Explicit CP-Violation in the MSSM
through $gg \rightarrow H_1 \rightarrow \gamma \gamma$

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The CP-Violating MSSM

- MSSM Higgs Sector
- Explicit CP-Violation
Outline

1. The CP-Violating MSSM
   - MSSM Higgs Sector
   - Explicit CP-Violation

2. Phenomenological Aspects
   - The Di-photon Decay Mode
   - Signatures of CP-Violation
Outline

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   - MSSM Higgs Sector
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2. Phenomenological Aspects
   - The Di-photon Decay Mode
   - Signatures of CP-Violation

3. Outlook
The simplest possible MSSM superpotential (with R-parity)

$$W_{\text{MSSM}} = \hat{Q}\hat{H}_u\hat{h}_u\hat{U}^C + \hat{H}_d\hat{Q}\hat{h}_d\hat{D}^C + \hat{H}_d\hat{h}_e\hat{E}^C + \mu\hat{H}_u\hat{H}_d$$

containing two Higgs doublets $\hat{H}_u$ and $\hat{H}_d$ with $Y = \pm 1/2$

The most general Higgs potential in the MSSM can be written as

$$L_V = \overline{m}_1^2(H_d^\dagger H_d) + \overline{m}_2^2(H_u^\dagger H_u) + B\mu(H_d^\dagger H_u) + (B\mu)^*(H_u^\dagger H_d)$$

$$\quad + \lambda_1(H_d^\dagger H_d)^2 + \lambda_2(H_u^\dagger H_u)^2 + \lambda_3(H_d^\dagger H_d)(H_u^\dagger H_u) + \lambda_4(H_d^\dagger H_u)(H_u^\dagger H_d)$$

$$\quad + \lambda_5(H_d^\dagger H_u)^2 + \lambda_5^*(H_u^\dagger H_d)^2 + \lambda_6(H_d^\dagger H_d)(H_u^\dagger H_u) + \lambda_6^*(H_d^\dagger H_u)(H_u^\dagger H_d)$$

$$\quad + \lambda_7(H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_7^*(H_u^\dagger H_u)(H_u^\dagger H_d)$$

where, at tree level, $\overline{m}_1^2 = -m_1^2 - |\mu|^2$ and $\overline{m}_2^2 = -m_2^2 - |\mu|^2$, and

$$\lambda_1 = \lambda_2 = -\frac{1}{8}(g_2^2 + g_1^2), \quad \lambda_3 = -\frac{1}{4}(g_2^2 - g_1^2),$$

$$\lambda_4 = \frac{1}{2}g_2^2, \quad \lambda_5 = \lambda_6 = \lambda_7 = 0.$$
The simplest possible MSSM superpotential (with R-parity)

\[ W_{\text{MSSM}} = \hat{Q} \hat{H}_u h_u \hat{U} + \hat{H}_d \hat{Q} h_d \hat{D} + \hat{H}_d \hat{\mu} \hat{E} + \mu \hat{H}_u \hat{H}_d \]

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+ \lambda_1 (H_d^\dagger H_d)^2 + \lambda_2 (H_u^\dagger H_u)^2 + \lambda_3 (H_d^\dagger H_d)(H_u^\dagger H_u) + \lambda_4 (H_d^\dagger H_u)(H_u^\dagger H_d) \\
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Explicit CP-violation

- Beyond born approximation, two physical CP-violating phases appear in the MSSM Higgs sector: \( \arg(\mu) \) and \( \arg(A_f) \).
- These phases introduce off-diagonal terms in the Higgs mass matrix:
  \[
  M^2_0 = \begin{pmatrix}
  M^2_S & M^2_{SP} \\
  M^2_{PS} & M^2_P
  \end{pmatrix}; \quad M^2_{SP} = (M^2_{PS})^T = v^2 \begin{pmatrix}
  I(\lambda_5 e^{2i\xi}) s_\beta + I(\lambda_6 e^{i\xi}) c_\beta \\
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  \end{pmatrix}
  \]
  where \( \lambda_6 \) and \( \lambda_7 \) are typically proportional to \( (\mu A_f) \).
- Rotation to mass eigenvalues is now carried out by a \( 3 \times 3 \) real orthogonal matrix \( O \) as \( (\phi_1, \phi_2, a)^T = O(H_1, H_2, H_3)^T \), resulting in CP-indefinite Higgs bosons.
- \( O \) enters the effective Lagrangian describing Higgs interactions:
  \[
  \mathcal{L}_{H_i \bar{f} f} = - \sum_{f=u,d,l} \frac{g m_f}{2 M_W} \sum_{i=1}^3 H_i \bar{T}(g^S_{H_i \bar{f} f} + ig^P_{H_i \bar{f} f} \gamma_5) f
  \]
  where \( (g^S, g^P) = (O_{\phi_1 i} / \cos \beta, -O_{ai} \tan \beta) \) for \( f = (l, d) \) and \( (g^S, g^P) = (O_{\phi_2 i} / \sin \beta, -O_{ai} \cot \beta) \) for \( f = u \).
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CP-Violation in $gg \rightarrow H_1 \rightarrow \gamma\gamma$

- We compute the process

- Gluon fusion - leading production process at the LHC for small $\tan \beta$
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Contd...

- $\gamma\gamma$ decay - a promising channel for Higgs discovery at LHC

- CP-phases enter at leading order in both production and decay
- The propagator undergoes CP-mixing at one-loop level

$$D(\hat{s}) = \hat{s}^{-1} \begin{pmatrix} \hat{s} - M_{H_1}^2 + i\mathcal{I}(\hat{\Pi}_{11})(\hat{s}) & i\mathcal{I}(\hat{\Pi}_{12})(\hat{s}) & i\mathcal{I}(\hat{\Pi}_{13})(\hat{s}) \\ i\mathcal{I}(\hat{\Pi}_{21})(\hat{s}) & \hat{s} - M_{H_2}^2 + i\mathcal{I}(\hat{\Pi}_{22})(\hat{s}) & i\mathcal{I}(\hat{\Pi}_{23})(\hat{s}) \\ i\mathcal{I}(\hat{\Pi}_{31})(\hat{s}) & i\mathcal{I}(\hat{\Pi}_{32})(\hat{s}) & \hat{s} - M_{H_3}^2 + \mathcal{I}(\hat{\Pi}_{33})(\hat{s}) \end{pmatrix}$$
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\end{array} \right)^{-1}$$

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Parameter scan for diphoton decay

- For the decay process, we used the fortran code CPSuperH
- MSSM inputs for the code include 
  \( M_{H^\pm}, \tan \beta, \mu, \phi_\mu, M_{(1,2,3)}, \phi_{(1,2,3)}, M_{(\tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3)}, A_f, \phi_{A_f} \)
- \( \phi_{A_f} \) fixed and \( \phi_\mu \) varied
- Collider constraints on loops (s)particle masses taken into account
- Scanned for regions in the parameter space where the difference in 
  \( \text{BR}(H_1 \rightarrow \gamma\gamma) \) due to CP phases is maximized wrt CPC case
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- Minimum variation in Higgs mass and BR with no light sparticle; maximized with a light stop

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Contribution due to Sparticles

- Rise in $BR_{CPV}$ when the $\tilde{t}_1$ is light; maximum variation in its mass

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- Rise in $BR_{CPV}$ when the $\tilde{t}_1$ is light; maximum variation in its mass.
- Negligible variation when the $\tilde{b}_1$ has mass close to the lower bound; $\mathcal{O}(300 \text{ GeV})$.
Total Cross-section

- Fortran code developed for computing $\sigma(gg \rightarrow H_i \rightarrow H_1 \rightarrow \gamma\gamma)$; matrix inversion for the propagator done using Lapack package

- $M_{H^+}$ varied to scan over the $H_1$ mass, along with $\phi_{\mu}$
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Conclusions and Outlook

- Considerable variation in the di-photon production cross-section via the lightest MSSM Higgs due to non-vanishing CP phases.
- Variation also sensitive to absolute values of $\nu$ and $A_f$.
- Need for certain MSSM parameters to be measured before, particularly $t_1$, for concrete evidence of explicit CP-vilation.
- Other Higgs decay channels, e.g. $\tau^+\tau^-$ could be employed for measurement of CP phases once it has been detected.
- Similar analysis of the NMSSM Higgs sector with explicit CP violating phases in progress.
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