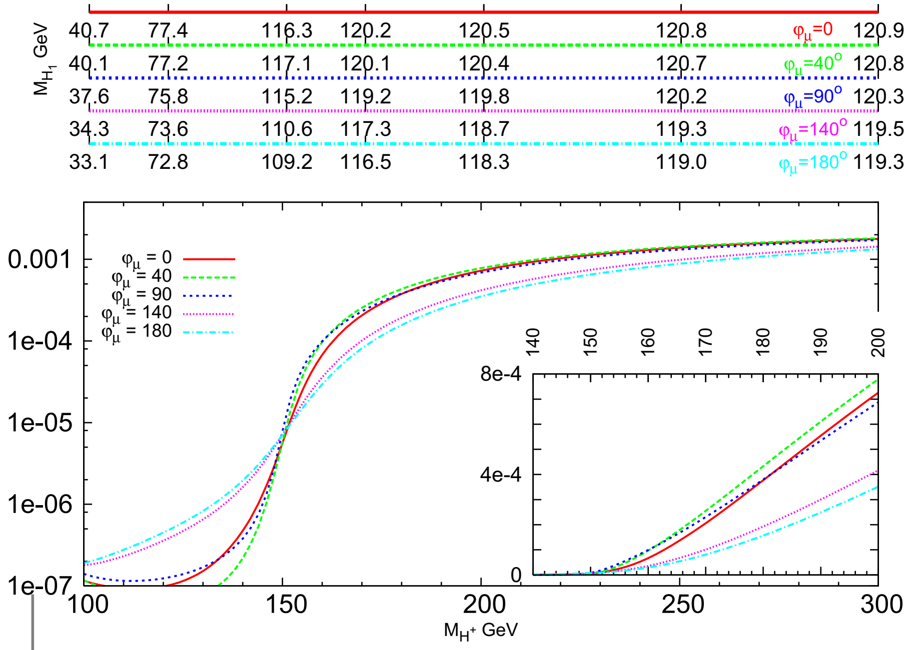
- $gg \to H_i$ studies:
  . [Choi, Lee '99; Moretti, Dedes '99]

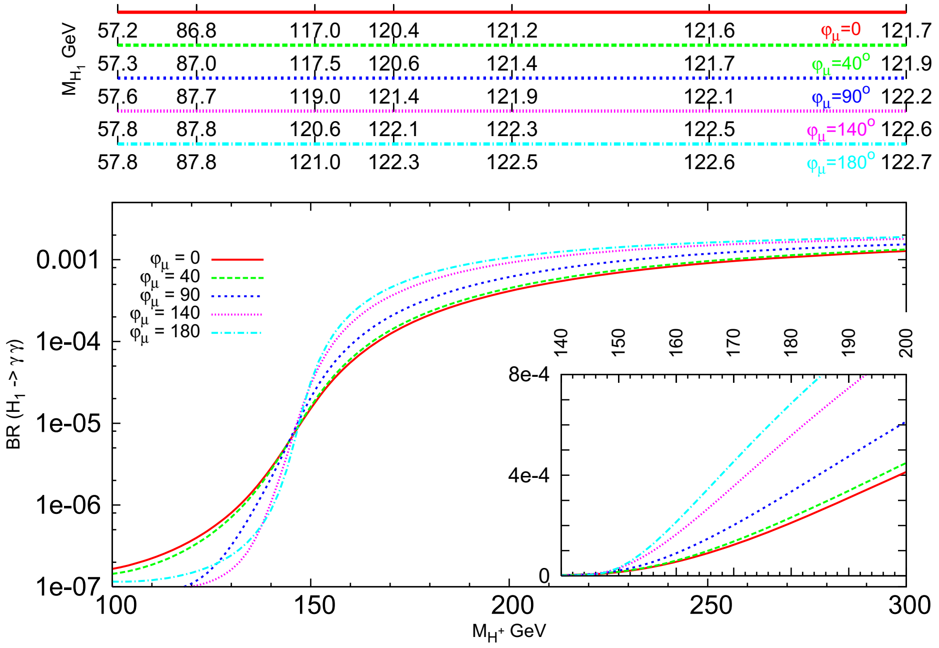
$H_1 \to \gamma\gamma$

Our investigation:

Light $\tilde{t}_1$ does have an effect. We compare this (left) with the no-light sparticle case (right).

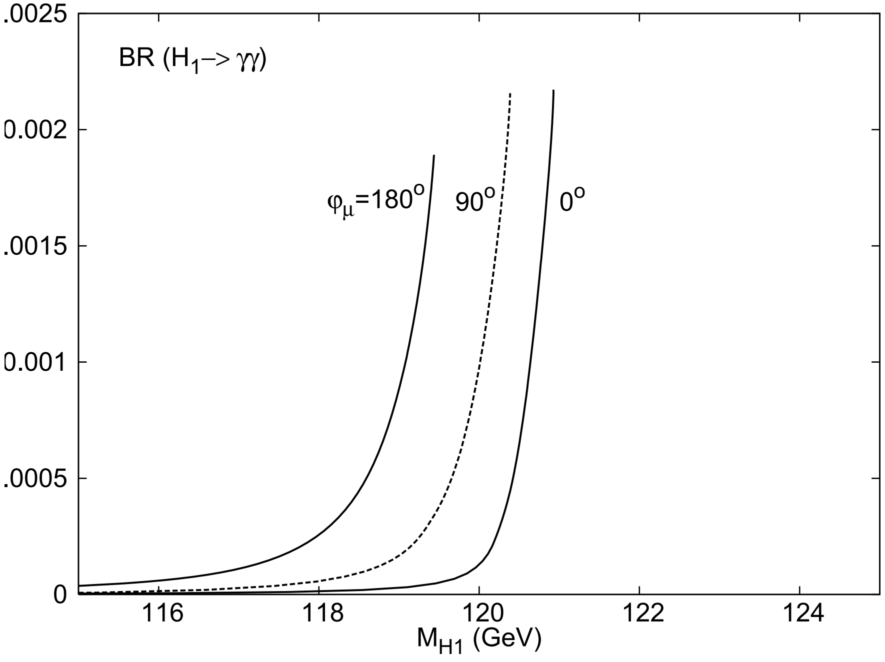
$$A_{\tau,b,t} = 1.5 \text{ TeV}, \;\; \mu = 1 \text{ TeV}, \;\; \tan\beta = 20 \text{ TeV}$$

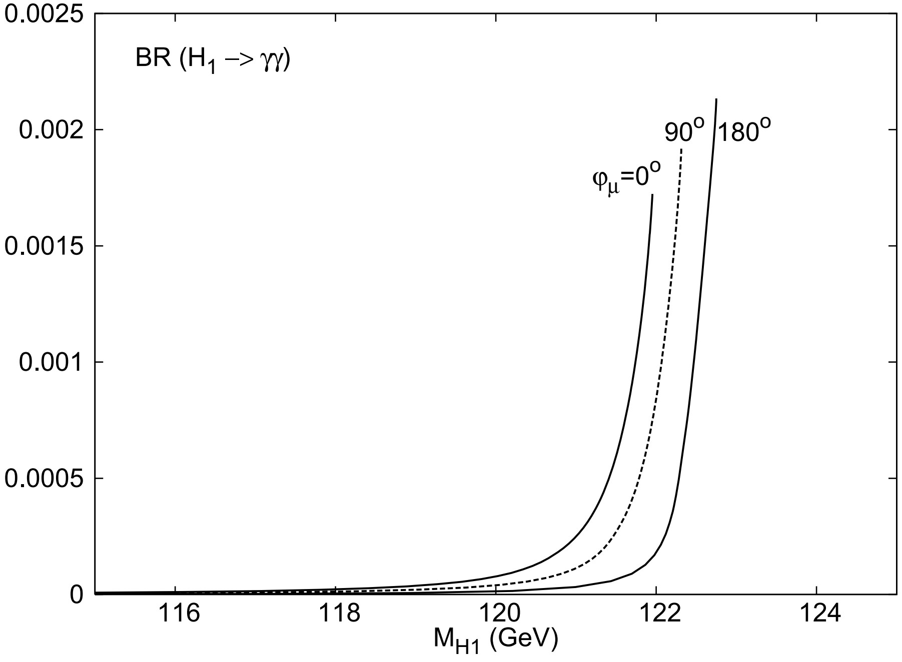




$H_1 \to \gamma\gamma$

Plotting against the physical higgs mass for the same set of parametes:





Summary

- $H_1 \rightarrow \gamma\gamma$ is capable of investigating CP property of MSSM Higgs.
- We worked in a scenario with two phases: those of μ and $A_{\tau,b,t}$
- Sensitivity to CPV phases through
  - Higgs-sparticle-sparticle coupling
  - Higgs mixing (mass eigenstates are CP-mixed states)
- There are parameter space regions where light stop influences the phenomenology
- Other relevant sparticles effects on the process are not significant.

Unfinished

- Production processes: especially the gluon fusion is studied along with diphoton decay.
- Preliminary study shows significant effects of CP violatioin.
- Sensitivity to the presence of light stop also remains.